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Toward in-line crack detection and localization during metal additive manufacturing using laser-based air-coupled ultrasound sensors

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Abstract

Laser Directed Energy Deposition (L-DED) is a maturing technology advancing towards industry-wide implementation. To improve quality assurance and process reliability, in-line monitoring strategies are mandatory for early defects detection. In this work, L-DED processes were monitored by analyzing their ultrasound emissions using air-coupled optical microphones. With these broadband acoustic sensors, the presence and position of cold cracks occurring during and after the fabrication of coupons were identified based on their characteristic ultrasound signatures. Synchronized acquisition of acoustic data from an array of optical microphones placed around the process area and tracking data from the fabrication robot enables the location of defects on large-scale manufacturing parts. Additionally, the array was used to evaluate an even more refined defect localization approach by using a trilateration algorithm. The promising results obtained under controlled conditions provide an encouraging prospect towards future implementation of real-time crack detection and localization in metal 3D-printing applications.

Keywords: L-DED; crack detection, defect localization, trilateration, optical microphones

1. Introduction

Additive manufacturing techniques such as Laser Directed Energy Deposition (L-DED) are continuously gaining industrial acceptance as they offer unique capabilities to clad or repair pre-existing valuable metallic components. However, a prevalent source of defects during this manufacturing process is the formation of cold cracks, which can occur during the cooling down phase of the fabricated sample. To detect this kind of defect immediately and avoid increasing costs in later manufacturing stages, a reliable real-time inline process monitoring system is essential (Hauser 2022).

Acoustic monitoring of L-DED processes offers several advantages compared to visual process monitoring techniques (Chen 2023). The most important among them are the increased flexibility in positioning the sensors, the very fast dynamic response and potentially cheaper hardware costs. In the case of cold cracks, a large part of their acoustic emissions is produced in the ultrasonic frequency band. Focusing on this frequency range has pivotal advantages, as it is unaffected by noise from other machines that are typically present in such an industrial production environment. Although acoustic monitoring has been extensively studied for the inspection of welding quality, the investigation of airborne ultrasound emissions to detect and localize cold cracks by determining the directivity of sound is a new field of research (Prieto 2020).

To enable precise analysis of the air-coupled ultrasound signal and the extraction of accurate, time-sensitive information about the origin of the emitted sound, an ultrasound sensor with a large bandwidth is necessary. This requirement is met by the membrane-free, laser-based acoustic sensors (Optical Microphones) provided by XARION Laser Acoustics, which measure sound waves in air up to 4 MHz. In this paper we present a newly designed experimental setup of three air-coupled Optical Microphones to localize the origin of cracks from their ultrasound emissions.

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2. Experimental Setup and Methods

The experimental setup can be divided into three parts. Firstly, the air-coupled ultrasound sensors to record the airborne acoustic emissions, secondly, the L-DED manufacturing workstation used to evaluate and optimize the overall monitoring solution, and, thirdly, the data processing equipment to perform the data analysis.

2.1. Acoustic Monitoring System

For the presented setup three units of the Optical Microphone Eta250 Ultra by XARION Laser Acoustics GmbH (Fischer 2016) were chosen. This Optical Microphone is an air-coupled acoustic sensor for sound pressure waves in a frequency range from 10 Hz to 1 MHz. Its working principle is based on interferometry, and it consists of a tiny sensor head (diameter: 5 mm, length: 38 mm) in combination with a signal conditioning unit (SCU). This SCU contains a laser which sends coherent light via an optical fiber to the sensor head. The sensor head encapsulates a pair of parallel, partially reflective mirrors representing a so-called Fabry-Pérot etalon. A sound wave passing through the cavity between the two mirrors causes small shifts in the wavelength of the laser light. This in turn affects the amount of reflected light returning from the interferometer to the SCU due to its interference with itself. The resulting laser light is converted into an electrical signal via a photodiode. As the sensor dimensions are very small and the sensor head is fiber-coupled, it can easily be mounted in proximity to the L-DED process.

The analog electric voltage signal from each of the three Optical Microphones is converted into a digital signal using an analog-digital converter (ADC). This multi-channel ADC captures the acoustic signal over time with a sampling rate of 2 MHz and a resolution of 14 bit and streams it to a computer for further analysis.

The array of three sensors was mounted on a custom-made fixture attached to the laser process head, so the sensors are placed at a radius of 20 cm from the laser head and orientated in a way that the direct line-of-sight of the sensor head points to the focus spot of the fabrication laser as shown in Fig. 1.

2.2. Setup of the L-DED Manufacturing Plant

The manufacturing workstation (Fig. 1) operates a 1070 nm, 6 kW disk laser for the L-DED fabrication. It is equipped with an L-DED laser processing head, which is mounted on a 6-axis robot. A double-hopper powder feeder is connected to an annular gap powder nozzle, which is attached to the laser head. Process and monitoring data such as the robot position coordinates, laser parameters, temperature development at the ultrasound sensor heads, and powder feeder parameters are collected.

The exact position and orientation of the ultrasound sensor heads in relation to the laser head and the coordinate system of the robotized setup were obtained by creating a CAD reconstruction of the whole setup using a 3D scanner.

2.3. Data Acquisition and Analytical Methods

An edge device was used to record the digitalized acoustic data and stream it to a digital cloud platform. Before the ultrasound signal can be analyzed, it is preprocessed by applying a band pass filter with a selected frequency range between 50 kHz and 600 kHz, which ensures that the monitoring system is not affected by background noise in the audible range. Thereafter, peaks in the acoustic signal with a characteristic shape that appear simultaneously on at least two out of three microphones are interpreted as cracks on the sample. To obtain their locations, the times of appearance of the detected peaks are correlated with the pathway of the robot.

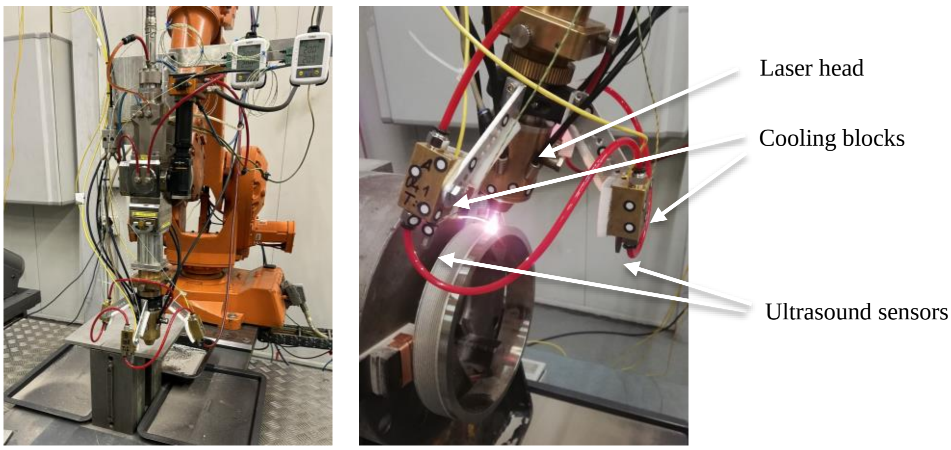

Fig. 1. Left: Picture of the 6-axis robot with the fabrication laser head and the ultrasound sensors attached to it; Right: Close-up of the laser head and the three acoustic sensors during a fabrication process.

3. Results

3.1. Detection of Cold Cracks

During L-DED processes such as laser cladding, which was performed on the samples presented in this section, cold cracks can spontaneously occur. This type of defect is caused by an unfavorable dynamic in the cool down process. For the evaluation of our monitoring system the number of cracks was intentionally increased by employing adverse processing parameters. Due to the rapid formation of such cracks, an acoustic signal containing extremely high frequencies is emitted into the air. The intensity of these sound waves is so high that, despite the strong attenuation of ultrasound in air, it is still possible in a distance of approximately 20 cm from the sound source to measure the emitted acoustic signal up to ultrasonic frequencies of 500 kHz.

These cracks produce a peak in the ultrasound data, which appears on all ultrasound sensors simultaneously and exhibits a characteristic shape. An example of such a peak is shown in Fig. 2. Experiments were conducted by laser cladding the surface of flat samples with an area of 25 cm x 25 cm. The analysis of the acoustic signal showed that cold cracks can be detected by this method in a reliable way. Furthermore, it was revealed that the information from two microphones is sufficient for crack detection.

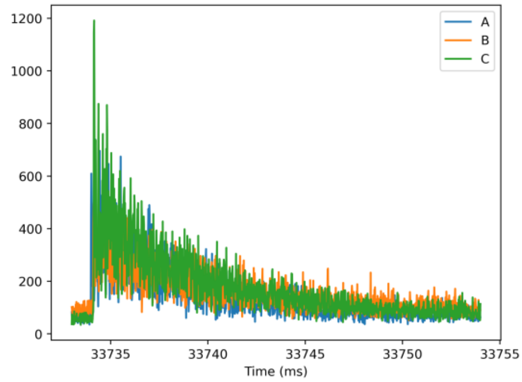

Fig. 2. Example of the characteristic peak shape of the ultrasound emission of a cold crack. The acoustic signal arrives at all three air-coupled ultrasound sensors (A, B, and C) within less than 0.5 ms.

3.2. Localization of Cracks

To determine the location of cracks on a sample, the exact time of crack formation is extracted from the acoustic signal and correlated with the position of the fabrication robot at that point in time. As cold cracks, usually, occur within a very short period of time after the laser process, the robot position at the time of the acoustic emission is a good estimator for the true crack location. To investigate the performance of this crack localization method, ring shaped samples were laser cladded on their outside surface. In Fig. 3 the results from the acoustic analysis are compared with visually obtained reference positions. A clear correlation between them is visible.

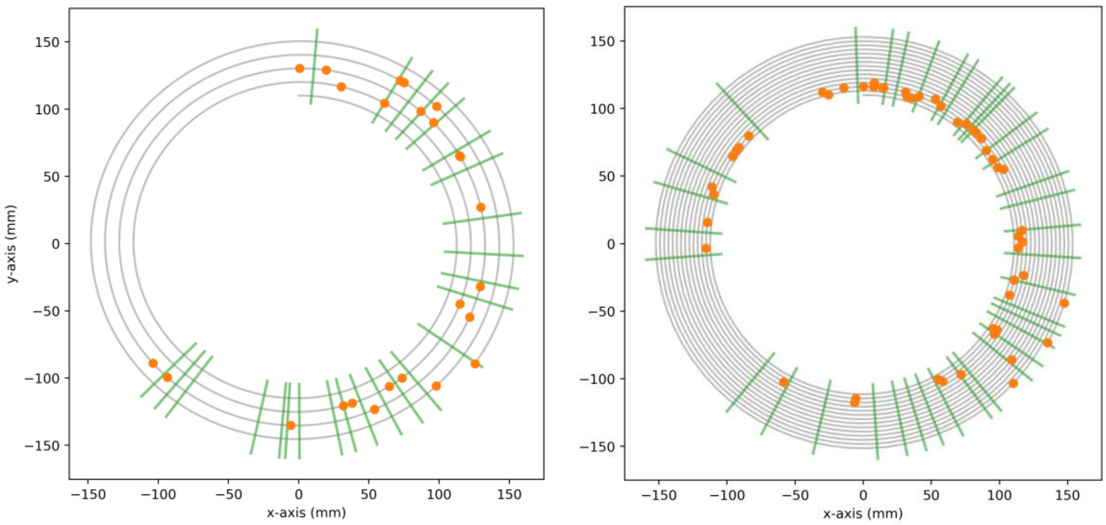

Fig. 3. Diagrams from two different samples showing the good agreement between acoustically located cracks and their visually confirmed positions. The gray spiral indicates the trajectory that was laser cladded, the orange dots mark the crack positions that were determined from their airborne ultrasound emissions and the green lines represent the visually confirmed crack locations.

3.3. Evaluation of a Trilateration Approach

One method that can enable an even more precise determination of the spatial origin of a crack is trilateration. With a trilateration algorithm the ultrasound signal measured at three different microphones in the proximity of the fabrication laser head can be compared to obtain the signal source' location with high accuracy. To investigate the capabilities of this approach an experiment under laboratory conditions was conducted. Therefore, three Optical Microphones were arranged in the same configuration as shown in Fig. 1 and pencil leads were broken in a controlled way at defined reference positions. The positions obtained from the trilateration algorithm were compared to the reference positions and the average deviation between acoustically obtained and reference positions was determined to be 11.6 mm. However, it has to be considered that during an L-DED process extremely high temperatures occur, which can negatively affect the performance of a trilateration approach.

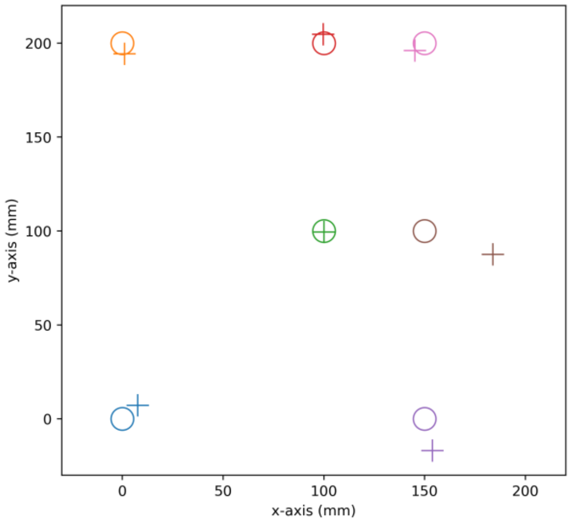

Fig. 4. Diagram of the positions where pencil lead break tests were conducted. The circles represent the original reference positions and the cross symbols show the positions which were determined with a trilateration algorithm applied to their ultrasound emissions.

4. Conclusion

A novel ultrasound sensor, the Optical Microphone, was used to construct an array of three sensors for detection and localization of cold cracks during an L-DED process. It could be confirmed that the formation of these cracks results in the emission of a characteristic airborne ultrasound signal which is unaffected by usual background noise and can reliably be detected by air-coupled ultrasound sensors based on the characteristic peak shape and the simultaneous appearance at multiple sensors. By extracting the exact times of arrival from the acoustic signal and correlating them with the pathway of the fabrication robot, the detected cracks can be acoustically localized on the manufactured part. The comparison with visually confirmed crack positions revealed good agreement. In addition, an array of three optical microphones provides the potential for an even more precise localization using a trilateration approach. For laser processes like laser metal deposition (LMD) and laser cladding (LC), where strong heating up of the surrounding air is prevalent, the presented first studies were not sufficient to prove the concept, but for processes with cooler ambient air conditions such as powder bed fusion (PBF) the results obtained with trilateration provide an encouraging prospect.

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