Online Monitoring of Additive Manufacturing Processes Using Ultrasound

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Abstract
Additive manufacturing processes have become commercially available and are particularly interesting for the production of free-formed parts. With Selective Laser Melting (SLM), components can be produced by localized melting of successive layers of metal powder. In order to be able to describe and to understand the complex dynamics of the SLM processes more accurately, online ultrasonic measurements have been performed for the first time. In this contribution, we report on the integration of the measurement technique into the manufacturing facility and on a variety of promising monitoring results.

Keywords: ultrasound, welding, aerospace, Inconel, monitoring

1. Introduction

Additive manufacturing processes have been investigated and some of them developed commercially since the late 1980s. With Selective Laser Melting (SLM), components can be produced by localized melting of successive layers of metal powder. In comparison with today’s conventional techniques, this way of manufacturing allows for considerably more freedom in designing and has a tremendous economic potential. Thus, it is particularly interesting for the production of geometrically complex aero engine components.

By local melting with a laser beam such engine components have already been manufactured from the heat-resistant nickel alloy Inconel 718. To ensure the quality, the starting powder and the manufacturing parameters are supervised; also, the built-up components are inspected using nondestructive as well as destructive techniques.

In order to be able to describe and to understand the complex dynamics of the SLM processes more accurately, online ultrasonic measurements have been performed for the first time. In this contribution, we report on the integration of the measurement technique into the manufacturing facility. We present first results based on generalized B-scans which illustrate the build-up of test specimens based on single layers of 40 µm thickness. The analysis of the ultrasonic signals allows to infer information about the fusion of the single layers and about the temporal formation of material defects. We also discuss the further potential of ultrasonic measurements.

2. Additive Manufacturing and Quality Assurance Considerations

Powder bed fusion is the most frequently applied technique for layer manufacturing of metallic objects. Figure 1 schematically illustrates the basic setup, where a laser beam melts the metallic powder according to a CAD-file of the component to be build. At MTU Aero Engines, Selective Laser Melting is used for components made of Inconel 718. Additional to a specifically installed SLM technology machine, on which the results presented in this contribution have been obtained, six SLM production machines (EOSINT M 270, [1]) are employed to investigate and enhance the manufacturing of high-quality aero engine parts.

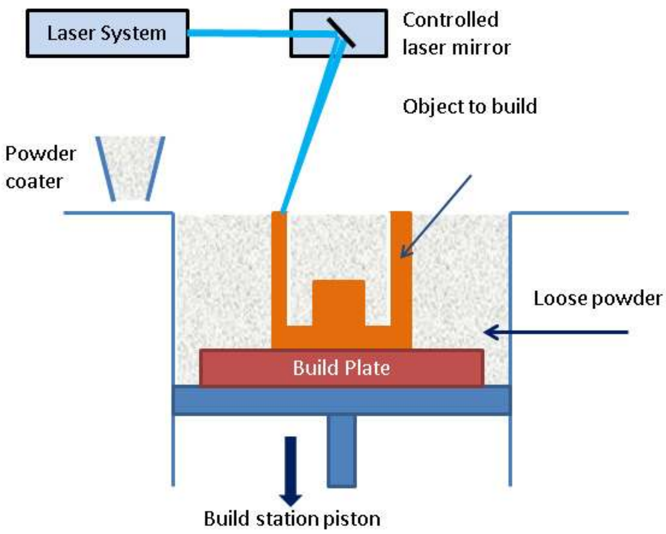

Figure 1. Schematic representation of the powder bed fusion process.

The usual procedures for quality assurance (QA) include the control of the machine parameters in view of process stability and repeatability as well as metal powder control with respect to chemical composition, particle shapes, sizes and size distributions [2]. However, due to the high quality standards pursued at MTU Aero Engines, additional measures for quality assurance have been developed and implemented to monitor each layer surface during the build-up process. Here, optical tomography (OT) is applied to monitor hot-spots, which might indicate the formation of possible defects [3,4]. After production, the manufactured parts are examined in view of deviations from the CAD-geometry using e.g. fringe projection methods, while X-ray and fluorescent penetrant inspection (FPI) methods supply information about porosity and the presence of surface defects. The set of MTU's QA-measures is complemented by materials testing where e.g. tensile tests and low-/high-cycle fatigue tests are employed for material characterization [2]. Further promising monitoring techniques, currently not pursued at MTU, are based on the observation of the welding process via thermography [5,6] or laser-generated ultrasound [7].

To complement the already implemented OT-monitoring of the welding process, an ultrasonic monitoring system has been integrated into the EOS technology machine to infer additional information about the manufacturing process and the state of the built-up component, as described in the following.

3. Ultrasonic Process Monitoring

3.1 Objectives and Chosen Setup

The aim of monitoring the layer build-up during the manufacturing process using ultrasound is the observation and/or surveillance of parameters which are only accessible online. These are the dynamics of the layer build-up, the interface coupling, the local material properties as well as the formation of residual stresses, distortions and porosity. For the installation of additional components in the build-chamber, restrictions have to be obeyed which are due to the specific environmental conditions, mainly the inert gas atmosphere and the elevated temperature of about 80° C.

In our approach, we have decided to fix the ultrasonic transducer at the lower side of the build-platform. Figure 2 shows the setup with the fixed probe and the sealed installation of the RF-cabling underneath the build-platform. We use an unfocused 10 MHz normal incidence probe of 6.3 mm (¼ inch) diameter generating longitudinal waves, which has been glued to the platform after grease coupling had been applied.

Figure 2. Ultrasonic probe arrangement underneath the build-platform.

3.2 Monitoring Inspection System

In the course of this study, a PC-based monitoring and inspection system especially designed for the integration in such production systems has been developed and set-up. The main characteristics of the four-channel ultrasound transmit-and-receive system are as follows: bandwidth ranging from 400 kHz up to 30 MHz, data acquisition rate of 250 Mega-samples per second, 14 bit resolution, process-induced triggering, time and event/welding controlled monitoring with up to 1000 A-scans per second, integrated DSP-functionality and on-line/off-line visualisation capabilities.

The system allows to record ultrasonic signals with a temporal resolution of up to 4 ns. Data acquisition is performed layer by layer, as it is synchronized with the start of each layer-wise welding process triggered by the EOS machine. During welding, the ultrasonic signals are recorded within an adjustable time window and the RF-signals are simultaneously visualised. The signals are stored and can be further processed, which is currently done off-line. The established inspection system complies with the required specification of being able to acquire data during build-jobs of up to 8 hours duration. Recording up to 1000 data A-scans per second results in several Giga-bytes of data to be stored, further processed and evaluated.

4. Demo Build-Job and Ultrasonic Signals

The final objective is to monitor and control the component build-up by giving feedback to the process if indications or deviations from the reference state or reference parameters are detected. However, due to the sophisticated manufacturing process, the relationship between the build-up parameters and the acquired ultrasonic signals has to be investigated gradually in respective studies with reference to well-defined build-jobs. For illustration of the first steps of these extensive investigations, we present preliminary results obtained on a cylinder of 20 mm in diameter and 10 mm in height supplied with a void as an internal defect. During the build-up, illustrated in Figure 3, a sphere of 2 mm in diameter has been created, filled with non-melted metallic powder. The characteristics of the build-job are: 40 µm layer thickness, 250 layers and approximately 90 minutes build-up time. The inspection procedure consists of

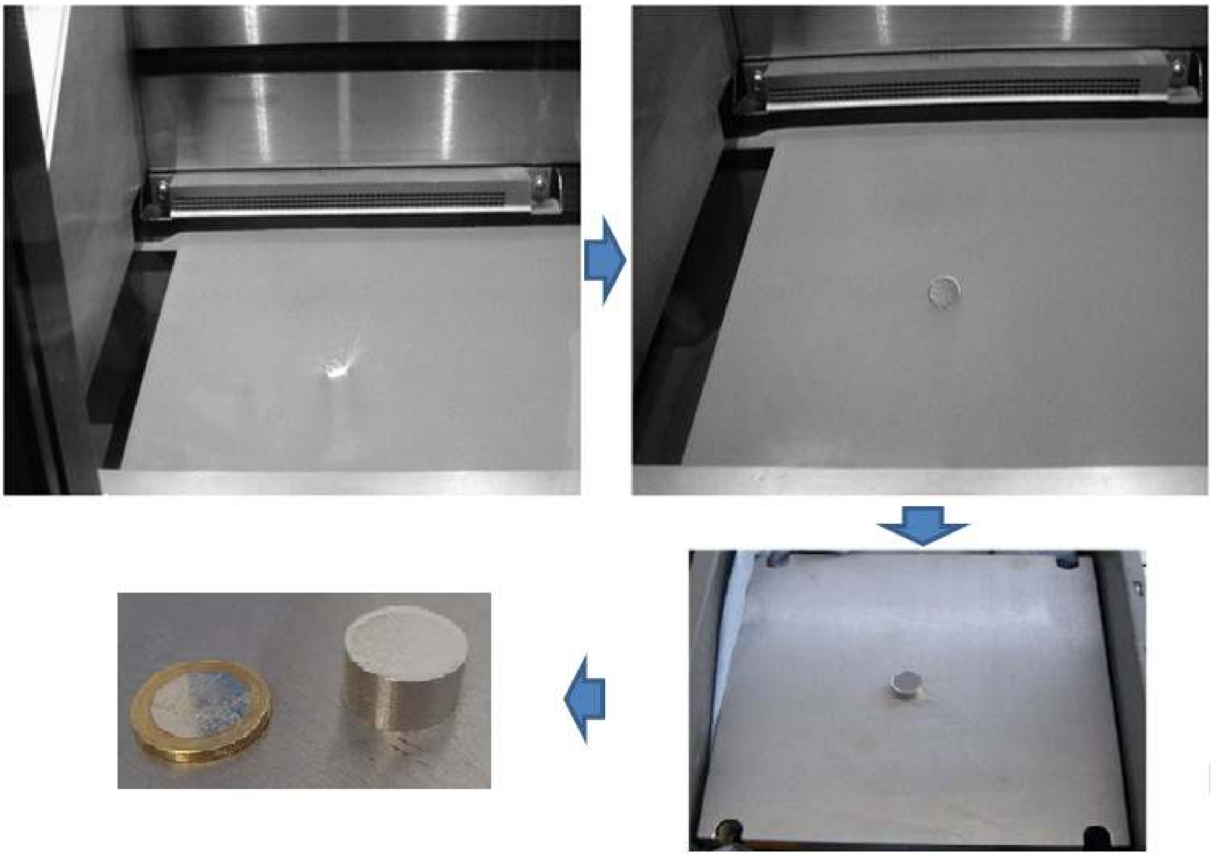

Figure 3. Illustration of the welding process and the build-up of the cylindrical specimen.

three steps: (i) warm-up of the build-chamber and recording of a sequence of various backwall echoes within the platform until the ultrasonic signals remain stable at about 80° C, (ii) start of the SLM-process and monitoring of the welding/build-up phase and finally (iii) off-line evaluation once the build-job has been completed. Figure 4 shows a detailed view of the backwall echo with a short time change after the build-up of the 40 µm layer.

By plotting the A-scans acquired after the end of each layer-wise welding, the build-up process becomes ‚observable‘. The representation of such a plot in Figure 5 shows some interrupts in the recorded data due to gain adjustments. Also, a small change in interface echo (IE) at a build-up height of 1.5 mm can be seen.

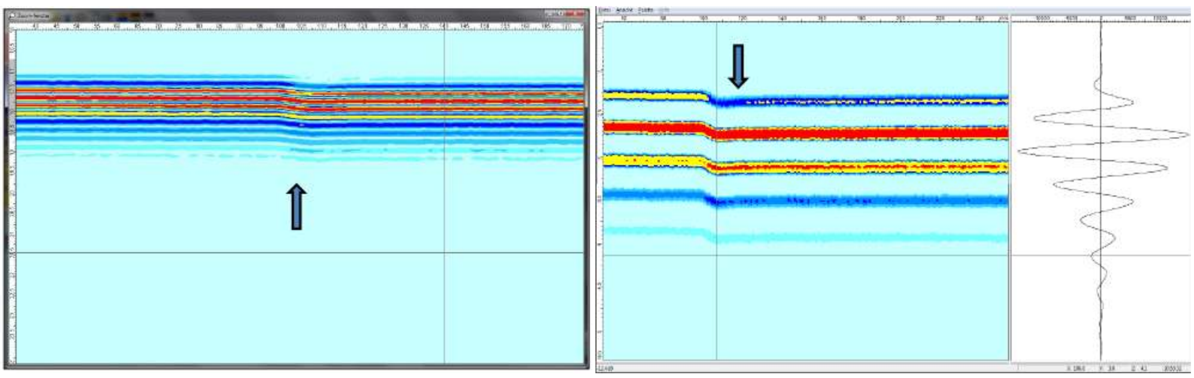

Figure 4. Detailed view of the backwall echo with a short time change after the build-up of another 40 µm layer.

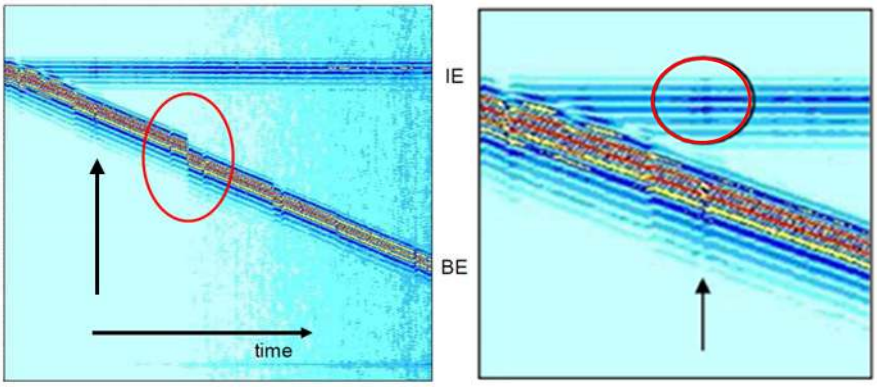

Figure 5. Visualisation of the ultrasound signals with the bottom plate interface echo (IE) and the backwall echo (BE); as time progresses the build-up height increases. Right: detailed view of the signals at a height of 1.5 mm.

With increasing build-up height, the recorded A-scans get more and more noisy. Therefore, a specific A-Scan representation has been chosen (Figure 6, left): the A*-scan constitutes the average of all A-scans recorded during the build-job. Due to the averaging, the incoherent signals, i.e. the noise signals are reduced and only static objects become visible such as the interface and defects, while the backwall echoes cancel out. However, as indicated in Fig. 6, the void in the built-up cylinder is only poorly visible, due to a misalignment of the probe relative to the void position. To validate the successful generation of the void as a model defect, we have performed immersion testing of the finished cylinder. The acquired C-scan is shown in Figure 6 (right), where we have used a 10 MHz focused transducer (focus 3 inches in water). The defect is clearly imaged and no further indications are present in the specimen.

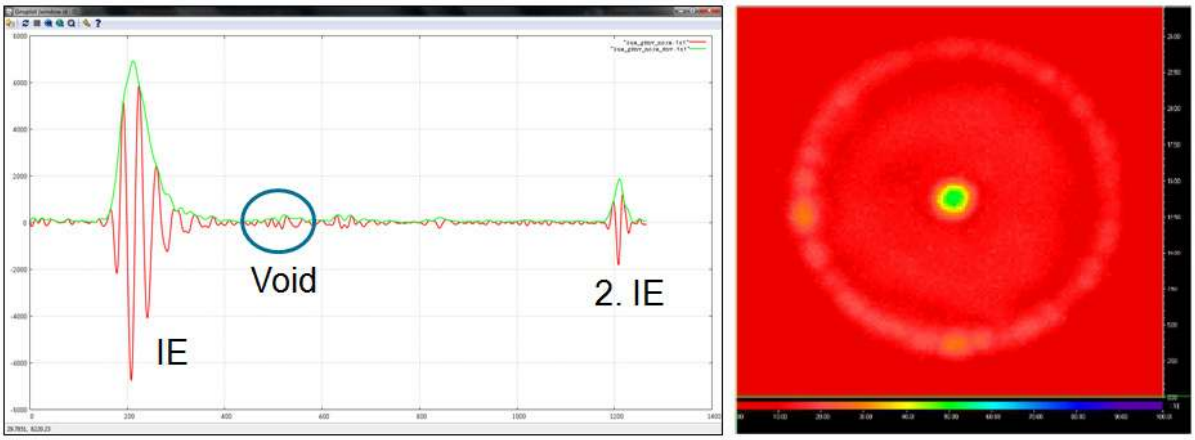

Figure 6. Left: the void is poorly visible because of misalignment of the probe relative to the void position; right: C-scan image of the void by immersion technique.

5. Further Processing Approaches and Evaluations

5.1 Determination of Ultrasonic Velocity

We have evaluated the longitudinal wave velocity after each layer build-up, assuming an average layer thickness of 40 µm. In order to obtain more stable results, the sound velocity was calculated using an average of 40 ultrasonic signals recorded for each layer. The results are presented in Figure 7 for increasing build-up height, showing a nonlinear, monotonous increase of the ultrasound velocity, which reaches an asymptotic value once a certain height has been built-up. It is assumed, that this effect is due to the heat influence induced by the melting laser as the heat penetrates through several layers. This effect is larger in the early stage of the build process due to the smaller volume which is present to absorb the laser energy. Additional experiments and evaluations are planned to validate this hypothesis.

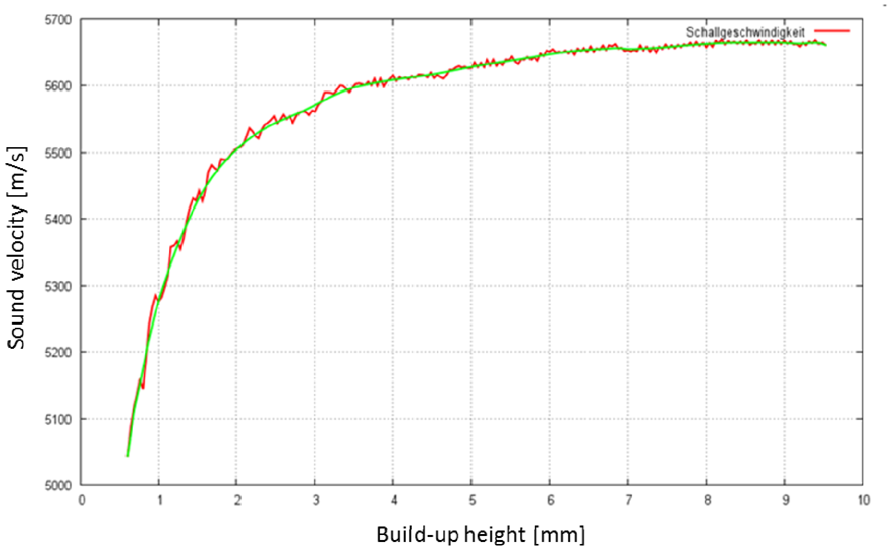

Figure 7: Ultrasonic velocity plotted as a function of build-up height.

5.2 *Frequency Behaviour*

Additionally we have evaluated the frequency behaviour on successive layer build-ups using Fast-Fourier-Transformation. A representative result is displayed in Figure 8. On the left, the colour-coded spectral distribution of the ultrasonic signals is shown before, during and after welding. Here, a clear 'distortion' during welding can be seen, which might be used to characterize the quality of the welding process. On the right of Fig. 8, the spectral distribution of different build-up layers are compared, where the different colours belong to different build-up heights. As can be seen, the spectrum changes with the higher frequency components decreasing with increasing build-up height.

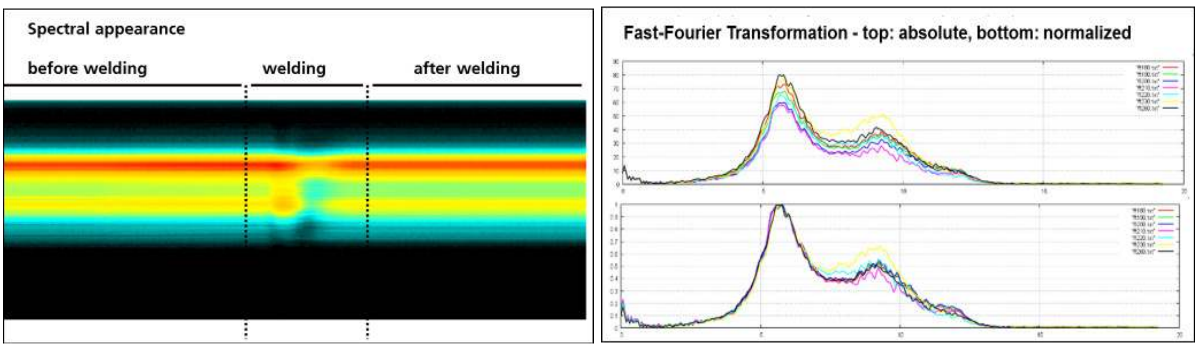

Figure 8: Representation of the frequency dependence during the welding process of one layer (left); spectral distribution as a function of build-up height (right).

5.3 *Build-Job with Variation of Laser Power*

In order to gain preliminary information about the influence of varying power of the melting laser beam on the quality of the manufactured part and the ultrasonic signals, a respective specimen has been built-up and monitored. The thicknesses of the different sections built with varying laser power are schematically shown in Figure 9, left. From the recorded A-scans (Figure 9, right) the start and the end of the build-up phase with 50 % power can be identified. However, the structure built with only 25 % power has no sufficient coupling to the preceding layer, so ultrasound cannot be propagated anymore which is indicated by the backwall signal which remains at the same position once the build-up height exceeds 12 mm (the respective A-scan is not shown in Fig. 9).

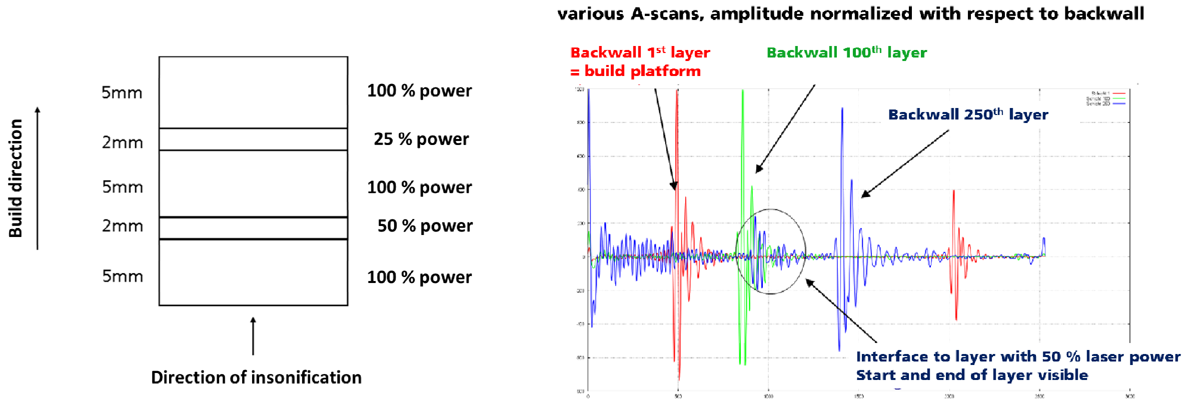

Figure 9. Schematic representation of the variation of laser power (left); monitored signals as a function of the number of welded layers.

6. Conclusion and Outlook

The results of our first investigations have shown that online monitoring of the complex AM processes using ultrasound through the build-platform is feasible. Observation of the surface dynamics during the build-up is possible by evaluating the backwall signals. The signals bear indications for qualitative evaluation of residual stresses. Also, statements concerning porosity seem to be possible by additionally evaluating the ultrasonic velocities.

In order to properly exploit the potential of ultrasonic monitoring, further research has to be performed. It should focus on the stabilization of the inspection conditions, as e.g. the probe coupling has proven to be critical for efficient data acquisition. The examination of various defect types in dependence of their position in the component and the evaluation of the ultrasonic signals in view of porosity are further issues to be pursued. As residual stresses are critical with respect to distortions of the built-up components we plan to investigate the online monitoring of respective reference specimens. The presented approach is currently limited to parts with non-complex geometries, but is as such particularly interesting for e.g. build-chamber control using test artifacts.

Acknowledgment

This project has received funding from the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration under Grant Agreement No. 266271, MERLIN.

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