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High speed melt pool & laser power monitoring for selective laser melting (SLM®)

Daniel Alberts[a,]*, Dieter Schwarze[a], Gerd Witt[b]

[a]SLM Solutions GmbH, Roggenhorster Straße 9c, 23556 Lübeck, Germany
[b]University of Duisburg-Essen, Institute of Product Engineering, Lotharstr. 1, 47057 Duisburg, Germany

Abstract

Layer based additive manufacturing can now look back on a long history of about two decades. Through today's establishment of SLM® process it is becoming more and more relevant in industrial production environments. Sensitive markets such as energy, medical and aerospace have the highest quality standards for complex, safety-related and highly stressed components which are to be met at competitive costs for each build job and part.
The development priorities for existing and new Selective Laser Melting machines are set by the SLM Solutions GmbH on continuous work and improvement of reliability, productivity and reproducibility.
To achieve existing QM requirements, various methods for in-situ process monitoring are designed to further process understanding and to demonstrate part quality. This paper presents the current state of development of two on-axis systems for real-time monitoring of the melt pool and laser power during the build job at a frequency of up to 100 kHz.

Keyword: High speed; melt pool monitoring; laser power monitoring; Selective Laser Maelting (SLM®); on-axis; in-situ.

1. Motivation and State of the Art

Due to further development of Additive Manufacturing (AM) systems customer requirements such as productivity, repeatability and reliability could enormously increased. Those results to a rising acceptance of the technology compare to conventional manufacturing processes. Besides, the technology application has already reached small-batch manufacturing and quantity production. To be able to illustrate this for a broader material choice and for safety-related as well as highly-stressed components at competitive costs, the calls for meaningful systems and methods for process monitoring and quality assurance are loud in sensitive markets.

From the history of laser material processing and in particular of laser deposition welding numerous examples of process monitoring are known, which have experienced the transition to production-ready conditioning systems and are used successfully today, Kogel-Hollacher et. al. (2014). In particular, Selective Laser Melting offers numerous examples of variants of on-axis and off-axis process observations which also due to lower measuring frequency, starting from a few kHz, are limited in their informational value. In addition to not ensured data interpretation, limited materials tests and conditional analysis of much more complex geometrical features such as lattice and honeycomb structures, supports, overhang and down facing surfaces, Tapia and Elwany (2014), systems are required for process monitoring, which enable with a high resolution and fast measuring frequency the basis for those challenges. Such reactive monitoring systems were usually implemented by different groups in a scientific environment on laboratory systems, Thombansen et. al. (2015). To meet industry demand for appropriate quality assurance systems and enabling the possibilities of an evaluation of the complete production process, there is a need to provide SLM® manufacturing systems with suitably equipped QM modules.

* Corresponding author. Tel.: +49-451-16082-186; fax: +49-451-16082-250 .
E-mail address: daniel.alberts@slm-solutions.com

2. Experimental

Below the machine system setup and additional adjustments of the optical system are described by sub-section 2.1. The implementation, operation and representation with respect to Melt Pool Monitoring and Laser Power Monitoring will be discussed in sub-section 2.2 and sub-section 2.3.

2.1. Machine and Optical System Setup

The in-situ process monitoring systems to be developed requires the possibility of integration and usage in established manufacturing systems of SLM Solutions. In addition, the systems are designed to work regardless of machine size and machine types, e.g. multi-laser / multi-scanner systems and the kW power range. Fig. 1 (a) exemplary shows a SLM 280^{HL} and the optic design of a modular-built manufacturing system of SLM Solutions as a part of the whole machine concept are schematically shown in Fig. 1 (b).

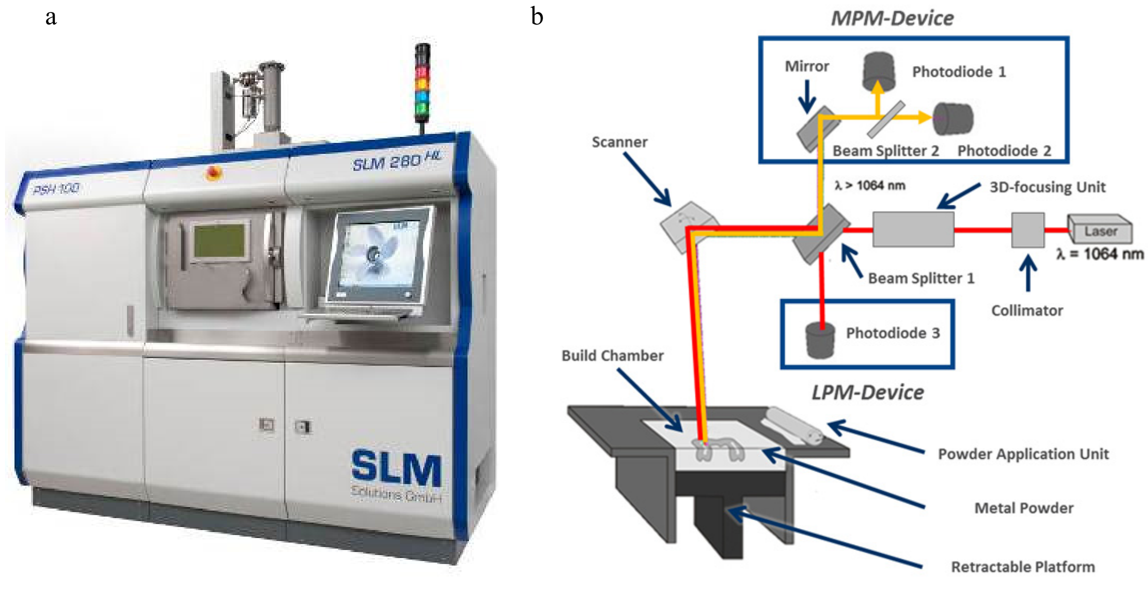

Fig. 1. (a) SLM 280^{HL}; (b) Schematic assembly of optic design with Melt Pool Monitoring and Laser Power Monitoring.

The fiber tip of a diode-pumped single-mode CW fiber laser is coupled into a collimation unit, which is adjusted for the particular machine system. The collimated beam is led axially to a dynamic focusing unit, which allows a highly dynamic and high-precision positioning of laser focus along the optical axis. This unit was optimized for applications with high power densities in particular and replaces elaborate flat-field objectives. A scan system with digital control electronics and customized coating is used for high-precision positioning and deflection of the process beam to the particular process plane.

The process radiation occurring from the exposure of several vector types and locally welded powder particles is a thermal signal which is diffusely emitted from the melt pool. It is utilized as input value of the Melt Pool Monitoring device. A special beam splitter 1 is applied to deflect the part of emitted thermal signals, which are back-reflected along the optical axis into the opposite direction of the beam. The beam splitter reflects thermal emissions at the rear surface seen from direction of the fiber. The upwards deflected wave lengths from primary optical axis are led vertically to the optical buildup of the Melt Pool Monitoring device in which beam splitter 2 divides the signals for photodiode 1 and 2.

The front surface of the beam splitter 1 transmits the laser wavelength and a proportion of a reflection serves as an input signal of the photodiode 3 for the Laser Power Monitoring device.

2.2. Melt Pool Monitoring

The presented Melt Pool Monitoring system uses two photodiodes with different sensitive areas. The signals are permanently taken up by the individual photodiodes, forwarded to an ADC (analog digital converter) and provided in an FPGA (field programmable gate array). ADC 1 is associated photodiode 1 and ADC 2 is associated photodiode 2. In favor of the signal-to-noise ratio measurements result by averaging of hundreds of individual measurements. Depending on machine and optical system setup as well as taking into account two different photodiodes the signal-to-noise ratio is at present up to 10. The measured value of the thermal emission of the photodiode 1 and 2 are output to these present x/y-coordinates (16-bit) in parallel as well as the laser-on/off signal from the FPGA to the PC every 10 µs. The FPGA controls the correct timing of the input signals, other potential operations and the subsequent measurement task of 10 µs. All data packages of a measurement task will be stored per layer in a data file and can be traced back clearly due to time function and are able to read out. After completion of the exposure of the current layer, a new file is created automatically. The completed file is represented in the form of a 2D representation of the whole build platform and the associated signals see Fig. 2.

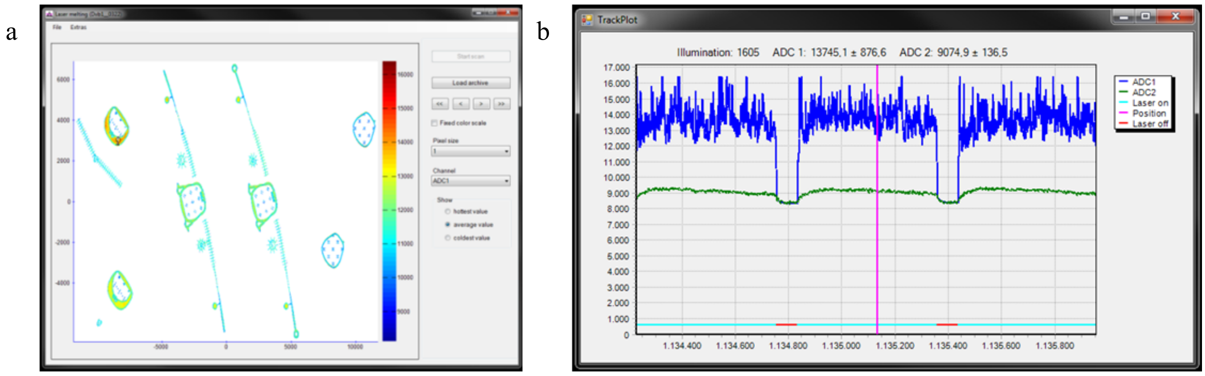

Fig. 2. (a) Layerwise x/y 2D representation of thermal emissions; (b) Complementary Track Plot of selected scan vector.

During the ongoing process monitoring viewing of the previously recorded layer information of the actual manufacturing process is possible. This ensures the direct analysis of the current process.

2.3. Laser Power Monitoring

As described in sub-section 2.1, the reflected part of the laser wavelength via beam splitter 1 is used as input signal (measured laser power) of the current laser power (laser power set value) by means of photodiode 3. The consumed electric current is converted into an electrical voltage and provided every 100 kHz via ADC while synchronous to that the laser power set value is also detected and transferred to the LPM device. The data are provided with a uniquely assigned time stamp and transmitted via LAN to a PC. The visualization of the time resolution measured laser power and the laser power set value is displayed directly in the software during the process. Fig. 3 illustrates a non-calibrated, (a), and a calibrated signal sequence, (b).

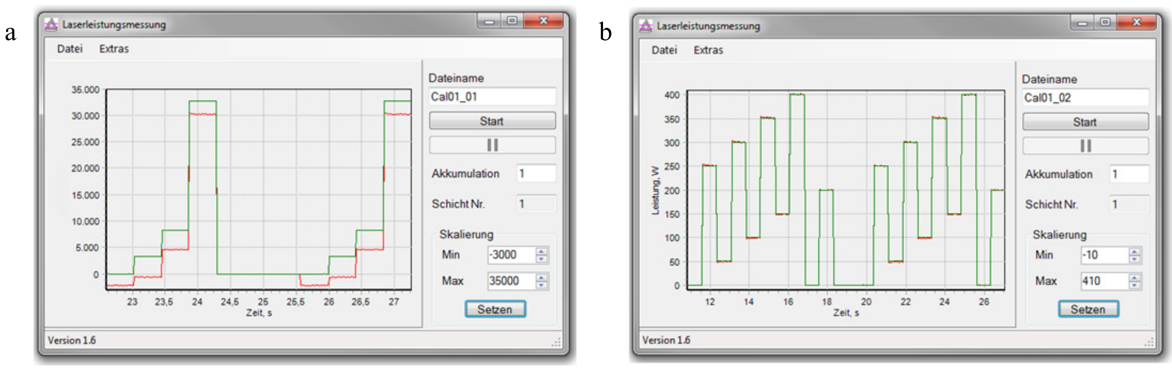

Fig. 3. (a) Adjustment for set and measured laser power; (b) Calibration rechecks for laser power adjustment up to 400 W.

The calibration of the Laser Power Monitoring system takes place immediately after the measurement of the laser power in the manufacturing system and the submission to the machine control environment. To be seen under (a) the green curve corresponds to the laser power set value of selected points for calibration. After detecting the corresponding signal strength at photodiode 3, that can perform a calculated match of the laser power curve. Under representation (b) it can be seen the laser power curve between 0-400 W now displayed at various laser power levels after calibration. To reduce the amount of data, a user-specific accumulation of the measured laser power is considered. During an active measurement, this can be paused and entails the possibility of direct analysis of the already recorded data. In the case that the measurement is not stopped the analysis of the active measurement is carried out without data loss.

3. Results and Outlook

By developing complementary quality assurance systems, it is possible to monitor the holistic production history of AM components and evaluate after individually customized quality characteristics. The presented Melt Pool Monitoring system provides by a repetition rate of 100 kHz (10 µs) the opportunity of a detailed x/y resolved representation of thermal emissions. Since the layer file contains all geometrical information as well as the exposure sequence a 2D visualization like Fig. 2 (a) can be drawn. Thus, it is possible by signal references to document and to classify the entire manufacturing process. The Laser Power Monitoring system offers the possibility of time-resolved and permanent on-axis control of the laser power. By the end user individual to be defined deviation boundaries between the laser power set value and measured laser power can thereby be used for quality assurance. Creeping inadequateness by contamination on the optical system (focusing unit, collimator, fiber end of the laser) or even failure of laser diodes can be registered and logged directly. Thus, downtime can be reduced due to specific service calls and components which do not meet their quality requirements are avoided.

The integration of the modules featured in current series systems of SLM Solutions forms the basis for further material-specific studies relating to various system, process and environmental influences. Further process relations and the constantly growing process understanding will lead to couple QM modules with each other to increase the informational value of existing quality features. Turns out to the need and the appropriate use of complementary control mechanisms that featured QM modules can be used. For example the presented Melt Pool Monitoring system provides for development purposes already a quasi closed-loop control function which allows an adjustment of the laser power in about 60 µs. Moreover, for these modules other potential fields of application are under development as well as solutions for multi-laser / multi-scanner systems, Wiesner et. al. (2014). This is the logical consequence to the existing value of these modules to be used for systems of higher productivity.

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