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Design of a research system for process monitoring and closed-loop control of laser powder bed fusion

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Abstract

Additive manufacturing by means of Laser Powder Bed Fusion (L-PBF) enables the fabrication of highly complex metal components. Currently, the L-PBF process is performed by predefined parameters that interact in complex manners and are determined by time-consuming and costly trial-and-error parameter studies. Nevertheless, geometry-dependent differences in heat balance can occur in the L-PBF build-up process, leading to local differences in microstructure, and further temperature-dependent process failures such as cracks, balling and pores. Therefore, a closed-loop control system using temperature feedback is an interesting approach to homogenize the heat balance and stabilize the melt pool during micro-welding. This contribution describes the design of an L-PBF research system using the Autodesk Machine Control Framework as the overarching software that provides closed-loop process data feedback of monitoring sensors and combines a modular L-PBF process unit with a fiber laser, 3D-scanner components (SCANLAB) and a Sensortherm two-color pyrometer for temperature measurement and control.

Keywords: Additive Manufacturing; Laser Powder Bed Fusion; Closed-Loop Control; Two-Color Pyrometer; Temperature Feedback; Process Data Feedback

1. Introduction

Additive manufacturing (AM) of metals enables the direct production of complex and individually designed 3D components. Therefore, AM processes are experiencing growing acceptance especially in medical, aerospace

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and automotive applications (DebRoy et al., 2018). Here, Laser Powder Bed Fusion (L-PBF) is considered to be one of the most commonly used processes. This method enables the production of high-density components with mechanical properties similar to conventionally manufactured parts (Schmidt et al., 2017).

However, part fabrication by means of L-PBF is associated with different kinds of quality-related process problems. These include porosity and temperature-dependent defects such as cracks, delamination as well as the balling effect (Sames et al., 2016). In addition, steep temperature gradients and cooling rates between 10^3 – 10^8 K/s are generated due to the local input of energy by the laser. These lead to critical residual stresses caused by material expansion and contraction, which possibly result in distortion of the component (Bartlett and Li, 2019). In addition, depending on geometry, a varying spatiotemporal temperature distribution occurs over process time. Here, changing interlayer geometries of the part in build direction lead to fluctuating exposure and cooling times of a single layer. In particular, this interlayer cooling time (ILCT) proves to be an important influencing factor for complex geometries. Yavari et al. show that the base of an impeller exhibits lower interlayer temperatures due to the larger area and the longer ILCT compared to interlayer with smaller areas. In addition, it is demonstrated that the layer temperature increases with rising component height due to the insulating effect of the adjacent powder. Especially overhang areas and thinner component cross sections with short ILCT show heat accumulation and increased temperatures (Yavari et al., 2021). Furthermore, overhanging areas exhibit longer cooling times, since the underlying unmelted powder material interferes with heat dissipation (Hooper, 2018). Depending on ILCT and geometry-dependent heat accumulation, local differences in melt pool dimensions may also occur (Mohr et al., 2020). Moreover, Williams et al. demonstrated that varying ILCTs lead to different surface temperatures, which affect density, microstructure, mechanical properties as well as the spattering behavior (Williams et al., 2019).

Currently, the process is predominantly applied with constant parameters, such as scan speed, laser power and hatch distance. In this context, time-consuming and costly trial-and-error parameter studies are necessary to minimize the described process errors (Khairallah et al., 2016). In addition, support material is used in overhang areas to provide mechanical support against distortion caused by residual stresses on the one hand and to dissipate heat on the other (Sames et al., 2016).

Furthermore, process monitoring solutions are used to gain an understanding of the process. Here, on-axis setups are used, e.g. for monitoring the melt pool dimensions with high-speed cameras (Goossens and van Hooreweder, 2021) or for evaluating the thermal process emissions using photodiodes (Artzt et al., 2020) and high-speed thermography solutions (Hooper, 2018). Beside this, off-axis systems are used for e.g. thermographic evaluation of the spatiotemporal temperature distribution (Williams et al., 2019).

A growing trend of approaches to homogenize L-PBF conditions is represented by advanced control strategies. Here, a distinction is made between feedback control (closed-loop control) and feedforward control (open-loop control) strategies (Riensche et al., 2022). Advanced feedforward control approaches are using models, based for instance on FEM (Renken et al., 2019) or graph theory (Riensche et al., 2022) to make predictions and to perform pre-process parameter adjustments. In contrast, closed-loop control strategies regulate the process online. Successful approaches are carried out, for example to control the melt pool temperature signal with pyrometry (Renken et al., 2019) and to control the melt pool area layer-wise and vector-wise based on NIR-CMOS-Camera melt pool images (Vasileska et al., 2022).

In this publication the design of an advanced flexible research system is presented. A closed-loop control system is integrated to reduce process errors and to homogenize the spatiotemporal temperature distribution. This is designed to control the temperature of the melt pool using a high-speed two-color pyrometer. In addition, the system is designed to incorporate various process monitoring solutions by a central open control device.

2. Conceptual Design of a Flexible Research System

2.1. Requirements for Closed-Loop Control by Using Melt Pool Temperature Feedback

For the integration of a control loop into the L-PBF process by using temperature feedback, different aspects regarding the temperature measurement, the optical setup as well as the control system have to be considered. To measure the temperature in the melt pool, it is necessary to integrate a pyrometer coaxially into the laser beam path of a scanner optics. Since wavelength-independent influences (e.g. process smoke and deposits on the process window) as well as low partial illuminations of the pyrometer measuring spot by the melt pool result in signal reductions, a two-color pyrometer is required. It should have a wide temperature measuring range for processing a variety of metallic materials. The integration of a control loop into the process of the L-PBF requires due to its high dynamic with scanning speeds of more than 1000 mm/s and melt pool dimensions of e.g. 150 µm short response times of the control loop components to ensure a real-time capability of the system. In this context, the properties and stability of the melt pool in the process must be considered in detail. In order to be able to prevent the emergence of instabilities, the entire signal chain of the control loop should be able to perform several adjustments to the target temperature specification within the dimensions of a melt pool. For instance, if a response to a target temperature deviation is required within half of a melt pool length l_{MP} of 150 µm at a scanning speed of 1000 mm/s, the delay of the entire signal chain consisting of sensor (t_{temp}), PID controller (t_{PID}) and laser (t_{laser}) should not take longer than 75 µs until the resulting adjustment of the laser power, see Fig. 1. With the given typical distances of the optical path and limitations of the aperture of the laser scanner optics, the achievable pyrometer measuring spots are several times larger than the small sized melt pool area, resulting in a part illumination of the pyrometer measuring spot and less thermal signal on the detector. In consequence, an optimized optical path is required to minimize radiation losses and limit signal noise. Further the optical components have to be optimized to prevent achromatic failures and position deviations between the two measuring channels.

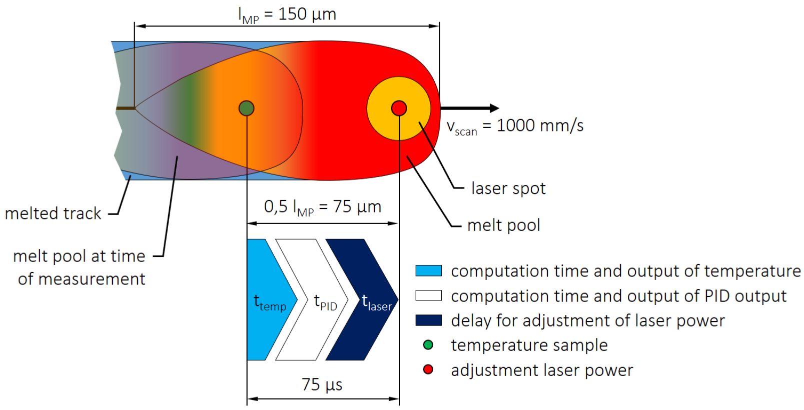

Fig. 1. Schematic representation of the delay chain of the control loop with temperature feedback.

2.2. Requirements for Process Monitoring

In order to analyse a temperature controlled L-PBF process in depth and to optimize the control loop of the high speed micro welding process of the powder bed, different kinds of process data is required, which has to be recorded. Here, the most significant recording values are the melt pool temperature, measured by the pyrometer, the set laser power of the PID control and the real time emitted laser power. Due to the high process dynamic and laser beam velocities, the monitoring of those process values has to be done with the same frequencies than the measuring setup provides. Here, it is necessary that the recorded data can be assigned to the current machining position in order to be able to allocate geometry-dependent deviations and defects, which requires a fast readout of the galvanometer scanner positions. The challenge here is to efficiently buffer the large amount of data during the layer exposure and to store it without secondary time losses, which slow down the overall printing process. The captured data has then to be graphically visualized, e.g. in a heat map.

In order to analyse the melt pool dimension and dynamics at different exposure conditions of a layer, high speed camera images with precise geometric resolution are necessary. They can be further used to evaluate the melt pool stabilization abilities at challenging exposing conditions, like overhanging structures by the temperature controlled L-PBF process.

For the evaluation of the overall heat distribution, detecting of different cooling properties and hot spots due to heat accumulation or defects like delamination or distortion, thermographic analysis has to be applied. The thermographic data can be used also to evaluate if the temperature controlled process enables a higher geometric independent temperature distribution and cooling rate. In order to be able to observe the process within the process chamber, a camera system is necessary, which is able to measure through glass with a wavelength range below 2.5 µm. To get the dynamic variations of the temperature distribution during the hatch-wise areal treatment and the position dependent differences of the cooling rates measurable, a measuring frequency of several hundred images per second is required at common processing speeds.

For the live process observation and detection of failures that require a process termination, it is necessary to integrate also a visual camera based monitoring solution.

All camera based monitoring solutions has to be synchronized by a trigger from the PLC, enabling the mapping of the frames from several devices to an individual process event.

In order to get correlations from the integrated sensors data in the further machine components, like process atmosphere conditions, circulation of process gas or the built platform temperature, all data has to be storaged with the same time stamp at a central control unit.

2.3. Conceptual Design of the Overall System

The conceptual design of the L-PBF laser cell aims to create an open and highly flexible research platform for the temperature controlled process and advanced process monitoring solutions. Hereto the machine can be equipped with modular L-PBF units for different applications and process requirements, which provide a high accessibility for camera based process monitoring solutions, like high speed imaging or thermography, see Fig. 2. A near infrared single mode fiber laser is used for the exposure of the powder layers. To dynamically change the beam properties within the layer wise exposure, a flexible 3D scanner optics with the ability to adjust the beam diameter over a wide range is used. In order to coaxially measure the process temperature within the melt pool, a two-color high speed pyrometer is coupled into the laser beam path by a beam splitter.

To avoid achromatic failures, causing scanner position dependent centering errors of the pyrometer measuring spot, a post objective setup is necessary, where no laser beam shaping element is in the pyrometer measuring path. To reach the required high control frequencies with minimal delays of the processing chain (see chapter. 2.1) a closed loop PID control value of the laser power has to be directly connected with the analog input of the laser source. Thus, in this case, the scanner card (RTC6 | SCANLAB GmbH | Puchheim | Germany) is only providing the laser gate signal and the processing positions. The target process temperature is defined directly at the vectors of the built file using the CAM software Autodesk Netfabb (Autodesk Inc.) and can be transferred straight into control loop.

The research platform aims to handle all data flow centrally, in order to have access to all machine actuators, machine axis, status information of the sub components and process data without creating unsynchronized delays and interface limitations. For this purpose, the complete L-PBF machine is controlled by an open central software platform provided by Autodesk Inc., called Autodesk Machine Control Framework (AMCF), where all components are controlled and the whole monitoring data is merged and recorded. The AMCF enables to communicate directly with the PLC module for the I/O, the axis controller and the modular gas circulation unit with integrated process gas management. Via the I/O all further machine sensors are connected to the overall control software. The triggering of the camera based process monitoring devices can be defined user-specific. The control of laser source and pyrometer by the AMCF is performed also via the PLC I/O. The AMCF is connected with the scanner control card by Ethernet, transmitting the scanner movement data.

In order to record high dynamic process monitoring data, e.g. Temperature synchronized with the relating position data of the current position of the laser beam, the process data feedback is performed with the SCANLAB Open Interface Extension (OIE), providing up to eight high frequency measurement channels. The current scanner position is read out from the encoders and merged with the sensor input. The recorded monitoring data is processed and visualized afterwards as heat maps.

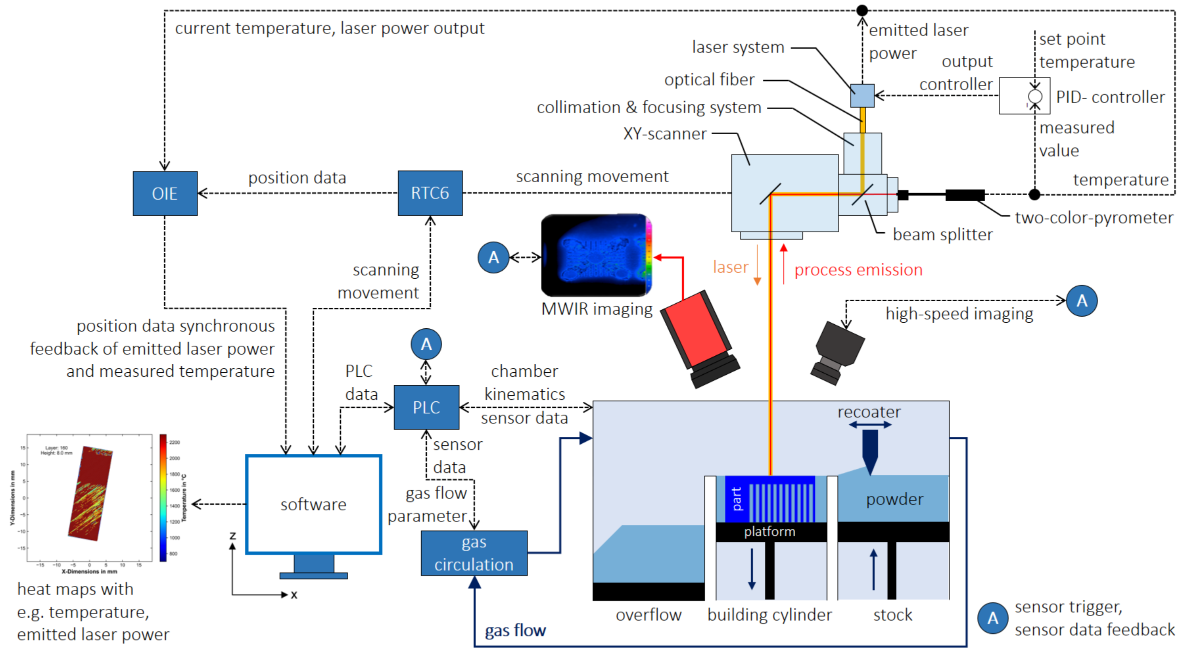

Fig. 2. Overall machine concept for a flexible temperature controlled L-PBF research platform with advanced process monitoring solutions.

3. System Architecture

3.1. Laser Cell with Modular L-PBF Process Unit

The research machine concept is built up on a self-made laser cell, which is equipped with a flexible four axis machine kinematics, controlled by a PLC (B&R Industrial Automation GmbH | Eggelsberg | Austria). The machining table, which is movable in X- and Y- direction has a size of 800 · 800 mm² and provides a flexible platform to mount different AM L-PBF-process units used for single and multi-material research applications. The working plane can be adapted to the respective mounted process unit by means of a Z-axis with a travel length of 380 mm. The large-volume laser protection cell around the machining table offers great accessibility for attaching process sensors such as high-speed or thermographic cameras. The laser cell is equipped with a 400 W single mode fiber laser TruFiber 400 (TRUMPF SE + Co. KG | Ditzingen | Germany) which has a glass fiber diameter of 11 µm. The laser can be operated in continuous and pulsed operation mode with a minimum pulse duration of 40 µs and has a fast analog input for laser power control on the ISA interface of up to 50 kHz. For the first tests of a inline process temperature control a glass fiber guided two-color pyrometer (METIS H322 | Sensortherm GmbH | Steinbach | Germany), operating in a wavelength range of 1.45 – 1.80 µm with a minimum response time t_{90} of 80 µs, is integrated. It has a built-in PID-controller, providing a control frequency 10 kHz. It is directly connected with laser power input of laser source interface card (ISA). For uncontrolled process studies with fixed laser power values the target laser power can be also transferred directly from the RTC scanner control card.

The modular L-PBF process unit, shown in Fig. 3 (c), has a circular printing platform with a diameter of 100 mm and enables a printing height of 80 mm. The process chamber provides two linear gas streams directly above the powder bed to throw away the spatters and material evaporations and a second gas stream which is located directly below the laser entrance window in order to protect it from process smudge. The circulated gas atmosphere is filtered by an external placed circulation unit, which is equipped with a process gas atmosphere control, measuring the actual oxygen content. Further logged atmosphere conditions are the gas stream velocity, gas temperature and filter condition by differential pressure. In order to achieve a high accessibility for optical process observations, the chamber and its cover have three additional windows for process monitoring from different directions, see Fig. 3 (b). The axis of the L-PBF chamber are driven by a separate Automation-PC from B&R Industrial Automation GmbH, which is the central unit to control the complete AM-process.

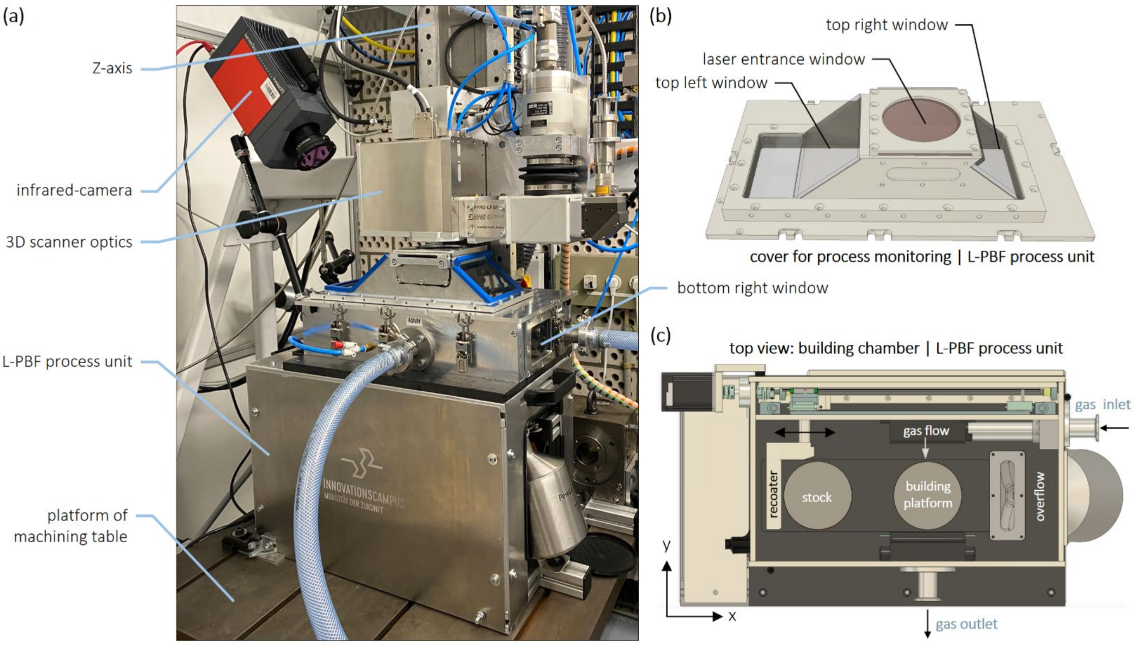

Fig. 3. (a) Laser cell with modular L-PBF process unit and installed thermographic camera; (b) Accessibility for process sensors in the process chamber cover; (c) Top view of the L-PBF process unit.

3.2. Optical Setup and coaxial pyrometer integration

The optical setup is based on a post objective scanning system, see Fig. 4 (a). Here, the laser is guided in its optical path into a collimation unit with a focal length of 100 mm. This is followed by a dynamic focusing unit (vario*SCAN*$_{de}$ II 40i PR | SCANLAB GmbH), which is used for flat field correction as well as for (de-)focusing of the laser beam. The beam is then deflected by a beam splitter (SCANLAB GmbH) into a scan head (intelli*SCAN*$_{se}$ 30 | SCANLAB GmbH), where the laser is moved in X- and Y-direction by two galvanometer scanners. The dynamic focusing unit includes a moving diverging lens as well as a fixed focusing lens. By moving the diverging lens in the Z-direction, a variation of the focal position along the optical axis is achieved. The focusing lens provides a back focal length of 577 mm, resulting in a focus diameter ($1/e^2$) of 43 µm. By adjusting the position of the internal diverging lens, the laser beam can be defocused to a maximum of 1200 µm.

The pyrometer is integrated coaxially through the monitoring outlet of the beam splitter. In the process, the thermal radiation follows the optical axis of the laser beam, passes the beam splitter, and reaches a two-axis tilting mirror and subsequently an optics for adjusting the measurement axis of the pyrometer. The optical characteristics of the beam splitter are optimized to provide high transmission in the sensitivity range of the pyrometer. A two axis tilting mirror is used to center the pyrometer and laser beam axis. By changing the angular position of the mirror, a stepless adaptation of the pyrometer axis in X- and Y-direction is provided. The pyrometer optics OQ30-90 (Sensortherm GmbH) guides the IR radiation along an optical fiber with a fiber core diameter of 200 µm to the detectors of the pyrometer. In addition to an achromat with a focal length of 90 mm, this contains a sliding aperture with a diameter of 9.5 mm, resulting in a measuring spot of approx. 2 mm. This allows the optical axis of the pyrometer to be shifted in Z direction in order to minimize the measuring field diameter in the working plane. For coaxial measurement using a pyrometer, all elements in its optical path are equipped with optimized transmission properties for the spectral range of the pyrometer in addition to the wavelength of the laser. The 3D scanner optics completely modeled by means of computer-aided design (CAD) is shown in Fig. 4 (b).

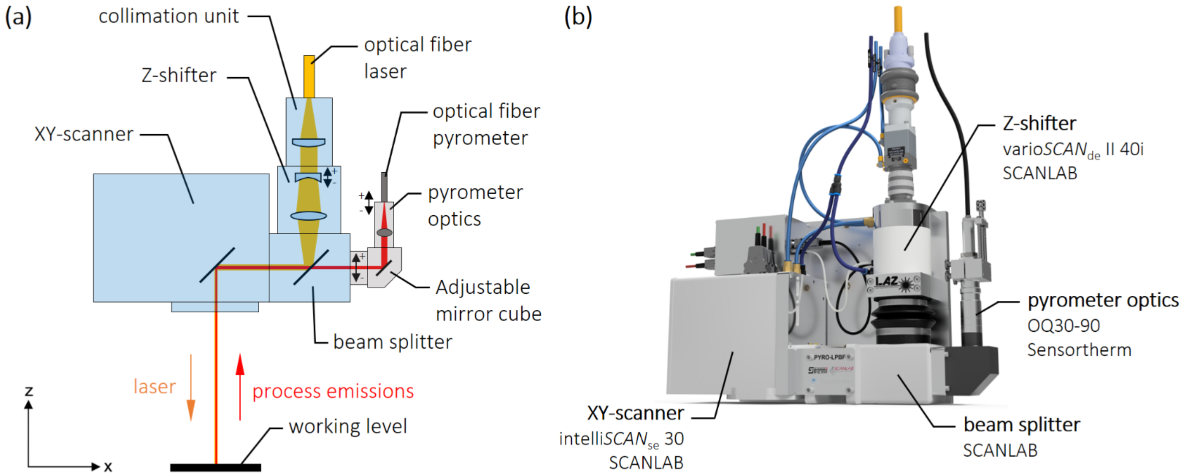

Fig. 4. Optical setup of the system: (a) schematic representation of the optical path of laser and pyrometer; (b) CAD model of the 3D scanner optics.

3.3. Overarching Software – Autodesk Machine Control Framework

Autodesk Machine Control Framework (AMCF) is a modular open source platform, provided by Autodesk Inc., to individually design a control software for an additive manufacturing process and a specific machine setup. Thus it enables an open platform for research in the field of L-PBF, which can be completely flexible adapted regarding to the research specific requirements. It contains a web server on which the web-based user interface runs. The AMCF has integrated drivers to run with several periphery. So, e.g. the RTC6 scanner control card from SCANLAB GmbH can be directly driven by the AMCF. The architecture of the AMCF is divided into several modules for the main process flow, the PLC communication or laser and scanner communication in order to parallelize the process flow.

At this research machine setup an Ethernet communication interface was developed to connect with the B&R PLC, which is controlling the axis of the modular process units, do the I/O with laser source, pyrometer, circulation unit and other process monitoring devices. In the opposite direction the data from the integrated process sensors, connected with the PLC, are transmitted to the AMCF. The software offers an interface to import printing jobs as a 3mf file, created in Autodesk Netfabb and includes a build library, were already uploaded jobs are archived. For each layer, the hatch patterns can be visualized. Within the main menu, the used type of L-PBF unit and the triggers for the observation cameras can be configured, see Fig. 5. The process parameter values for the axis movements of the L-PBF unit, the circulation and process atmosphere as well as the used powder dose can be defined directly by the user within the user interface. The software is equipped with a manually mode, which can be used to prepare the machine for a built job, referencing and moving the axis individually and control the circulation unit. Here, for a better user support, the current axis positions and movements are visualized graphically in the build preparation window. For process and machine diagnosis all machine states, variables and log messages are displayed and saved.

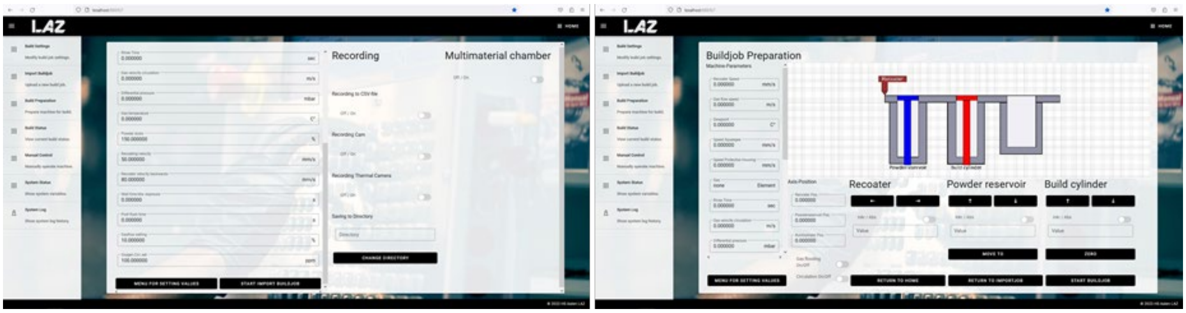

Fig. 5. AMCF User interface: (a) Main menu; b) Window for build job preparation.

3.4. Position-assigned Process Monitoring

The position-assigned process sensor data of the actual process temperature in the laser spot, the controlled target laser power and the real emitted laser power are read out by the OIE with a frequency of 50 kHz. The raw data is directly stored at the connected PC. Currently, the data processing is executed by the AMCF after the end of the exposure of an individual built layer in order to parallelize it with the recoating cycle. For further analyzation the OIE data contains the laser-on signal from the RTC in order to differentiate between scanner treatment vectors with emitting laser and jump movements for repositioning. Additionally the timestamp of the RTC card is added as well to match those high dynamic process data with other monitored sensor data of the process chamber and circulation. The data is processed and visualized via Python. Heat maps are created which can represent local component areas (vector wise resolution) or the entire building platform, see Fig. 6.

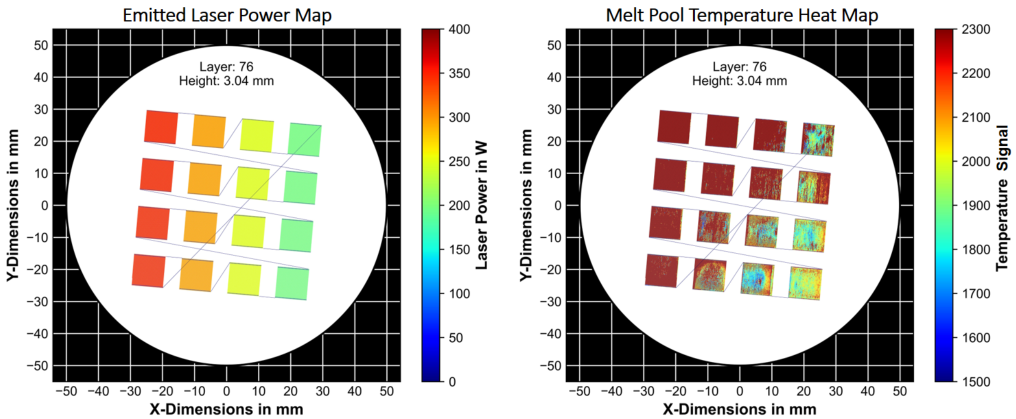

Fig. 6. Example of process data visualization with heat maps of emitted laser power (left) and temperature (right).

3.5. Closed-Loop Control by Using Temperature Feedback

The temperature control circuit is controlled via the AMCF. The design of the research platform contains two kinds of a temperature control loop. On the one hand, the closed-loop control can be executed via the internal PID controller of the pyrometer. Another possibility is to work with the integrated closed-loop control algorithm of the OIE. In the case of control via the pyrometer, the set temperature specification read out vector wise from the built file is transferred by the AMCF to the RTC6, which sends the analogue set point temperature (0 – 10 V) to the pyrometer. The pyrometer control loop can be activated by the AMCF for each layer exposure at the I/O interface, over the connections to the PLC. The pyrometer unit measures the IR-radiation, transfers it to a digital equivalent and calculates the temperature in the two-colour channel, then in the same calculation cycle the PID output, which is then transferred as laser power equivalent (analogue: 0 – 10 V) to the laser via the laser source interface card ISA.

When using the integrated closed loop control algorithm of the OIE, up to 68 different PID parameter sets can be defined in the configuration file. The AMCF can set and activate the configuration off the OIE via an API. The current process temperature as an analogue value, provided by the Sensortherm pyrometer, is read in and controlled with up to 100 kHz. The algorithm calculates a PID output based on vector-dependent definable PID parameter sets. The control value is then transferred also as an analogue signal (0 – 10 V) to the laser power input ISA of the laser via the RTC6. Additionally the OIE enables to freeze the control value during the jump vector, were the laser is off, in order to prevent overshooting at the beginning of the next scanning path, which can stabilize the control loop when treating short vectors with high jump frequencies.

4. Conclusion and Outlook

A flexible L-PBF research platform is built up, which can handle with different L-PBF units and enables a high accessibility for a comprehensive process monitoring. The system is equipped with a two-color inline pyrometer with an integrated fast temperature control loop, enabling measuring frequencies up to 25 kHz. The pyrometer is inline integrated into a 3D post- objective scanner unit with an optimized measuring path to reduce transmission losses. The machine is controlled by a central control unit, running with a self-built up software platform, based on the Autodesk Machine Control Framework. Process data, assigned to actual treatment position within the scanner coordination system, can be recorded at up to 50 kHz. A python based visualisation for the creation of heat maps was developed.

In the ongoing project, a new pyrometer is developed by Sensortherm enabling two-color measuring rates up to 50 kHz and a reduced control loop cycle time of less than 75 µs. Additionally the measurement wavelength ranges are shifted to higher wavelength (1.85 to 2.1 µm) in order to get a higher thermal radiation signal with less signal noise, when treating with lower process temperatures e.g. on Aluminium. It’s planned to build up a temperature control-loop at the OIE, which enables to act with switchable PID parameter values within a scanning vector, due to the synchronization with the current scanner position. The processing and visualization of the monitoring data will be performed later directly in the AMCF and displayed in the user interface as a 3D data model of the part. Further, the process sensor data of the further integrated sensors by the PLC will be integrated and matched with the same time stamp in order to get all available process data within one recording for advanced data mining.

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References

Artzt, K., Siggel, M., Kleinert, J., Riccius, J., Requena, G. and Haubrich, J. 2020 "Pyrometric-Based Melt Pool Monitoring Study of CuCr1Zr Processed Using L-PBF", Materials (Basel, Switzerland), vol. 13, no. 20.

Bartlett, J. L. and Li, X. 2019 "An overview of residual stresses in metal powder bed fusion", Additive Manufacturing, vol. 27, pp. 131–149.

DebRoy, T., Wei, H. L., Zuback, J. S., Mukherjee, T., Elmer, J. W., Milewski, J. O., Beese, A. M., Wilson-Heid, A., De, A. and Zhang, W. 2018 "Additive manufacturing of metallic components – Process, structure and properties", Progress in Materials Science, vol. 92, pp. 112–224.

Goossens, L. R. and van Hooreweder, B. 2021 "A virtual sensing approach for monitoring melt-pool dimensions using high speed coaxial imaging during laser powder bed fusion of metals", Additive Manufacturing, vol. 40, p. 101923.

Hooper, P. A. 2018 "Melt pool temperature and cooling rates in laser powder bed fusion", Additive Manufacturing, vol. 22, pp. 548–559.

Khairallah, S. A., Anderson, A. T., Rubenchik, A. and King, W. E. 2016 "Laser powder-bed fusion additive manufacturing: Physics of complex melt flow and formation mechanisms of pores, spatter, and denudation zones", Acta Materialia, vol. 108, pp. 36–45.

Mohr, G., Scheuschner, N. and Hilgenberg, K. 2020 "In situ heat accumulation by geometrical features obstructing heat flux and by reduced inter layer times in laser powder bed fusion of AISI 316L stainless steel", Procedia CIRP, vol. 94, pp. 155–160.

Renken, V., Freyberg, A. von, Schünemann, K., Pastors, F. and Fischer, A. 2019 "In-process closed-loop control for stabilising the melt pool temperature in selective laser melting", Progress in Additive Manufacturing, vol. 4, no. 4, pp. 411–421.

Riensche, A., Bevans, B. D., Smoqi, Z., Yavari, R., Krishnan, A., Gilligan, J., Piercy, N., Cole, K. and Rao, P. 2022 "Feedforward control of thermal history in laser powder bed fusion: Toward physics-based optimization of processing parameters", Materials & Design, vol. 224, p. 111351.

Sames, W. J., List, F. A., Pannala, S., Dehoff, R. R. and Babu, S. S. 2016 "The metallurgy and processing science of metal additive manufacturing", International Materials Reviews, vol. 61, no. 5, pp. 315–360.

Schmidt, M., Merklein, M., Bourell, D., Dimitrov, D., Hausotte, T., Wegener, K., Overmeyer, L., Vollertsen, F. and Levy, G. N. 2017 "Laser based additive manufacturing in industry and academia", CIRP Annals, vol. 66, no. 2, pp. 561–583.

Vasileska, E., Demir, A. G., Colosimo, B. M. and Previtali, B. 2022 "A novel paradigm for feedback control in LPBF: layer-wise correction for overhang structures", Advances in Manufacturing, vol. 10, no. 2, pp. 326–344.

Williams, R. J., Piglione, A., Rønneberg, T., Jones, C., Pham, M.-S., Davies, C. M. and Hooper, P. A. 2019 "In situ thermography for laser powder bed fusion: Effects of layer temperature on porosity, microstructure and mechanical properties", Additive Manufacturing, vol. 30, p. 100880.

Yavari, R., Williams, R., Riensche, A., Hooper, P. A., Cole, K. D., Jacquemetton, L., Halliday, H. and Rao, P. K. 2021 "Thermal modeling in metal additive manufacturing using graph theory – Application to laser powder bed fusion of a large volume impeller", Additive Manufacturing, vol. 41.