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Design of an Optical system for the In Situ Process Monitoring of Selective Laser Melting (SLM)

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Abstract

Selective Laser Melting (SLM) is an Additive Manufacturing technology that enables the production of complex shaped individual parts with series identical mechanical properties. Areas of improvement are up to now quality and reproducibility of parts made by SLM due to different kinds of errors. Therefore the integration of a monitoring and control module into a SLM-machine is aspired. The design of such an optical system capable of monitoring high scanning velocities and melt pool dynamics is introduced as a first step.

Keywords: Selective Laser Melting; SLM; process monitoring

1. Introduction

The market competition originated from countries with low-cost work forces exerts pressure on companies worldwide and leads to a focus on innovation. Besides this, the increasing competition is also compelling industries to improve the efficiency of production processes, e.g. increasing automation level or process productivity.

Considering industrial production in high-wage countries today, these trends can be cut down on two dilemmas (see Figure 1 (a)). [1] The first dilemma refers to the “value-oriented vs. planning-oriented” production. The former approach focuses on value adding processes (without consideration of planning-, preparation-, handling- and transport processes) while the latter focuses on extensive planning in order to optimize value-adding (modeling, simulation, information gathering). The second dilemma is related to the “scale-scope” dimension. Either the production system is designed for high scale output without variances in the product design (critical mass, business and manufacturing process decomposition, mastered processes) or it is designed for individual products down to a production batch of a unique product (one-piece-flow, complex and highly integrated processes). The resolution of this production-related polylemma is the main target of the Cluster of Excellence “Integrative Production Technology for High Wage Countries”

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Especially the scale-scope dilemma is boosted by global trends like mass customization and open innovation which result in a demand for highly individualized products at costs matching or beating those of mass production. One of the areas of greatest potential for the resolution of this dilemma are Additive Manufacturing (AM) technologies due to their almost infinite geometrical variability and freedom of design without the need for part-specific tooling. Selective Laser Melting (SLM) is one of the AM technologies for metallic parts that additionally provides series identical mechanical properties without the need of downstream sintering processes, etc. which predestines it for individualized manufacturing.

However, quality and reproducibility are still areas of improvement and are often referred to as Achilles' heel of AM technologies. [2] During the SLM-process different kinds of errors can occur e.g. insufficient powder supply, internal errors such as incomplete melting, pores, sinkholes or even part deformation. Errors cannot be avoided by improved process conduct due to their dependence on the geometrical variability. Furthermore, their internal location often impedes a downstream repair process. The first step to a closed-loop process control module for the prevention of those errors is the development of a process monitoring system. Such a system has to be capable to observe the melt pool and its dynamics time and space resolved in order to detect the occurrence of build errors while they emerge.

2. SLM process

The ILT-developed SLM process is an Additive Manufacturing process that fabricates metallic components – layer by layer – directly from 3D-CAD data. This process enables the production of nearly unlimited complex geometries. The material used in the SLM process is a metallic or ceramic powder which is deposited as a thin layer (approx. 50 µm) on a substrate plate. The powder is selectively melted under an inert atmosphere by a laser beam according to the CAD model (see Figure 1 (b)).

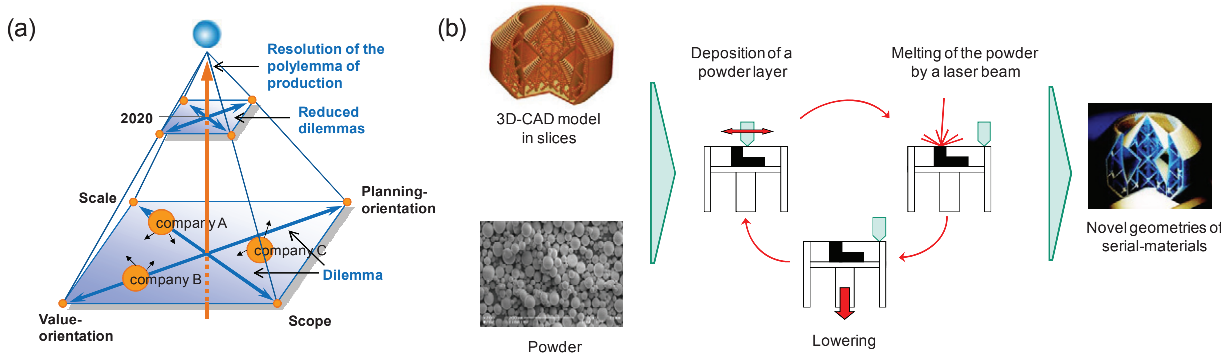

Figure 1. (a) Polylemma of production, (b) Schematic representation of the SLM process

Subsequently, the substrate plate is lowered by one layer thickness and a new powder layer is deposited above. Again, this layer is selectively melted and metallurgically bonded to the layer below. The scan direction is alternated after each layer in order to deter imperfections from growing throughout several layers. Hence the final component is built of many single layers. The use of standard metallic powders and the complete melting enables a density of approximately 100% which in turn assures mechanical properties that match or even beat those of conventionally manufactured parts. In sum the SLM process enables a single component to combine the benefits of high geometrical freedom and functional integration with series suitable mechanical properties.

3. Process Monitoring

3.1. Monitoring laser material processing

Different methods and sensor types exist for process monitoring of laser material processing. Most frequently used are the observation of back reflected laser radiation (for Disc laser sources at a wavelength of $\lambda = 1030$ nm), plasma induced radiation ($\lambda = 400$ nm to 650 nm) and thermal radiation ($\lambda = 900$ nm to 2300 nm). The used detectors can be separated into two types; spatially integrating, e.g. photodiodes and spatially resolving, e.g. CCD- and CMOS-cameras. Yet, these methods provide only limited information about the material surface structure. Therefore imaging sensors in combination with an external illumination of the interaction zone and its neighborhood are required for capturing the surface structure and the melt pool shape. [3]

Examples for coaxial process control systems in laser material processes are laser brazing, hybrid laser-arc welding, laser welding and cutting. In laser brazing process parameters like position and orientation of the solder wire or the dimension of the liquid phase can be determined by analyzing the images taken by a CMOS camera. Additionally, the surface of the solidified seam can be evaluated. [4] In hybrid laser-arc welding the melt pool and the solid-liquid phase boundary can be determined. It is possible to visualize welding defects in the state of their emergence. [3] The relative displacement between laser processing head and work piece as well as the measurement of the melt pool geometry can be obtained by a process monitoring system in laser welding and cutting. [5]

3.2. Monitoring SLM

Kruth et. al. demonstrate a system capable of monitoring the SLM-process to adjust the laser power and improve the problem of overhang structures. [6] The process image recording is carried out coaxial with two types of sensors, a CMOS-camera and a photodiode. Through the correlation of the melt pool size which is obtained by the CMOS-camera and the integrated signal of the photodiode the system is able to adjust the laser output power according to areas of varying thermal conductivity (e.g. overhang structures). However, the requirements for the imaging of the melt pool dynamics, e.g. an additional illumination source for high resolved pictures, are not met by this system

4. Optical Setup

For imaging the melt pool dynamics space and time resolved an additional illumination is necessary for high resolved pictures at high scanning velocities. Internal experiments show that with a lateral assembling of camera and illumination source from a certain amount of illumination power the powder begins to sinter. Additionally the area which can be imaged by a stationary camera is very limited. Therefore the process monitoring system is to be designed with a coaxial assembling structure.

4.1. Basic Structure

The basic structure of the process monitoring system is shown in Figure 2 (a). The machining laser beam is deflected towards a scanner by means of a dichroic mirror. The scanner deflects the beam according to the geometric information acquired from the CAD model. Finally, the beam is focused onto the machining plane by means of an f-Theta objective. The processing area is illuminated via an illumination laser beam. The illumination beam is deflected by means of a beam splitter and transmitted by the dichroic mirror. Positioning and focusing are achieved according to the machining laser beam. The image information from the processing area is transmitted through the f-Theta objective, scanhead, dichroic mirror and beam-splitter backwards throughout the entire system. The assembling has to be designed to avoid ghost images and enable the image information to be focused on the high speed camera chip. The beam-splitter, the dichroic mirror and the single optics only have to be designed for one wavelength whereas the scanner and the f-Theta objective have to be designed for both wavelengths (illumination and machining).

4.2. Requirements

Magnification of the optical system is the essential requirement and is defined by the ratio of the camera's imaging size to the image spot in the machining plane. Due to the application of the system in SLM prototype with an integrated multi beam concept two different laser spot diameters need to be imaged on the camera chip. [7] Furthermore, this prototype offers includes a 1 kW disc laser source. Hence, monitoring a wide range of parameters in an approved concept with a big experiential background will be possible. Based on the two laser spot diameter of 0.2 mm and 1.05 mm and the request for imaging both the entire melting pool and the melting front in detail, the image spot size varies between 0.2 mm x 0.2 mm and 5 mm x 5 mm (see Figure 2 (b)). The camera's imaging area is calculated by the pixel size times the desired resolution. With a camera's pixel size of 14 µm and two desired resolutions of 128 x 128 and 256 x 256 pixel the imaging area sizes are 1.79 mm x 1.79 mm and 3.58 mm x 3.58 mm respectively. Therefore the optical system has to cover a magnification range from 0.35 to 18. Instead of using a zoom lens the wide range of magnification is to be enabled by a modular optic casing system which allows a rapid and precise lens change.

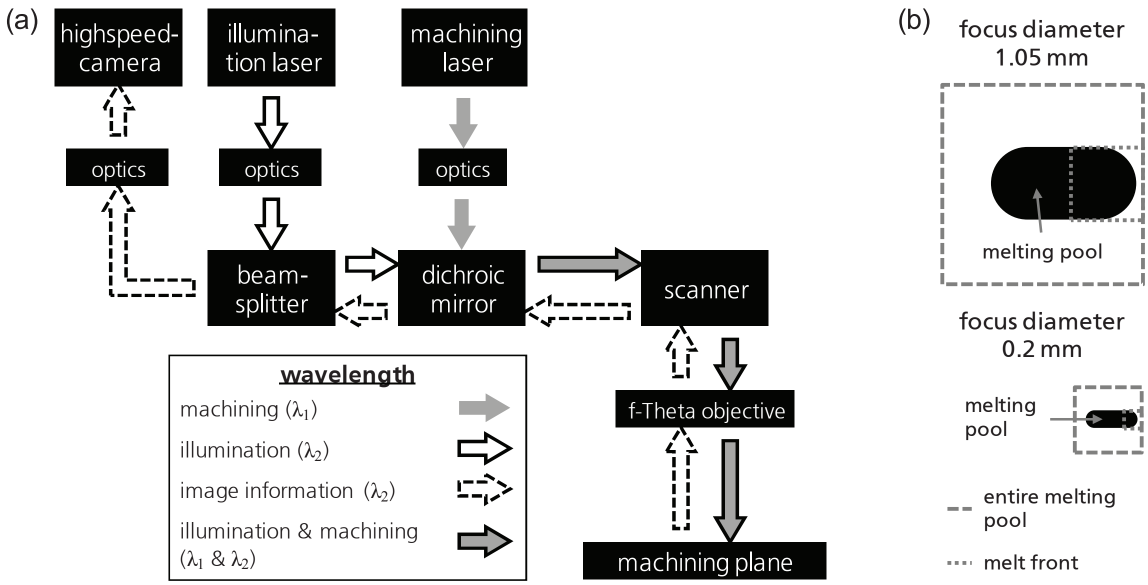

Figure 2.(a) basic structure of the process monitoring system, (b) illustration of the different imaging sizes

4.3. Optical Design

In order to ensure a good imaging quality over the entire magnification range, three different optical concepts are used; 1. the principle of a Relay-objective, 2. a Telephoto-objective and 3. a simple one lens system. The Relay-objective is a microscope alignment combining two lenses both with a positive focal length. The second lens is thereby placed in short distance after the focal point of the first lens. The Relay-objective is used for high magnifications. For magnifications from 1.2 to 3.5 a Telephoto-objective is used. It combines a lens with a positive focal length with a lens with a negative one. The latter is positioned before the focal point of the former. Simple one lens systems are used for the lowest magnifications. Criteria are imaging quality, overall length, distance between camera plane and last lens and sensitivity of adjustment.

In a first step a paraxial design approach is used to compare different lens combinations regarding the given criteria. Based on this paraxial design several lens combinations are selected while keeping in mind the minimization of the overall number of lenses, time reduction and changing effort between different magnifications.

Based on a first setup the entire imaging light path is modeled in the ray tracing software ZEMAX© (see Figure 3). Starting in the object (machining) plane three different object positions are modeled. One in a central position resulting in a perpendicular bunch of rays and two further positions linked with a distance of approximately 70 and 100 mm to the central position. The first interaction takes place with the protective glass of the process chamber. This glass is necessary to build up an inert atmosphere during the process. The next object is the f-Theta objective which can only be approximate by two paraxial lenses due to the fact that no objective-model with a color-correction for the two wavelengths and the desired focal length is available on the market. Being reflected by the scanner mirrors the imaging rays are transmitted by the dichroite and the beam splitter respectively. At this point the actual imaging optic system begins. The lens combination in Figure 3 is a Telephoto-objective arrangement that focuses the rays coming from the object plane onto the image plane which is in this case the camera chip.

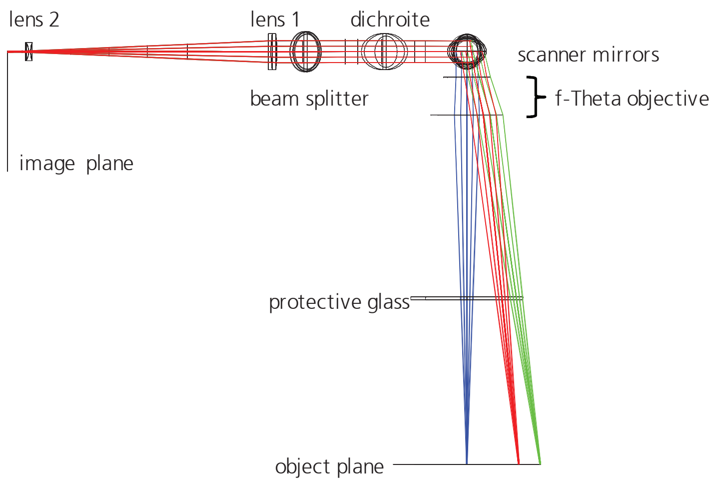

Figure 3. ZEMAX model of the imaging light path

4.4. Analysis

For analyzing and optimizing the optical system spot diagrams and fast fourier transformation (FFT) modulation transfer functions (MTF) are used. Figure 4 exemplifies the diagrams for a magnification of 3.5 and an object size of 1.5 mm x 1.5 mm. Thus, the selected camera resolution is 256 x 256 pixels. According to Figure 3 the diagrams represent the three different object positions (central and linked with a distance of approximately 70 and 100 mm respectively, from top to bottom). The object size is described by three field points, one central and two with a distance of 0.75 mm. To analyze the imaging quality the Airy-diameter is shown in the spot diagrams and the diffraction limit in the MTF-diagrams.

The spot diagrams for the central object position shows scattering figures with a centroid central inside the Airy-diameter. All rays are concentrated in a circle. For the left and right field point the centroid is slightly shifted to the border. Due to the off-axis position the scattering figures show comatic aberration. With regarding the linked position the phenomenon of coma can be observed also for the central field point. The left field point which is closer to the center shows for both linked positions less comatic aberration than the right field point. Nevertheless, in all spot diagrams no ray is located outside the Airy-diameter. Therefore, the imaging performance of the model is limited by the diffraction and not by the optical system's aberrations.

The MFT-diagrams does not show a significant difference to the diffraction limit for all positions and field points. Other magnifications and object size show similar results. Yet, definite conclusions only can be drawn as soon as an f-Theta objective model is implemented into the simulation.

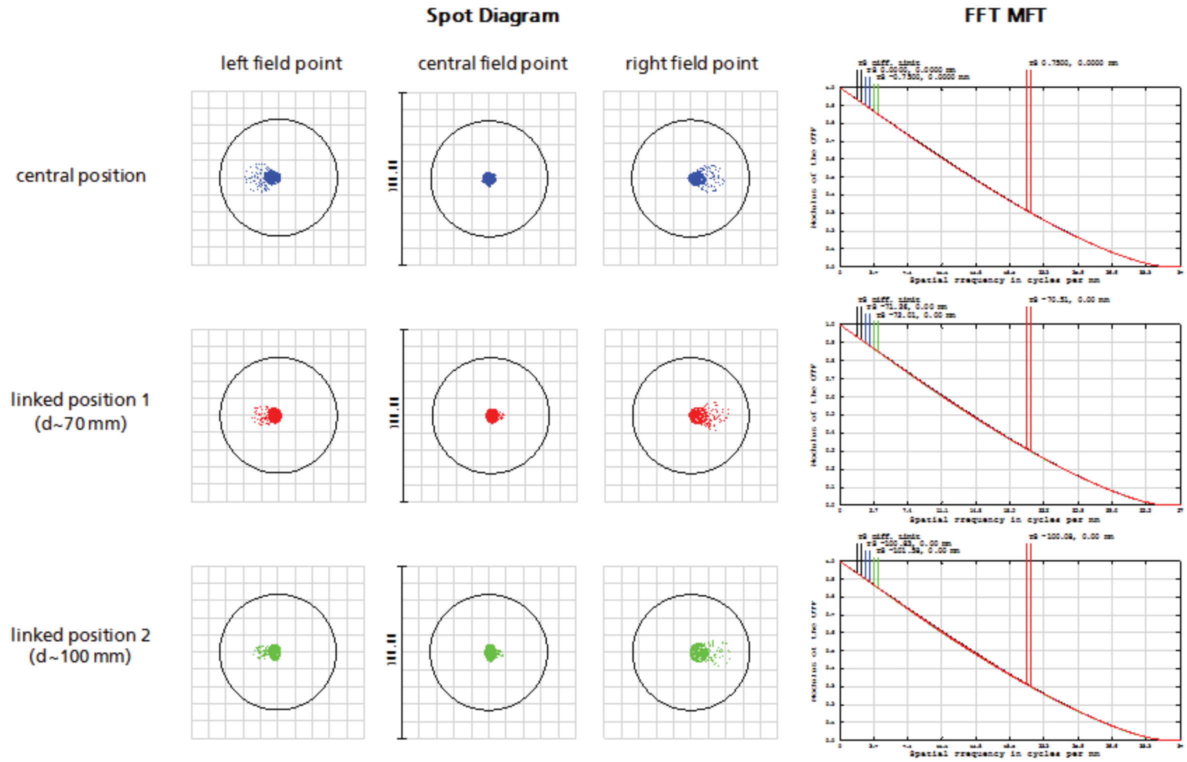

Figure 4. spot diagrams (left) and FFT MTF diagrams (right) for a magnification of 3.5 and an object size of 1.5 mm x 1.5 mm for different object positions

5. Preliminary tests

In order to validate the concept preliminary tests are conducted to show the concepts abilities and possible drawbacks. In Figure 5 (a) the test assembling is shown. The light path is oriented in the horizontal plane to allow easy adjustments. The tests are carried out using a colour-corrected f-Theta objective for two wavelengths with a shorter focal length than desired and a galvano scanner with silver mirrors. Aim of the test is to prove the performance of the imaging system. Therefore, imaging has to be tested at high scanning velocities.

A screenshot of a high speed recording is shown in Figure 5 (b). Based on the millimeter paper background the illumination spot has a size of approximately 5 mm in diameter and is not perfectly homogenous over the entire spot. Due to the preliminary test setup a better adjustment is not possible. Still, concerns that f-theta back reflections could disturb the imaging quality can be negated. Hence, the preliminary test supports the system's ability to provide for the first time a tool generating deeper insight into the melt pool dynamics of the SLM-process.

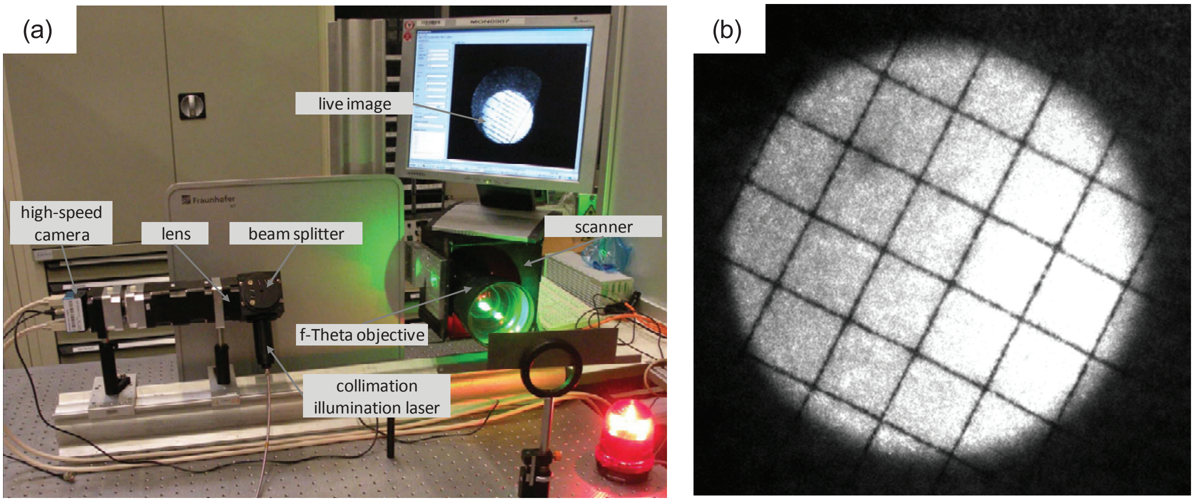

Figure 5. (a) test assembling, (b) screenshot of a high speed recording of a rectangle with a edge length d of 50 mm, a velocity v of 750 mm/s, a frame rate of 2000 Hz and a resolution of 448x448 pixel on a millimeter paper background

6. Conclusion and Outlook

Additive technologies like SLM offer the possibility to solve the dilemma for high wage countries that opposes economies of scale and scope. For example either the low-cost production of high quantities or the high end and thus cost intensive low volume production of individualized goods. However, quality and reproducibility are still areas of improvement. The first step to a closed-loop process control module is the development of a process monitoring system. In contrast to other systems imaging at high scanning velocities with a high resolution requires an external illumination source.

The introduced optical system is designed to enable a deeper understanding of the SLM process' melt pool dynamics and offer a basis for an online monitoring and control system. Based on the request for imaging both the entire melting pool and the melting front in detail a wide range of magnifications is identified as requirement. To ensure a good imaging quality over the entire magnification range three different optical concepts are selected. In conducting a paraxial design approach different lens combinations are compared. Then the entire imaging light path is modelled and analyzed in ZEMAX using spot and MTF diagrams. To validate the concept and simulation's results preliminary tests are conducted. Simulation analysis and preliminary tests show both encouraging results.

The next steps include the integration of a colour-corrected f-Theta objective model into the ZEMAX simulation and the final optical design. Subsequently, the mechanical design, the fabrication and the assembling of the system are carried out.

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