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Industrial Paper

Monitoring of remote laser processes using air-coupled ultrasound

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Abstract

We present a versatile and innovative method for quality control of remote laser material processing based on analyzing the process‘ air-coupled ultrasound emission. An optical microphone serves here as a sensor for the full acoustic process emission bandwidth in a contact-free and thus easily integratable manner. Two industrial use case developments are presented. The first concerns welding of metal sheets and addresses real defect detection through deviations from known reference signals. The second case focusses on welding of direct copper bonded substrates used in high-power electronics applications. Alongside irregularities in the ultrasound emission of the welding process, which relate to defects confirmed by visual inspection, also thermal shock-induced cracks in the ceramic substrate are detected. Aspects to further industrialize the acoustic monitoring solution and how to adapt it to other related applications are discussed.

Keywords: real-time monitoring, acoustics, remote laser welding

1. Introduction

Remote laser welding processes are typically performed at high speeds and with high part throughput. Therefore, it is crucial for a monitoring system to deliver fast and highly automated process quality assessments (Purtonen et al., 2010). The optical microphone as an air-coupled ultrasound sensor enables the setup of a monitoring chain, which satisfies both of these requirements and, thus, was used in the two use cases presented in this paper.

2. Monitoring Methods

In both of the presented use cases the XARION optical microphone Eta250 Ultra for the detection of sound pressure waves in a frequency range from 10 Hz to 1 MHz was used. The most important advantages of this instrument concerning the presented cases are the broadband measurement capabilities, the easy off-axis integration and the wide field of view of the sensor. Due to the small size of the sensor head it can be mounted in very close proximity to the process minimizing the impairment caused by background noise (Prieto et al., 2020; Fischer, 2017). To perform real-time in-situ monitoring the analog voltage signal is processed by a high-frequency measurement (HFMES) system. The HFMES instrument performs analog-digital conversion with a sampling frequency of 2 or 3 MHz with a bit rate of 24 or 16 bit, respectively, thus enabling very high temporal resolution of the process acoustics. In the next step from this raw time signal a spectrogram with 512 frequency bins and up to 31 250 spectra per second is calculated using an FFT algorithm.

In the second one of our use cases the spectrogram is integrated over a selected range of frequency bins yielding a so-called energy curve, which describes the total acoustic energy in the mentioned frequency range over time. The energy curve is then used to conduct an envelope analysis method. This method allows to compare any incoming energy curve with a predefined region of acoustic energies (called the envelope) which are related to flawless weld seams.

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3. Results

For the industrial use case in high-power electronics, we present two monitoring applications. These include the detection of welding irregularities on direct copper bonded (DCB) substrates and the identification of cracks in the ceramic of DCB substrates due to thermal stress. The meltpool itself as well as mechanical deformations are known to be a cause for acoustic emission (Lee, 2014; Wang, 2018).

Concerning the use case of welding metal sheets, we show results of two different welding defect scenarios.

3.1. Laser process monitoring of DCB substrates

To obtain useful acoustic data for our analysis, 10 weld seams with standard parameters and 10 seams with excessive parameters were produced with an active crossjet. In Fig. 1 a picture of the seam and the corresponding spectrogram of its acoustic emission are presented for a good welding process and a faulty one.

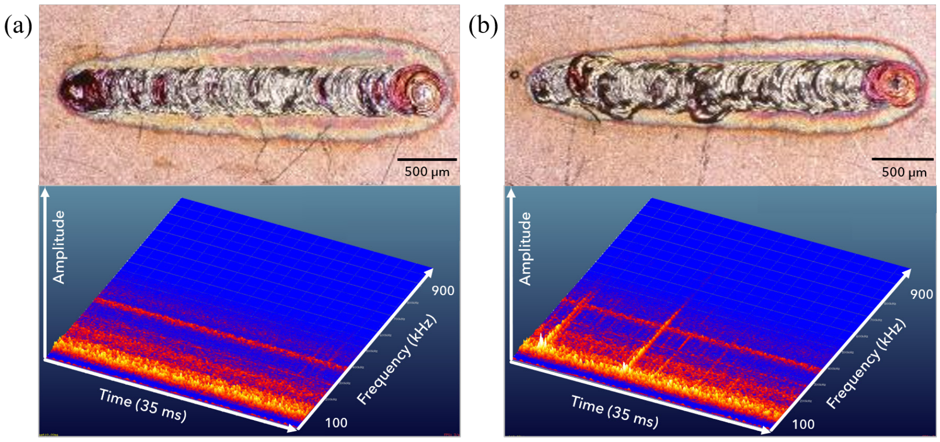

Fig. 1. (a) Picture of a good weld seam with the spectrogram of its acoustic emissions; (b) Picture and spectrogram of a faulty weld seam

In the spectrograms it is apparent that the observed faulty weld seam exhibits several short broadband signal peaks with a substantial portion of the acoustic energy above 150 kHz. This makes the measurement to a great extent immune against audible noise in the environment and cuts out a large part of the crossjet emissions. It is also visible that the location of the defects within the weld seam strongly correlates with their time positions in the acoustic signal.

For a quantitative analysis an energy curve was derived from the mentioned spectrogram by integrating over the frequency bins in a range from 150 kHz to 1 MHz. Then the standard deviation of this energy curve was calculated over the complete process duration. In Fig. 2 the standard deviations of the 10 good and 10 faulty welding processes are shown. It is visible that the variation within the ultrasound signal is significantly higher for weld seams with defects than for flawless ones. Indeed, an overall threshold can be set, which clearly differentiates faulty welding processes from good processes.

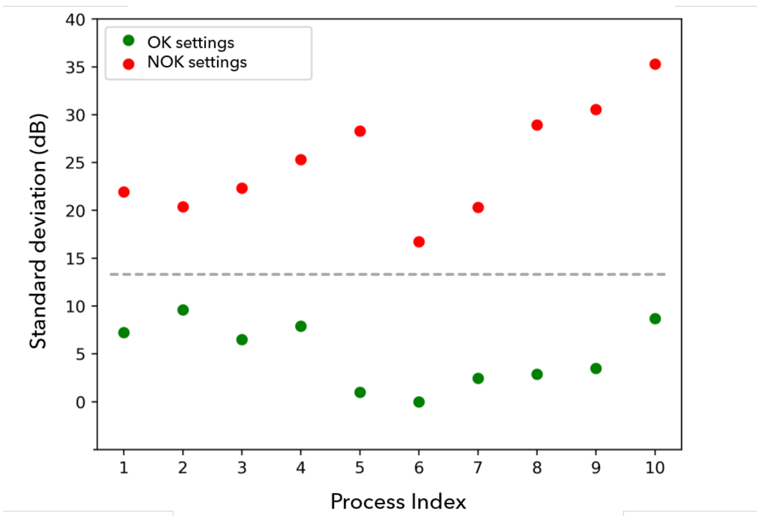

Fig. 2. Diagram of the standard deviations of the acoustic energies emitted by welding processes with good settings (marked in green) and with faulty settings (marked in red)

3.2. Identification of thermo-shock related cracks in DCB substrates

Another important application of this measurement setup is the detection of cracks caused by thermo-shocks in DCB workpieces. These cracks can occur if the welding laser produces too fast temperature changes in the sample. To obtain the best-possible sensor position for the acoustic monitoring, the sensor head of the optical microphone was mounted on the opposite side on which the laser is processing. With this setup it was possible to achieve very impressive results in the spectrogram as presented in Fig. 3. The crack in response to the thermo-shock exhibits a remarkably obvious acoustic signature, which comprises both a significantly high amplitude and very broad frequency range. The existence of the mentioned crack could be validated with an ultrasound microscope image.

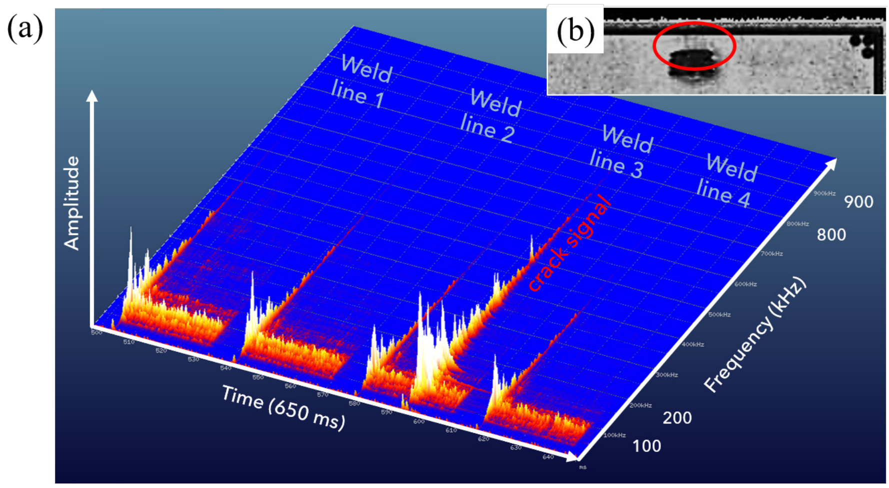

Fig. 3. (a) Spectrogram of four welding processes with a crack due to thermo-shock appearing during the third weld seam. This defect produces a high-amplitude and very broadband acoustic signal. (b) Microscope image of the crack (in red circle) in the ceramic due to thermo-shock

3.3. Defect detection during remote laser welding of metal sheets

The second industrial use case we present concerns the monitoring of metal sheet laser welding using the envelope analysis method mentioned in section 2. To evaluate the quality of weld seams, the ultrasound emission of the welding process is compared with the acoustics of stable reference processes. In particular, for every weld seam an energy curve is derived in the frequency range from 75 kHz to 500 kHz. From the energy curves of reference processes, a mean curve and their standard deviation is calculated. If the energy curve of a new unvalued weld seam lies inside a region of +/- 3.5 times the standard deviation around the mean curve (this region is called the envelope), it is considered as being flawless. However, if its energy values are outside the envelope region, a defect score is calculated.

To test our algorithm, we produced weld seams with two types of intentionally introduced welding defects. The first one being a silicone contamination, which is deposited between the metal sheets, and the other one being a misalignment of the weld seams. Both types of defects clearly could be detected with the envelope method. Deposited silicone causes positive excursions of the energy curves while a weld seam misalignment yields negative excursions.

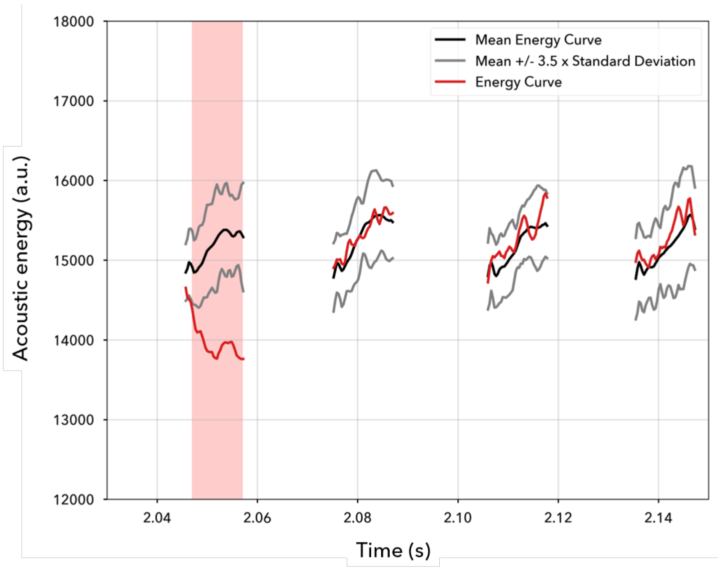

Fig. 4. Diagram of an envelope analysis on the misalignment of weld seams. The first one contains the defect (misalignment), while the other three are flawless.

4. Summary

We presented the results of a process monitoring method, which analyzes the airborne ultrasound emissions of laser welding processes using XARION's optical microphone. The possibilities of this method are demonstrated on the basis of three industrial applications.

Weld seams on direct copper bonded (DCB) substrates could successfully be evaluated by observing spectrograms which reveal the welding defects as excessive amplitudes with a frequency range beyond 150 kHz. Quantitatively it is possible to distinctly differentiate faulty from flawless weld seams by deriving the standard deviation of their respective energy curves.

The occurrence of a crack due to a thermo-shock in a DCB substrate is clearly visible in the spectrogram as it exhibits an exceptionally high acoustic energy peak over a very broad frequency band. The existence of the crack could be validated by images of an ultrasound microscope.

For the other industrial use case an elaborated algorithm was developed which compares the energy curve of a laser welding process to the energy curves of stable reference processes. This analysis method was tested on two different welding defect scenarios which are relevant to its particular industry, however the methodology generally can be adapted to other laser welding applications as well. Both defect types could be detected at every single of the affected weld seams with a graphical and with a quantitative version of the evaluation method.

By using the numerical analysis method an even further industrialized acoustic monitoring system can be developed providing a fully integrated real-time evaluation of every single weld seam. Furthermore, by summarizing the envelope puncturings into a single score for the entire workpiece and implementing a thresholding system in order to categorize the process quality assessment, a final overall monitoring result can be fed back to the laser machine for further processing.

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