Concept for In-process Measurement of Residual Stress in AM Processes by Analysis of Structure-Borne Sound

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Abstract. Process-induced residual stress is a major challenge in today's additive manufacturing (AM) processes, such as powder bed fusion by laser beam melting of metal. After the AM process, the exact stress state is usually unknown, and parts often require heat treatment to relieve residual stress. In-process measurement of residual stress is currently not possible. This paper presents a concept to derive the measurement of the residual stress by analyzing the structure-borne sound induced during the AM process. The first step of the concept is to integrate a device into a build plate to set a defined mechanical load during the manufacturing process. Then, samples can be fabricated on this build plate in several steps. By applying mechanical load with the device, the stress state in the samples can be changed between the fabrication steps. During this stepwise fabrication process, the structure-borne sound signal is recorded. Subsequently, the correlation between the stress states and the acoustic process emissions is analyzed using FFT, STFT and cross-spectral analyses. The overall goal is to establish a model to determine residual stress in AM components by evaluating the acoustic process emissions.

Keywords: Additive manufacturing · Residual stress · Structure-Borne sound · Quality control

1 Introduction

Due to the high freedom of design and the processing of a wide range of materials, additive manufacturing is becoming increasingly widespread, so that the technology has changed from "rapid prototyping" to series production of components [1]. In powder bed fusion (PBF), a coater applies thin layers of powder to a build plate or previous layers in a build chamber under an inert gas atmosphere or in a vacuum, and then an energy source (e.g. laser) selectively melts the powder. During this process, powder particles bond with each other and with previously manufactured layers. Unused powder is removed after the process and recycled [1].

One challenge in PBF processes is the formation of residual stresses during the manufacturing process. The local melting of metal powder leads to temperature gradients and eventually to the formation of thermal residual stresses in the component, which can

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lead to cracking in the build-up process or to component distortion [2, 3]. In addition, residual stresses have effects on the fatigue strength, static strength, chemical resistance, and anisotropy of the manufactured components [4, 5].

2 State of the Art

Kruth et al. [3] have identified several influencing factors for the reduction of residual stresses in PBF processes. For example, component residual stresses can be reduced by specific settings of process parameters, such as laser power, scanning speed, build temperature and exposure strategy, as well as by the appropriate use of support structures. Despite these factors, it has not yet been possible to completely suppress the formation of residual stresses and the associated defect patterns [3].

A variety of technologies exist for characterizing the residual stress state of components, such as X-ray diffraction or mechanical methods, such as the contour method [6]. These methods can only be used off-process. Another option for measuring residual stresses is the use of ultrasound [7]. This technology is based on the acousto-elastic effect, which describes the relationship between the propagation velocities of ultrasonic waves in bodies as well as the prevailing stress state [8]. The propagation velocity is measured, for example, via time-of-flight measurements of ultrasonic pulses. For this purpose, an ultrasonic pulse is coupled into the sample with a piezoelectric transmitter and the transmitted signal is measured with a receiver. The propagation velocity can be inferred from the time difference between the input and output signal and the sample geometry. Roy et al. and Holoch et al. have carried out extensive investigations for the characterization of the propagation velocities of sound waves [9, 10].

In laser-based manufacturing processes, structure-borne sound is emitted in the component as a result of exposure to the laser [11]. Eschner et al. have carried out investigations into structure-borne sound in laser-based additive manufacturing (PBF-L/M). For this purpose, a structure-borne sound sensor was integrated into a PBF-L/M system. Through this, sound emissions occurring during the manufacturing process could be recorded and correlated with the formation of defects [12, 13]. Furthermore, the recorded signals can be assigned to an area within the manufactured component by matching them with the laser trajectory.

3 Objective and Approach

The central hypothesis of this work is that the structure-borne sound emitted during the PBF-L/M process correlates with the resulting residual stress. Assuming this hypothesis is true, residual stress could be measured time and cost efficiently improving the industrialization of the PBF-L/M technology. Based on this hypothesis and motivation, the objective of this work is to develop a concept pursuing the goal of verifying the described correlation. The general approach of this concept is to measure and compare the structure-borne sound signals during additive manufacturing on test specimens with different stress states. The basic experimental setup is shown in Fig. 1.

To implement this idea, the proposed concept consists of three steps. The first step of this concept handles the creation of a defined mechanical load causing different stress

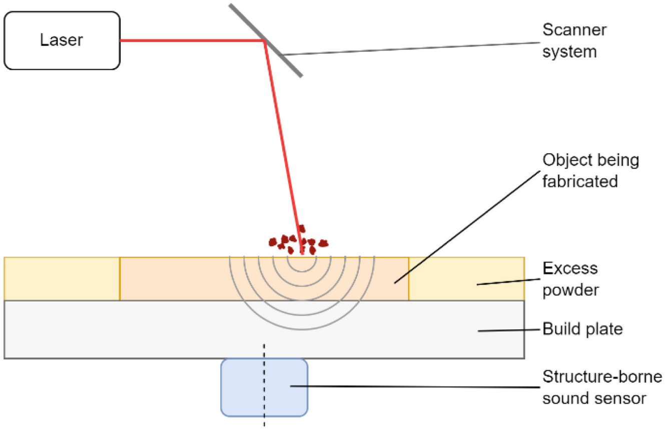

Fig. 1. Experimental setup for measuring structure-borne sound

states. In order to create this mechanical load, a device for setting a mechanical load on test specimens has to be designed. In addition, suitable test specimens need to be designed. The second step describes the execution of experiments to record structure-borne sound data. In the third step, the data obtained is analyzed to check whether there is a correlation between the stress state and the recorded structure-borne sound signal.

3.1 Device for Setting a Mechanical Load and Design of Test Specimens

The purpose of the device is to introduce a defined mechanical load into the test specimens and thus create a defined stress condition. For the design of the fixture and the test specimens, several requirements must be considered. First, the mechanical load must be changeable without having to open the process chamber. Fortunately, there is an access under the build plate that can be used if the device is advantageously designed. Second, the device must be integrated within the specified dimensions of the build plate and without protruding parts so as not to obstruct the coater of the additive manufacturing machine. Finally, the sensor measuring the structure-borne sound must be integrated under the build plate.

Considering these requirements, the device shown in Fig. 2 was designed. As geometry for the test specimens a cut-open ring was chosen. By spreading this ring with a wedge, which is tightened with a screw using a torque wrench, the mechanical load can be easily increased. In a simulation, a tensile stress of approximately 190 MPa is generated at a displacement of 1.3 mm, which corresponds to a load of 100 N. Due to this design of the device and specimen, no force flow is introduced into the build plate, unlike, for example, a design with flat bending specimens, so that the entire device can be built very compactly and with low complexity.

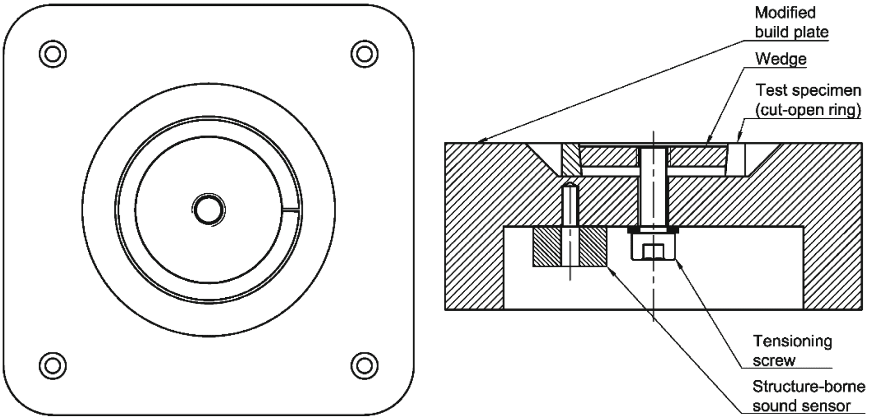

Fig. 2. Top view (left) and cross-sectional view (right) of the concept for the device for setting a mechanical load

3.2 Experiments

The aim of the experiments is to collect data of structure-borne sound signals under different stress conditions in order to analyze them later and determine possible correlations. It is to be expected that the actual additive manufacturing process will influence the recorded signal, e.g. through the powder, possibly formed pores or the change in geometry. For this reason, experiments are carried out first in which no powder is used and thus there is no influence of the additive manufacturing process. In further experiments the additive manufacturing process is carried out conventionally, i.e. with powder. In order to additionally investigate an influence of the heat input of the laser on the measurement results, the tests are performed with two load curves: from no load to maximum load and vice versa. This way, possible influences of the experiment order can be eliminated. In preparation for the experiments, the milled specimens are first stress-relief heat treated to relieve any residual stresses that may be present. The planned experiments are listed in Table 1 and are described below.

Table 1. Experimental plan

Experiment Nr	Specimen Nr	With (✓) / without (–) powder	Load curve
1	1	–	
2	2	–	
3	3	✓	
4	4	✓	

For the experiments without powder, a print job with one layer with the geometry of the specimen is created and the machine is prepared by inserting the presented device including the previously manufactured specimen. Subsequently, the print job is executed without applying powder and the structure-borne sound signal is recorded. The next step is to increase the mechanical load by one tenth of the maximum load, for example. This changes the stress state in the specimen. After that, the print job is executed a second time, and the structure-borne sound signal is also recorded. These steps are repeated ten times until the maximum load is reached. The maximum load can be determined by simulating the stress distribution in the test specimen, as shown in Fig. 3. In consideration of the mechanical properties, a maximum load of 100 N is selected so that the specimens deform only elastically and plastic deformation is prevented.

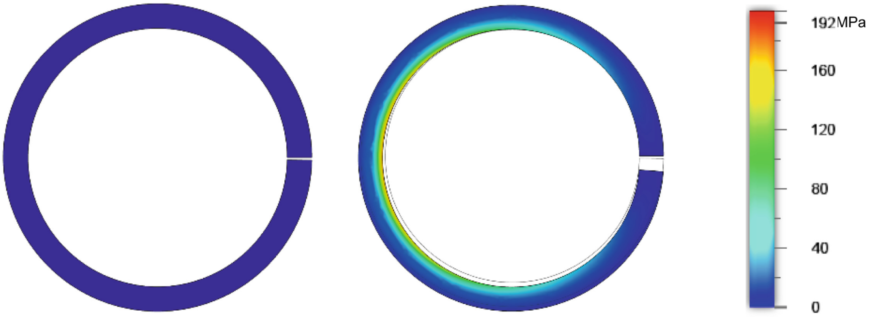

Fig. 3. Simulation of the 1st principal stress in the ring as an effect of no load (left) and a mechanical load of 100N (right)

For the experiments with powder, the influence of the additive manufacturing process is considered. For this purpose, a print job with a test specimen of several layers is created. Then a few layers are produced on the milled test specimen while it is not under load. After that, the manufacturing process is stopped, the load is increased and the manufacturing process continues. During this step-by-step manufacturing process, the structure-borne sound signal is recorded. All experiments are then followed by a comparative study of the signals recorded in the individual process steps, which will be discussed in the next section.

After the experiments, measures are taken to validate the results. In order to determine the actual stress state, one measure is to investigate the stresses that occur using reference measurement techniques. The X-ray diffraction method can be used for this purpose. In order to characterize the repeatability of the stresses generated by the proposed device, a measurement is performed with all samples applying the same mechanical load and the results are then compared. The sonic velocity of additively manufactured components is influenced not only by the residual stress state present but also by other effects, such as porosity. In order to analyze the influence of these effects, computer tomographic as well as metallographic investigations of the built-up test specimens are to be carried out as a second measure [14].

3.3 Analysis

During the experiments, data sets for the studies with and without an additive manufacturing process are recorded for different load conditions. The objective is now to check whether there is a correlation between the stress state and the recorded structure-borne sound. For this purpose, the signals from low stress states are compared with those from high stress states.

A simple way to perform this comparison is to compare the acquired signal under the different load settings of the instrument for each test, e.g. a setting with no load and a setting with maximum load for a first test. A second method of extracting data from different stress states is based on the idea that the stress within the test specimen is not constant, but has a spatial distribution. For example, the simulation shown in Fig. 3 indicates a high tensile stress at the inner edge and a low stress at the outer edge. By pre-processing the structure-borne sound signal with software developed in preliminary work at the institute (soon to be published), the signals can be related to the location where they originated. Based on this assignment and in consideration of the calculated stress in the simulation, the signals generated under different stress conditions can be compared.

Regardless of the method used to extract data from different stress states, the structure-borne sound signals must be analyzed and compared. For this purpose, an existing data processing setup is used, which was developed in previous work [13]. The data processing setup consists of several steps. First, the data is decoded from a proprietary file format and then converted to the frequency domain using Short-time Fourier transform (STFT) [12, 13]. Noise is still present in the resulting spectrogram, for example due to stepper motors installed in the system. For this reason, noise suppression is performed by applying a difference mask that subtracts the noise from the spectrogram [12, 13].

After the data has passed through this processing setup, it can be analyzed. If the hypothesis of this work is true, it is expected that a change can be seen in the processed data, e.g. a shift of frequencies or differences in amplitude. Therefore, visualizations of spectrograms from different stress states are compared manually, e.g., by subtracting them from each other, to check for obvious anomalies or features. In addition, more sophisticated methods such as the DBSCAN algorithm can be used. The DBSCAN algorithm is an unsupervised learning method that is capable of grouping data based on their density and which works well despite the presence of noise [15]. Another method for comparing spectrograms of different stress states is to perform a cross-spectral analysis. This method is analogous to linear regression, but functions for data in the frequency domain. It therefore allows to reveal correlations in spectra [16].

If the experiments and analysis show a correlation between stress states and the acquired structure-borne sound signal, it is desirable to extend this concept into a more sophisticated model predicting residual stress.

3.4 First Results

In a first test, we set up a build plate as shown in Fig. 1 and focused the laser on exactly centered on the build plate. Without applying any powder, the laser was then switched on and the structure-borne sound signal was recorded. This signal was then processed using STFT. The results are shown in Fig. 4.

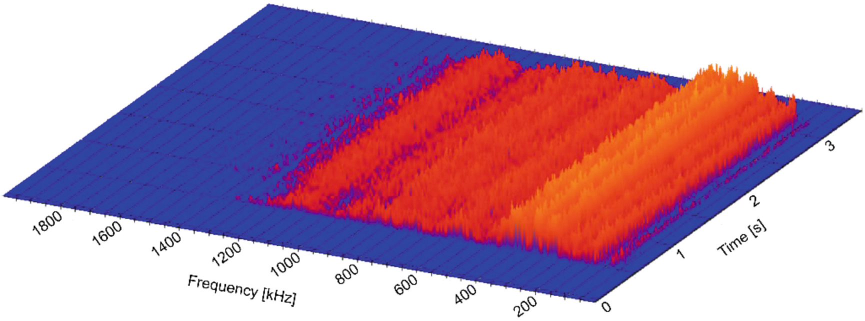

Fig. 4. STFT spectrogram (with noise suppression) of the structure-borne sound signal generated by melting of material

It can clearly be seen in Fig. 4 that it is possible to detect a signal of material melting using the structure-borne sound sensor. Further investigations are now required to determine whether this signal correlates with the residual stresses at the location of the interaction.

4 Conclusion and Outlook

This work addresses the development of new, intelligent sensor technology for additive manufacturing in order to make the manufacturing process robust for use in highly versatile production systems. The residual stresses that arise in additive manufacturing have been a hurdle so far as the process parameters have to be adjusted empirically until the component meets the required properties. This is in contradiction to the idea of highly flexible production that additive manufacturing promises.

If the results are positive, there is an opportunity for follow-up projects that address research into the measurement of residual stress states and the spatially resolved measurement of residual stresses using the structure-borne sound signal. In perspective, this can be used to selectively adjust process parameters and control residual stress states. In-process measurement of residual stresses during the additive manufacturing process would reduce process uncertainties, cost of treatment as well as time and, thus, enable the cost efficient production of higher-quality products.

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