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Reducing process variation of laser powder bed fusion by real-time closed-loop control

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Abstract

The powder bed fusion process continuously increases market share, as it offers the production of metal parts with complex geometries by selectively melting a metal powder. However, the process is disturbed by inconsistent geometrical heat flow and atmospheric variations. Since commonly used sensors are not able to detect crucial states in-process and no possibility is given to adapt the process parameters in a closed-loop control strategy, a real-time control is developed with a high-speed pyrometer as sensor and Field Programmable Gate Arrays (FPGA) as control unit. The approach is validated at scanning speeds up to 1400 mm/s for the powder bed fusion process. The standard deviation of the pyrometer signal as a measure of the melt pool temperature was reduced by 25 % for simple cubic geometries and by 40 % for more complex geometries. Hence, the control concept allows to stabilize the process and to reduce manufacturing errors, especially in ambitious production tasks.

Keywords: Control; closed-loop; pyrometer; powder bed fusion; real-time

1. Introduction

The demand for industrially manufactured metal parts is constantly rising. The object geometries are becoming more complex while the demand on reduced weights increases for aviation and space applications. Powder bed fusion (PBF) also known as selective laser melting (SLM) offers the opportunity to manufacture parts with complex geometries that are still stable and exhibit a low weight [Her16]. However, the complex part geometries lead to higher effort to reach the quality requirements. The origin of production errors such as porosity, binding defects or microstructural effects is a current focus of scientific activities [Bou17]. Achieving high repeatability with low uncertainties and thorough quality control during the manufacturing process is challenging. Thus, a large number of produced parts do not meet the quality standards regarding quality criteria such as porosity and mechanical properties [Kha16]. State of the art PBF applications do not use a closed-loop strategy to achieve the quality demands. Sensor information of the melt pool are only used for documentation purposes and measured process parameters are used to generate predictive models that are used to adjust process parameters in the following jobs [Spe16]. In scientific applications, there are only a few approaches implementing closed-loop control, so far. A pyrometer is used to switch-off the energy input whenever a maximum temperature limit is exceeded. This leads to an optimized hardness of the parts, but increases job times because of the additional waiting times

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[Nas15]. For laser cladding, a similar approach has been presented, leading to a stabilization of the molten pool temperature in combination with a predictive controller [Son11]. However, for the short timing requirements in PBF applications, with reaction times of below 100 µs, Song's approach with a sampling time of 10 ms is insufficient. For PBF a fundamental closed-loop approach using a pyrometer with a sampling time of 100 µs is introduced [Cra11]. The standard deviation of a pyrometer measurement could be reduced by a closed-loop control approach [Ren19]. In this approach, a control time of below 50 µs is reached using a fast field programmable gate array (FPGA) system.

The goal of this work is to realize an in-process control loop in order to detect fluctuations of the melt pool temperature by measuring the radiation with a pyrometer. The pyrometer signal is then used to control the laser power in build jobs using metal powder in order to reduce process variations. In the following sections, the experimental setup and the closed-loop control approach is given. Finally, the parameters of the controlled process are validated.

2. Approach

The machine used for the experiments is a laboratory PBF machine (AconityMIDI by Aconity GmbH, Germany). The energy input for melting the powder is an integrating fiber laser with a nominal power of 500 W and a continuous wavelength of 1070 nm. Besides the fiber laser, two pyrometers have been integrated into the optical path and are connected to the build platform via a focus shifter and a 3D scanning system. The two pyrometers work at wavelengths in near infrared at 800 nm (manufacturer Optris) and 1500 nm (manufacturer Kleiber) to assure a sufficient wavelength difference to the used laser in order to preclude a measurement of the reflected laser light on the object surface falsifying the heat radiation to be measured. Both pyrometers have a time constant of about 10 µs and transfer the signals with an analog voltage output that is logged and used as input for the controller.

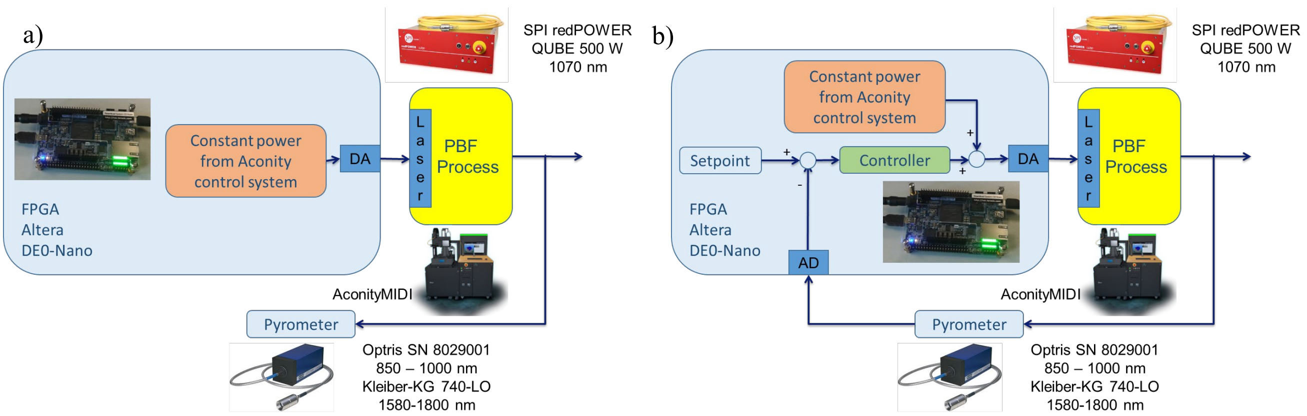

Fig. 1. – control implementation for a) open-loop and and b) closed-loop control cycle.

In Figure 1, the control implementation for the open-loop and closed-loop approach for the PBF process is given. In the open-loop approach, the laser power is held constant at the same value used without any control loop. The laser is connected to an Altera FPGA system of type DE0-Nano via a digital to analog converter. The fiber laser system (type SPI redPOWER) controls the laser power within a response time of below 20 µs. The resulting melt pool temperature is measured by pyrometers that are integrated into the optical path directed to the melt pool area of the actual exposure. In the closed-loop approach the pyrometer measurement is connected to the FPGA system via an analog to digital converter and closes the control cycle, resulting in a closed-loop control. The controller uses the measurement values to calculate a control error to the given setpoint of the pyrometer signal. The controller is parametrized by the proportional value kp. The controller output is an offset to the given laser power. Thus, the laser power is increased or decreased dependent on the melt pool temperature being too low or too high compared to setpoint of the pyrometer signal.

3. Results

In the validation experiment a build job has been conducted with a scan speed of 1000 mm/s and a nominal laser power of 300 W. For the first 180 manufacturing layers, the power has been kept constant in an open-loop control. For the layers 180 to 420, a P-controller is applied in closed-loop. Finally, an open-loop section with constant laser power was exposed for the top layers again. Figure 2 a) shows the manufactured parts of the PBF process. In Figure 2 b), the mean values of the pyrometer measurements of each powder layer are given. Since the part is built from bottom up, the lower layer numbers reflect the bottom of the part with the layer number increasing to the top of the object. The pyrometer signal increases within the first layers due to an increased heat flux to adjacent regions in the first layers compared to limited heat flux in the middle and top layers. The Kleiber pyrometer has a larger signal, which is caused by the higher amplification compared to the Optris. The Optris pyrometer however exhibits smaller integration times that lead to a larger noise signal. The comparison of the open-loop and closed-loop experiments offers no notable difference between the approaches for the mean values. In Figure 2 c), the standard deviation of the pyrometer signal is given. Here, a clear difference between the constant open-loop and closed-loop is recognizable. The standard deviation of the closed-loop approach is about 25 % smaller compared to the open loop experiment. In Figure 2 d) the standard deviation of another experiment is given. For this experiment, the cubes are built half on a fully filled substrate plate with 5 mm thickness and half on a thin bridge substrate with a thickness of 0.5 mm. The difference between the closed-loop and the open-loop approach is increased by 40 % within this heterogeneous heat flux environment. Thus, it is evident that for more complex building parts the closed-loop control approach increases the advantages.

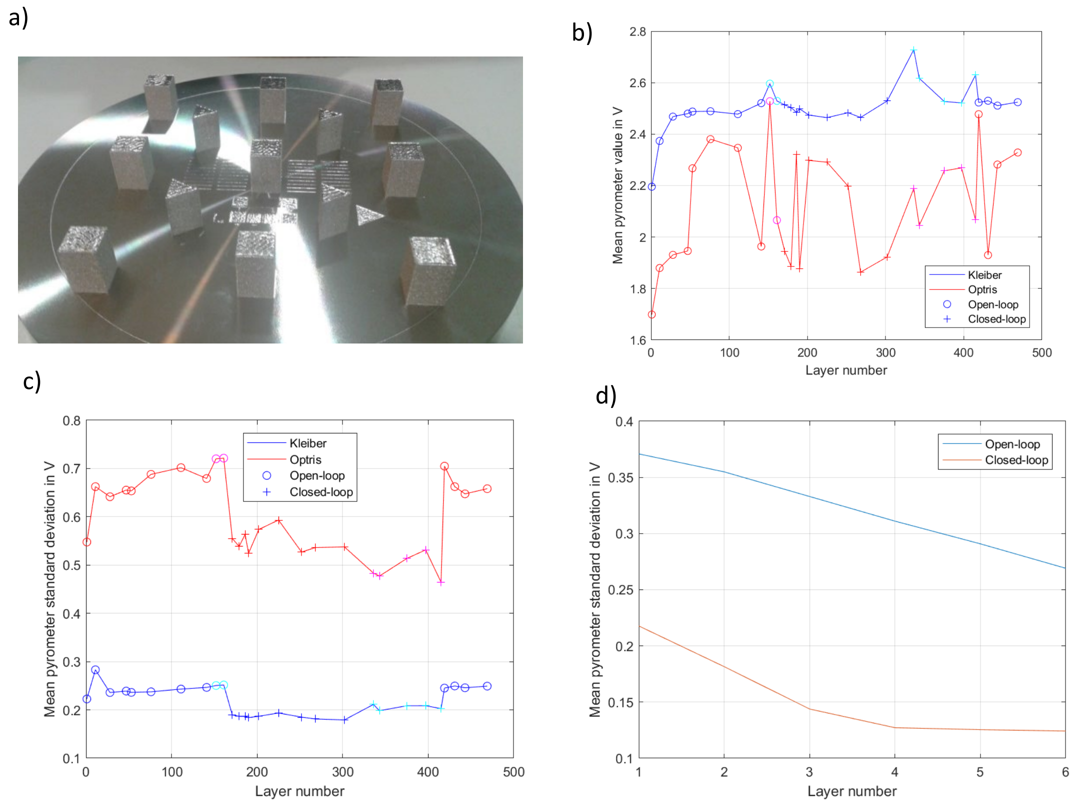

Fig. 2. - a) the scene of the first build job with 9 cubes and 4 triangles, b) the pyrometer signal mean values per layer, c) the standard deviation per layer and d) the standard deviation of second build job with varying heat flux.

4. Conclusion and Outlook

The validation results show that a stabilization of the process temperature can be reached by applying a closed-loop control for the laser power. The standard deviation of the pyrometer signal is reduced by 25 % for simplified fully built cubes and triangles and is reduced by up to 40 % for more heterogeneous heat flux caused by the part geometry. Thus, it is promising to apply a closed-loop approach for these jobs. It is supposed that the error quote will decrease, when applying the strategy for parts at limit. Following work will be an investigation of the part quality parameters, such as roughness and porosity in a comparison of the open-loop and the closed-loop controller approach.

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