Acoustic data acquisition for quality monitoring during Powder Bed Fusion with Laser Beam (PBF-LB)

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Abstract

Additive manufacturing such as Powder Bed Fusion with Laser Beam (PBF-LB) is gaining attention in the producing industry. Monitoring the quality of the PBF-LB products in situ is crucial for ensuring that the desired product criteria are met. Currently, the state of the research focuses on optical process monitoring using CCD cameras, photodiodes, high-speed cameras, and pyrometers. A disadvantage of these approaches is that knowledge can only be extracted from the last manufactured layer, whereas defects such as cracks or warpage in deeper layers can remain hidden. A way to extend such monitoring systems is the use of microphones to analyze the sound pressure generated by PBF-LB. We describe possible defects in PBF-LB and how to detect them with ultrasonic microphones. The experimental setup is optimized regarding the acoustic conditions in the manufacturing chamber and the Signal-to-noise ratio. The optimized setup is exemplified as used in the experiments in the project "Development of machine learning algorithms based on virtual sound data for lightweight construction for quality assurance in additive manufacturing" (ML-S-LeAF). Finally, an outline is given for future work.

Introduction

The PBF-LB additive manufacturing process produces components following the solidification mechanism of cyclic melting and solidification [1]. The material is present as powder and is melted by local energy input using a laser beam. The manufacturing process is carried out by cyclic application of powder and local melting of the powder. In this way, complex structures can be produced directly and close to the end geometry. PBF-LB hardly restricts the component design and is therefore very interesting, especially for lightweight applications. However, the complex melting and solidification mechanisms in PBF-LB are currently only partially mastered, defects such as porosity can occur depending on the parameters influencing the process.

The main influencing factors leading to defects are the exposure parameters and strategy, the material, the inert gas, as well as the quality and production method of the powder [2, 3]. In addition, strong cross-sectional changes or overhanging structures favour defects such as pores, cracks, warpage, and material bulges, so that quality requirements are not met, for example in the aerospace industry. Process monitoring can improve quality in additive manufacturing and increase process reliability. An in-situ monitoring technique could help to better control the layer-wise production of components and deliver information about the condition of a component.

Previous systems for quality assurance by process monitoring in PBF-LB use optical sensors or cameras that record the images of the melt pool. However, plume formation and the temperature and wavelength dependence of the radiation intensity distort the measurement signals. Moreover, only anomalies in the current process layer can be detected and localized [4]. Defects such as cracks or delamination occurring in already processed layers are hidden for optical process monitoring. Thus, an experienced machine operator is usually needed to decide whether to stop the process, making quality monitoring subjective and not automated.

In contrast, acoustic quality monitoring could complete the missing part of optical monitoring systems. Experienced production employees can hear deviations from the "normal sound" of a production plant and thus conclude the process or component quality. This sound evaluation is purely subjective, but it allows conclusions to be drawn about the condition of machines and is therefore decisive for component quality. The demands on high-quality components, for example in the aerospace industry, go far beyond this inconsistent subjective evaluation, which is why an automated and objective evaluation of

process sound is necessary. In this context the use of process monitoring systems can also generate deeper levels of process understanding, e.g. quantified correlations between process anomalies and resulting defects.

The aim of the project "Development of machine learning algorithms based on virtual sound data for lightweight construction for quality assurance in additive manufacturing" (ML-S-LeAF, funded by BMWK, Germany) is to evaluate noises in an automated way and thus monitor the quality for PBF-LB. Based on sound data, machine learning algorithms recognize pre-learned error patterns or deviations of the system sounds from the "normal sound" of the PBF-LB process. For this purpose, it is essential to record high-quality audio signals and to preprocess the acquired data based on process knowledge as well as knowledge about internal and external influencing factors. In this paper, a first attempt is made to record the process sound on a PBF-LB machinery EOS M290 using MM 302 ultrasonic measurement microphones from Microtech Gefell GmbH. The influencing factors and the disturbance variables are identified and quantified.

Experimental setup

In PBF-LB manufacturing processes for production purpose, the laser melts the metal power in lines right next to each other, so that the local defects turns out not recognizable by the lines next to it and the layers on top of it, which means the local defects accumulate in the final product. To investigate the non-accumulated local defects through visual inspection and acoustic event detection, single-line tests are used to reduce the complexity of the experiment at the beginning of the investigations, to ensure consistent measurement conditions, and to test several verified parameter combinations. A pause in time series and a spacial distance between lines is provided after each welded line to separate the individual signals. During the pause, the reflected sound waves have enough time to decay to avoid increased noise in the audio recording of the next lines. Sources of inconsistency such as different thermal boundary conditions as well as re-melting of defective areas can also be excluded, which should enable a clearer assignment of the process results to the acoustic signals. The generated samples (single lines) are then examined in visual inspection using a high definition microscope, with anomalies being identified, labeled, and located. Using the audio data, it could be shown that the process can be identified in the audio signal using a short-time Fourier transform (STFT) (see Fig. 1). The laser scanning takes a much shorter time than the pause to separate each line. The peaks in the spectrogram 1 correlate with the processing of single lines. And the gap between the two peaks corresponds to the pause. Thus, the airborne sound measurements show a clear difference between signals of laser welding and background noise, which offers a good potential for defect detection (see Fig. 1).

In the following, the influence of the microphone positioning on the quality of the audio signal and the factors that influence the quality differences are listed. In addition, further process-related influencing factors on the

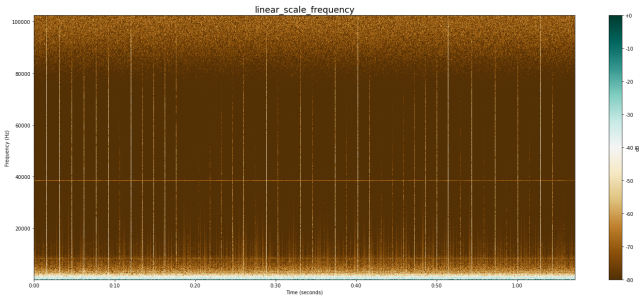

Figure 1: Spectrogram of sample audio recording

acoustic measurement are shown. Finally, a summary and a conclusion follow.

Acoustic Measurement Conditions

In this study, we use ultrasonic microphones to collect acoustic data for defect detection in a Powder Bed Fusion (PBF) chamber as shown in Figure 2. The PBF-LB building chamber has a size of 250 mm x 250 mm x 325 mm. Previous research shows that the acoustic event of laser welding is detectable in the ultrasonic frequency range up to 65 kHz [5]. In that chamber, two ultrasonic microphones are equipped in different positions from the specimens. The microphones are able to capture acoustic signals from 5 Hz to 100 kHz in an environment up to 110°C. Since only the building plate is preheated to 80 °C and the atmosphere has for our experiments a constant temperature around 20°C, the microphones are not overheated.

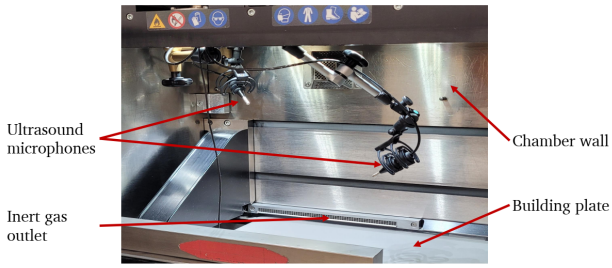

Figure 2: Building chamber of PBF-LB machinery with two mounted ultrasonic microphones

To ensure a safe and efficient laser welding process, it is common practice to use a protective atmosphere in the building chamber. In this study, the chamber was filled with Argon gas at a pressure of 0.56 mbar. Acoustic signals were sampled with a frequency of 204,800 Hz and acquired using a Soundbook manufactured by Sinus Messtechnik GmbH. Simultaneously, the position of the laser welding point was monitored by a PBF-LB Melt Pool Monitoring system. To synchronize the time series from the (Sinus Messtechnik GmbH Soundbook) and the PBF-LB Melt Pool Monitoring system, the same acoustic signal is sent from the acoustic data acquisition to the PBF-LB Melt Pool Monitoring system.

Cubic specimens are prefabricated with an edge length of 10 mm using 316L stainless steel powder on the build-

ing plate. Prior to each build job, a layer of 316L powder is applied on top of the specimens with a thickness of 60 µm. The acoustic data is acquired during single lines are exposed by the laser on these specimens. We use the specimens for two reasons. To generate a solid, plane and homogeneous surface at a discreet height for the single-line experiments. Second, we have the opportunity to separate the specimens from the build plate after the experiment for further microscopic evaluation of the produced single lines.

The quality of the ultrasound recording is influenced by various factors, such as external noise, inert gas flow, and sound reverberation. To maintain a steady pressure and purity of the inert gas, the inert gas was pumped into the building chamber through the gas outlet by a high-speed turbine which introduces external vibration and noise in the measurement environment. The gas outlet was designed to be located near the building plate to dissipate the heat generated by laser welding. However, a conflict of goals occurs with the selection of the microphone positions. While the microphones needed to be placed near the building plate to capture the airborne noise of laser welding, the convective flow of inert gas would directly blow onto the microphones and create wind noise. The selection of the microphone positions will be discussed and quantified in the next section.

Another influencing factor that can affect the quality of the acoustic data is sound reverberation. Because the chamber walls are bare aluminum plates, little damping is introduced for airborne noise in the chamber. As a result, the sound wave could be still measurable after multiple reflections, leading to a longer reverberation time for certain frequencies. If the direct sound overlaps heavily with the reflected noise, an acoustic event will be less detectable.

Microphone Positions

To test the dependency of the recording reliability on the location of microphones, the measurement setup employs two ultrasonic measurement microphones in the PBF-LB chamber. These microphones were positioned at 40 cm (position 1) and 25 cm (position 2) from the center of the building plate for the first setup, as shown in the first picture of Figure 3. The second setup is shown in the second picture of Figure 3, where two microphones were positioned at 25 cm, the same location as position 2, and 10 cm (position 3) from the center of the building plate.

Figure 4 shows the frequency density distributions of the sound pressure levels. For the analysis, 47 welding samples were taken into consideration, for each microphone position. The x-axis of the plot represents the range of sound pressure being plotted. It is divided into a set of bins (or buckets) that cover the range of the sound pressure, and each bin shows the count or frequency of observations that fall within its range. The y-axis of the plot represents the statistic frequency density of the sound pressure corresponding the x-axis. The frequency density is estimated and a smooth curve is plotted to

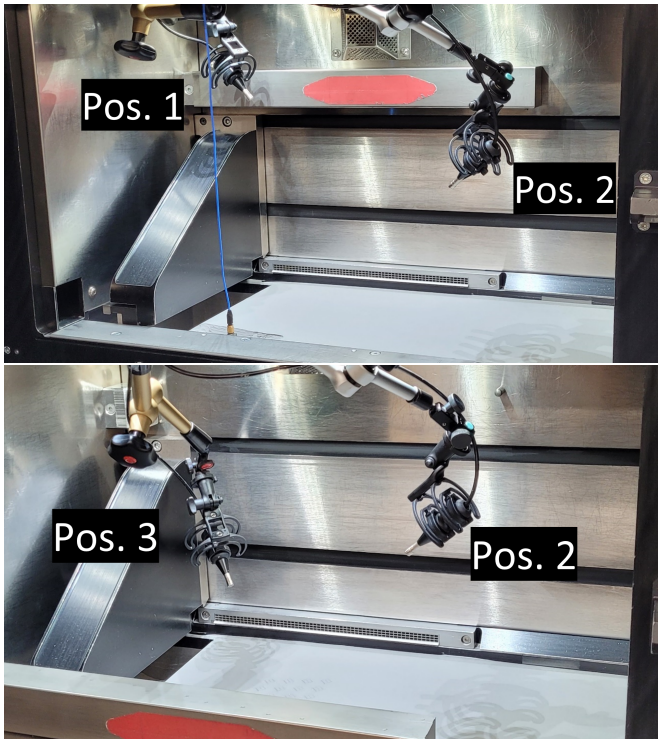

Figure 3: PBF-LB chamber with two setups and three mounting positions of ultrasonic microphones

show the distribution of the sound pressure. Our results provide valuable insights into the behavior of sound pressure levels during welding and their distribution across different microphone positions.

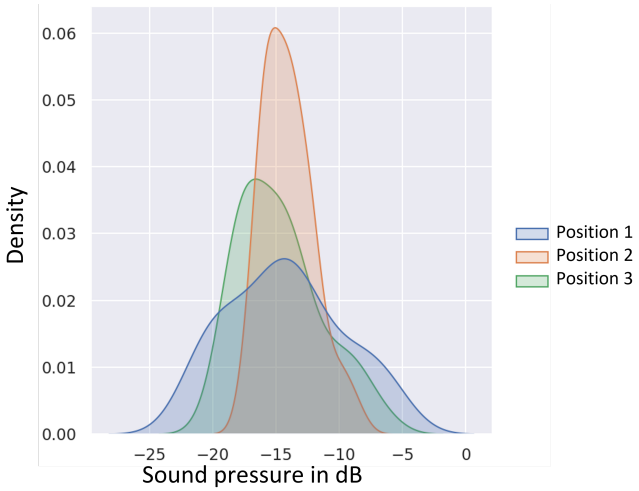

Figure 4: Frequency density distributions of sound pressure

The sound pressure distribution indicates that the majority of the recorded samples exhibit a central tendency falling within the range of −10 dB to −20 dB as shown in Figure 4. To capture the airborne noise generated during laser welding, it is recommended to position the microphones in close proximity to the building plate. Although microphone position 3 is located closest to the process, it does not exhibit the highest statistic frequency density. This is attributed to the direct exposure of the inert gas.

On the other hand, at position 2, located at a distance of 25 cm from the center of the building plate within the PBF-LB chamber, the frequency density curve is steep and narrow, indicating that the audio recording remains stable and the signals are highly reproducible.

Summary and outlooks

The PBF-LB additive manufacturing process can produce components with complex structures, but it is prone to defects such as porosity due to incomplete mastery of the melting and solidification mechanisms. Process monitoring is crucial for quality assurance, and although optical sensors and cameras have been used, they have limitations, such as difficulty dealing with smoke formation. Acoustic quality monitoring is a promising approach as it allows for the automated and objective evaluation of process noise. This study aims to evaluate and optimize the acoustic measurement setup for monitoring PBF-LB quality. Among several factors influencing acoustic measurement, the selection of microphone positions is discussed and quantified in detail through experiments. The position near the building plate, without being directly impacted by the inert gas flow, delivers the most repeatable sound pressure distribution.

In future work, other factors such as reverberation should be investigated. Additionally, this work should establish a foundation for generating reliable acoustic recordings in various manufacturing setups to introduce different defects. These acoustic recordings are crucial for building a database for the automated detection of defects.

Acknowledgement

This work is funded through ML-S-LeAF project of the Federal Ministry for Economic Affairs and Climate Action of Germany (BMWK) with the grant number 03LB5006D.

Gefördert durch:

Bundesministerium
für Wirtschaft
und Klimaschutz

aufgrund eines Beschlusses
des Deutschen Bundestages

References

[1] Gibson, I.;Rosen, D.;Stucker, B.: Additive Manufacturing Technologies. Springer, New York (2015), 107-108.

[2] Lu Q. Y.; Nguyen N. V.; Hum A. J. W.; Tran T.; Wong C. H.: Identification and evaluation of defects in selective laser melted 316L stainless steel parts via in-situ monitoring and micro computed tomography. Additive Manufacturing 35 (2020), 101287.

[3] Imani F.; Chen R.; Diewald E.; Reutzel E.; Yang H.: Deep learning of variant geometry in layerwise imaging profiles for additive manufacturing quality control. Journal of Manufacturing Science and Engineering 141 (2019) 111001.

[4] Grasso, M.; Remani, A.; Dickins, A.; Colosimo, B. M.; Leach, R. K.: In-situ measurement and monitoring methods for metal powder bed fusion: an updated review. Measurement Science and Technology 32 (2021) 112001.

[5] Ye, D.; Hong, G.S.; Zhang, Y.; Zhu, K.; Fuh, J.Y.H.: Defect detection in selective laser melting technology by acoustic signals with deep belief networks. International Journal of Advanced Manufacturing Technology 96 (2018), 2791–2801.