Available online at www.sciencedirect.com

SciVerse ScienceDirect

Physics Procedia 39 (2012) 753 – 759

Physics Procedia

LANE 2012

Detection of process failures in Layerwise Laser Melting with optical process monitoring

Tom Craeghs[a,*], Stijn Clijsters[a], Jean-Pierre Kruth[a], Florian Bechmann[b], Marie-Christin Ebert[b]

[a]*University of Leuven, Department of Mechanical Engineering, division PMA, Celestijnenlaan 300B, 3001 Heverlee, Belgium*
[b]*Concept Laser, An der Zeil 8, 96215 Lichtenfels, Germany*

Abstract

Layerwise Laser Melting (LLM) is an Additive Manufacturing process which allows producing complex metallic parts by building parts layer by layer. Monitoring and control of the melting process is needed for further development of the process and future adoption of the process by industry since it allows to monitor the quality of the building process during the actual build job. Furthermore, melt pool monitoring enables a better and more fundamental understanding of the thermal behavior of the process. This paper describes a system for monitoring of the melt pool during LLM and a data processing algorithm to map the measured melt pool data in space. With this so called mapping approach the data interpretation can be significantly reduced. It will be shown that with this system a wide range of process failures can be detected during the process.

Keywords: Laser Melting; optical process monitoring; process control

1. Introduction

Layerwise Laser Melting (LLM) is a layerwise production technique enabling the production of complex metallic parts. In this process thin layers of metal powder are deposited by means of a powder coating system. Next the powder is molten at selected places according to a predefined scanning path by means of a laser source [1]. The laser source is deflected by two galvano mirrors towards the building platform, according to a predefined scan pattern. The process chamber is filled with an inert gas, typically nitrogen gas for processing of steels and argon for processing of reactive materials as e.g. titanium or

* Corresponding author. Tel.: +32-16-32-27-72 ; fax: +32-16-32-29-87.
E-mail address: Tom.Craeghs@mech.kuleuven.be .

1875-3892 © 2012 Published by Elsevier B.V. Selection and/or review under responsibility of Bayerisches Laserzentrum GmbH
Open access under CC BY-NC-ND license. doi:10.1016/j.phpro.2012.10.097

aluminium. Processing in ambient air leads to formation of brittle oxides in the material. The LLM process has a large potential: almost infinite geometric freedom, no need to design/make dedicated tools for production, flexibility for customised individual parts. Since material properties of LLM parts are nowadays comparable to the properties of the corresponding bulk material, applications of the process can be found in quite diverse domains, like the medical sector, e.g. dentistry [2, 3], in tool making industries for manufacturing of tools [4, 5, 6, 7], the general manufacturing industry (machine construction, automotive, etc.) while the potential in production of lightweight structures [8] is investigated for aerospace applications.

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 actions 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 economical feasible - to check the whole part, for instance inner structures, in a non-destructive way.

This paper will discuss detection of process failures in the LLM process using optical process monitoring (i.e. Real-Time monitoring of the melt pool during processing). First section 2 will discuss the LM-Q machine of KUL-PMA, which has a melt pool monitoring system integrated in the optical set-up. The machine control system of the LM-Q allows logging the position of the laser beam with respect to the powder bed, simultaneously with the melt pool data. This opens the possibility for a novel way of representing the melt pool data, namely by mapping the melt pool data on the XY-plane. Section 3 will discuss the results of using this system and data processing tool for a range of processing problems.

2. Melt pool monitoring system

2.1. Melt pool monitoring sensor system

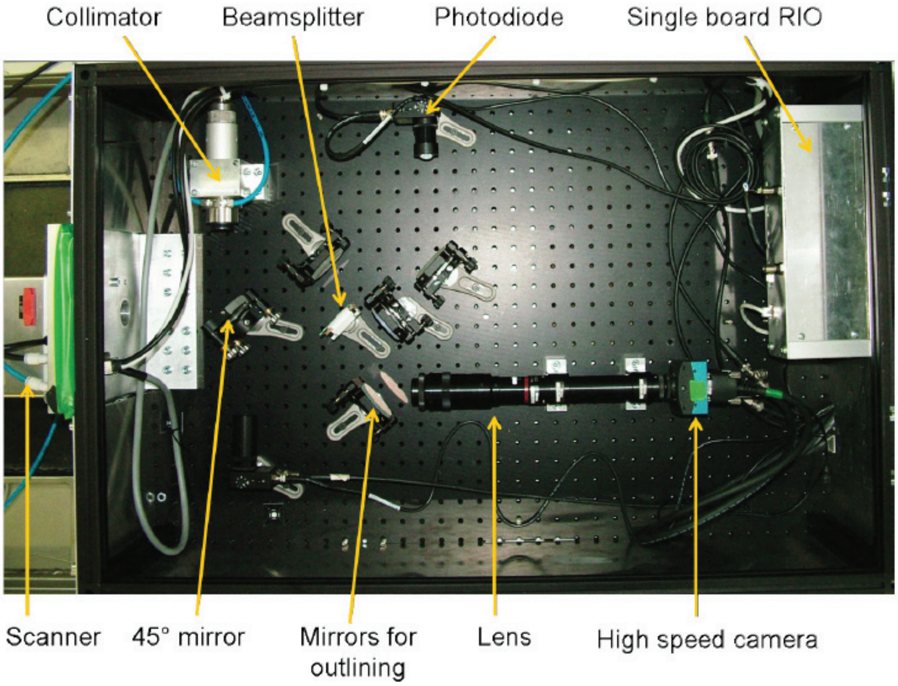

Fig. 1. Optical monitoring set-up of the in-house build LM-Q machine of KU Leuven

Figure 1 shows the optical set-up of the melt pool monitoring system of the in-house developed LM-Q machine of KU Leuven. The working principle 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.

Similar systems have been developed by other research institutes, for instance by Lott et al. [12]. However, their system makes use of an external light source (laser) to illuminate the melt pool.

2.2. Data processing: mapping of melt pool data

This section describes a novel method to present the melt pool data in function of space in stead of in function of **time**, which is called 'mapping of melt pool data'. Interpretation of the melt pool signals on a time scale (in function of time) is not very practical: with this presentation the signals are difficult to interpret since a spatial connection between the various data points cannot be seen directly. A better way of presenting the melt pool signals is by 'mapping' the melt pool data in **space**, on the X-Y plane. If the (X,Y) positions of the laser beam on the powder bed are simultaneously sampled with the melt pool data (see figure), each data point from the melt pool signal can be plotted on an X-Y graph at the corresponding detection location from the powder bed, with the intensity at that point on the graph proportional to the magnitude of the signal. In this way a 'map' can be constructed showing at each location of the map the magnitude of the melt pool which occurred at the corresponding location of the build platform. This method is therefore called 'mapping of melt pool data'. Examples will be discussed in the next section.

The measured melt pool data are actually mapped on a regular grid. Thus, all melt pool data are assigned to the pixel which is closest to the corresponding measured position. When more than one data point is assigned to a pixel, the average of all data inside the pixel is taken. In this way for every layer a two dimensional picture is constructed, consisting of 'pixels'. If mapping of all layers is achieved, also a three-dimensional 'voxel' model can be constructed. This 3D-model can then be used to calculate other cross-sections through the data.

Next paragraph will show examples of using the mapping approach for detection of several processing problems during SLM.

3. Results and Discussion

This section discusses using of the melt pool monitoring system and the mapping approach for detection of typical processing problems during SLM: detection of deformation due to thermal stresses and overheating at overhang structures.

3.1. Detection of deformation due to thermal stresses

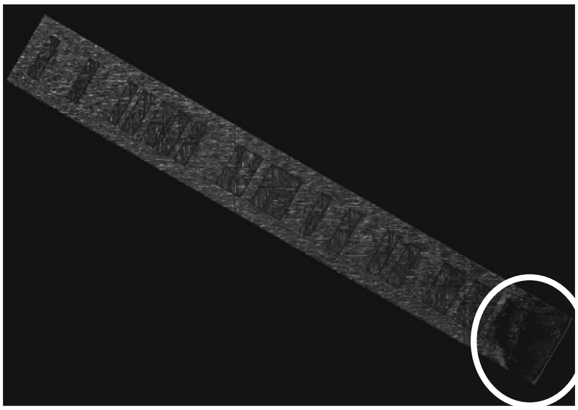

Fig. 2. Mapping of the melt pool area signal. The dark zone on the right side of the part is due to the deformation of the part

A typical physical phenomenon in Selective Laser Melting is the occurrence of high thermal stresses. These stresses are caused by the so called 'Temperature Gradient Mechanism' (TGM). It is important to detect deformation of the part in the earliest possible stage of the process since this problem causes the part to fail. Figure 2 shows mapping of the melt pool area of a layer in a rectangular part. In the middle of the part, some zones are scanned with 20% less laser power than the nominal power (42W). The mapping of the melt pool area shows a dark zone at the right side of the part (at the bottom of the image). This dark spot results from the curling of the part and sticks out above the powder bed. When the laser scans on this zone, the laser beam is out of focus (the focal plane is on the powder bed) and the heat input from the laser can flow away more easily when the melt pool is surrounded by (insulating) powder material. Because of the enlarged beam diameter and the reduced thermal resistance, the signals captured by the melt pool sensor are reduced in magnitude. Therefore the zone appears as darker (signal reduced in magnitude) than the nominal situation.

3.2. Mapping of overheating at overhang structures

An overhang zone corresponds to a zone in a layer where the melt pool is surrounded by powder material. During scanning of an overhang zone the melt pool size will grow substantially larger, due to the lack of heat conduction from the melt pool to the surrounding. The overheating of the melt pool at the overhang zone has a large negative effect on the surface quality of the downfacing surface.
In practice, overhang structures are always build with structures supporting the overhang, because of two reasons: they prevent the overhang layer from curling up and they provide a heat sink for the overhang layer to cool down.

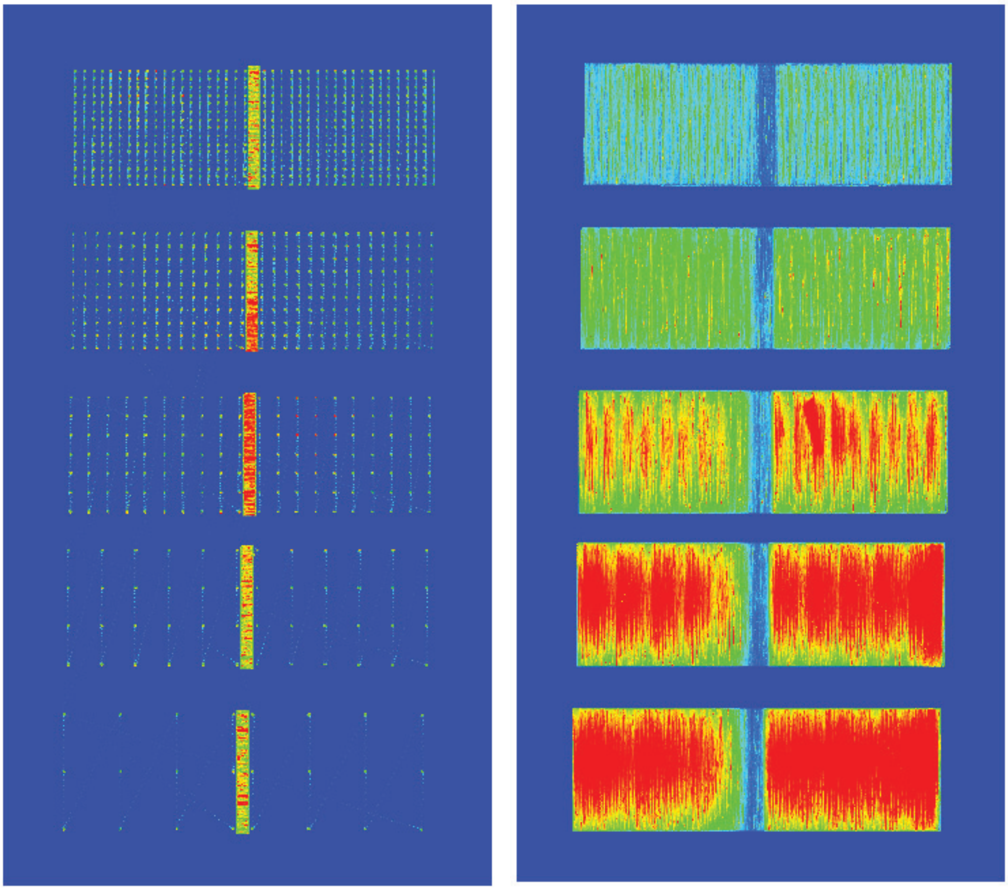

Fig. 3. Mapping of the melt pool area signal. (a) the last layer before the overhang zone (showing the support structures); (b) the overhang layer. More overheating occurs at zones with less supports

Figure 3 shows mapping images of the melt pool area signal of the layer before and the overhang layer itself (in figure 1.6 support structures are visible as dots in the images). The produced parts are T-shaped, with varying amount of support structures underneath the overhang layers, increasing from top to bottom. It can be expected that the overhang layer of the top part experiences less overheating than the bottom part, since there is a larger heat sink. The mapping confirms the expected melt pool behavior: the overhang layer of the top part is more uniformly heated and much less overheating occurs than in the bottom part, where in the middle of the overhang layers (most far from the heat sink of the supports) the overheating is the strongest.

The monitoring system and mapping method are tools which can strongly support further development of automatic support generation. It is for instance not always possible to measure a posteriori the effect of various support structures on the quality of the overhang zones, but with the monitoring system during processing accurate information on the melt pool overheating (and thus surface quality and density) can be obtained.

4. Conclusions

This paper presented a monitoring system for real-time process monitoring of the melt pool during the Layerwise Laser Melting process. A novel way of presenting the data has been discussed, namely by mapping of the melt pool data on the X-Y plane. This can be achieved by simultaneously sampling and logging of the position and melt pool data. The mapping approach is a very powerful method to assess and interpret the captured data. Examples have been discussed in which the melt pool mapping has been used to detect deformation due to thermal stresses and overheating at overhang zones.

This system and data processing method can be used as a start point for automated melt pool inspection in the LLM process. However, algorithms still need to be developed further which allow to extract the necessary information from the mapping pictures.

References

[1] J.-P. Kruth, P. Mercelis, J. Van Vaerenbergh, L. Froyen, and M. Rombouts. Binding mechanisms in selective laser sintering and melting. Rapid Prototyping Journal, Vol. 11/1, pages 26-36, January 2005.

[2] J.P. Kruth, J. Van Vaerenbergh, P. Mercelis, B. Lauwers, and I. Naert. Dental prostheses by selective laser sintering. In 10mes Assises Europennes de Prototypage Rapide, Paris, 14 & 15 September 2004, 2004.

[3] B. Vandenbroucke. Rapid manufacturing of dental prostheses by means of sls/slm. In 11e Assises Europeennnes du prototypage rapide, Paris- Maison de la Mecanique, 4-5 October, 2005, 2005.

[4] F. Abe, K. Osakada, M. Shiomi, M. Matsumoto, and M. Shiomi. The manufacturing of hard tools from metallic powders by selective laser melting. Journal of materials processing technology, 111:210–213, 2001.

[5] F. Klocke, H.Wirtz, and W. Meiners. Direct manufacturing of metal prototypes and prototype tools. In Proceedings solid freeform fabrication symposium, Austin, august 1996, 1996.

[6] U. Berger. Rapid tooling and computertomography for aluminium casting of automotive components. In uRapid 2001 International users conference on rapid prototyping & rapid tooling & rapid manufacturing, 2001.

[7] A. Voet, J. Dehaes, J. Mingneau, J. P. Kruth, and J. Van Vaerenbergh. Study of the wear behaviour of conventional and rapid tooling mould materials. In International Conference Polymers & Moulds Innovations PMI, Gent, Belgium, April 20-23, 2005, 2005.

[8] O. Rehme and C. Emmelmann. Rapid manufacturing of lattice structures with selective laser melting. In Proceedings of SPIE Photonics West, LASE 2006 Symposium, LBMP-III conference, San Jose, California, USA, January 2006.

[9] David L. Bourell, Ming C. Leu, and David W. Rosen, editors. *Roadmap for Additive Manufacturing: Identifying the Future of Freeform Processing.* The University of Texas at Austin, Laboratory for Freeform Fabrication, Advanced Manufacturing Center, 2009.

[10] Tom Craeghs, Florian Bechmann, Sebastian Berumen, and Jean-Pierre Kruth. *Feedback control of Layerwise Laser Melting using optical sensors.* Physics Procedia, 5:505 – 514, 2010.

[11] J.-P. Kruth and P. Mercelis. *Feedback control of Selective Laser Melting of iron based powder.* In Proceedings of the 14th International Symposium on Electromachining, Vol. 2, 2007.

[12] Philipp Lott, Henrich Schleifenbaum, Wilhelm Meiners, Konrad Wissenbach, Christian Hinke, Jan Bültmann, Design of an Optical system for the In Situ Process Monitoring of Selective Laser Melting (SLM), Physics Procedia 12, 683-690, 2011.