September 2021 www.techbriefs.com Vol. 45 No. 9

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application. For a more detailed analysis tailored for your application, contact your optical component supplier. They should have historical data that will help better determine the effects of coating stress for your specific optics.

This article was written by Cory Boone, Lead Technical Marketing Engineer, Edmund Optics (Barrington, NJ). For more information, contact Mr. Boone at cboone@edmundoptics.com, or visit ***http://info.hotims.com/79417-222***.

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Monitoring Additive Manufacturing with an Optical Microphone

Additive manufacturing (AM) technologies have seen remarkable adoption in the industry over recent years. As digitalization and on-demand manufacturing shift the face of production sites to fully automated operating lines, reliable process monitoring methods are becoming increasingly important.

In laser-based processing of metals it is a well-known fact that optical and acoustic emission during the process can be analyzed in real-time and correlated to the final part quality.[1][2][3] This approach delivers significant value, as the occurrence of pores, cracks or other inhomogeneities created during the production process greatly influence the mechanical properties and increase the risk of defective components. Immediate reaction to warning process signals can thus reduce scrap material and save time.

Nowadays, optical systems such as pyrometers, high-speed cameras, IR-cameras and photodiodes are widely used to monitor laser-based AM processes in academic as well as industrial contexts.[4] Even though they yield important insight into the laser-metal interaction zone, they are blind to relevant aspects happening after the laser has switched off, e.g. cracking due to thermal stress.

Structure-borne acoustic sensor systems have recently become commercially available, for instance within Powder Bed Fusion (PBF) processes.[5] However, structure-borne sound detectors are challenged when it comes to processes like laser metal deposition (LMD) or wire arc additive manufacturing (WAAM) in which the structure-bound signal path changes or can even get interrupted throughout the build time. In such cases, a fixed-distance air-coupled acoustic sensor provides a capable solution.

A New Ultrasound Inspection Technique

In contrast to conventional membrane or piezo-based acoustic sensors,

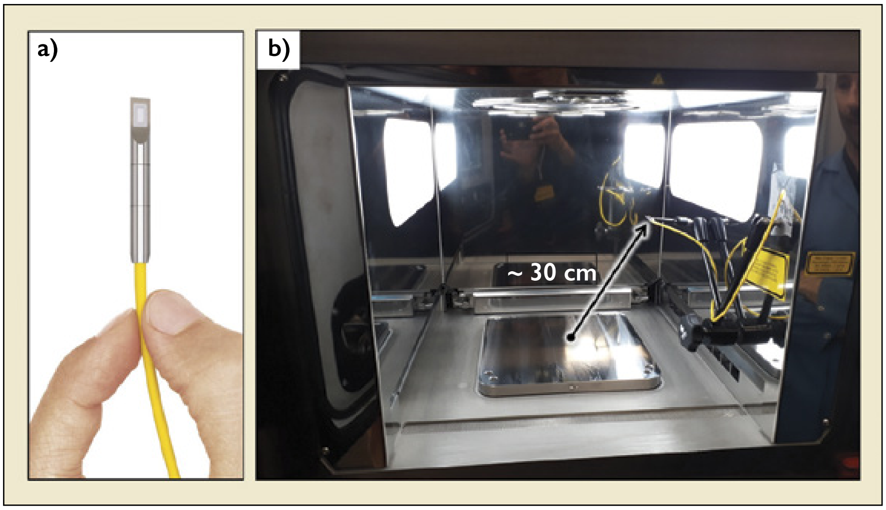

Figure 1. The fiber-coupled ultrasound sensor (a) within the PBF build chamber (b) at 30 cm measurement distance from the center of the build plate.

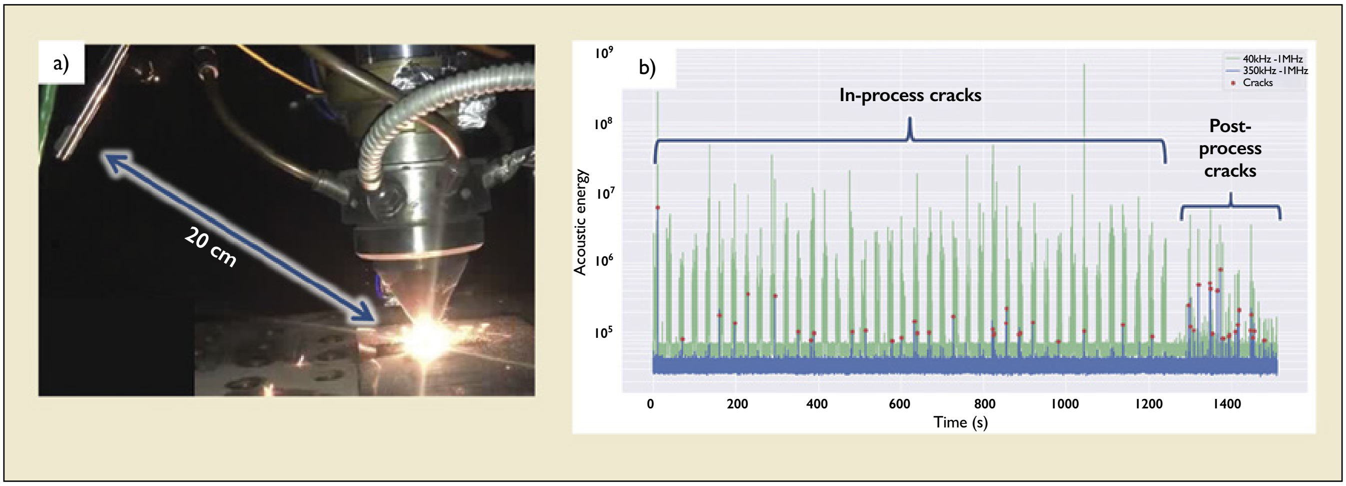

Figure 2. Typical measuring distance in an LMD process (2a). Ultrasound signals in the range of 350 kHz-1 MHz associated to cracks during and after a 20 min building process (2b).

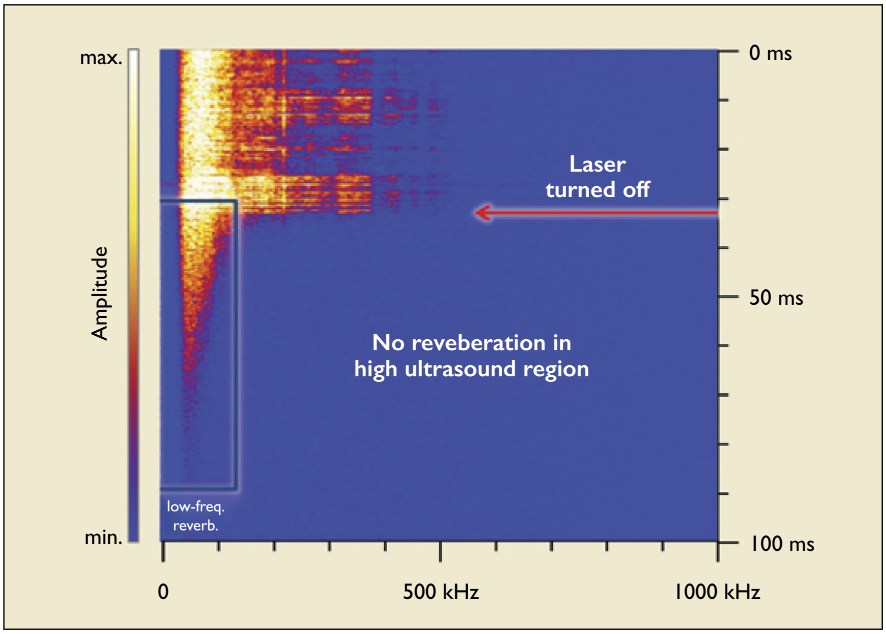

Figure 3. Typical acoustic 3D-spectrogram of PBF process (end sequence) captured by the Optical Microphone. Lack of reverberation in the high ultrasound regime enables superior resolution of process events.

XARION Laser Acoustics' broadband optical microphone works by means of interferometry. Its akinetic detection principle relies on sound waves causing a change in the refractive index of air within the 2 mm interferometer cavity sitting at the top of the sensor head shown in Figure 1a. This causes small shifts in the wavelength of the laser, contained and reflected back and forth within the cavity. The slight deviation of wavelength causes a variation of interference and, thus, of light intensity coming back from the cavity. The variation of intensity is then measured by an external photodiode.

This acoustic transducing method – working completely without moveable elements – provides the broadest frequency range available on the microphone market, exceeding the state of the art by a factor of 10. Since background noises, e.g. from nearby machinery, are typically limited to lower frequencies (<100 kHz), the optical microphone's range from 10 Hz up to 1 MHz enables clear spectral separation between valuable process signal and unwanted noise.

The upper bound of this frequency response is in part predetermined by the medium itself as the absorption of air dampens the propagation of the sound very strongly. For instance, the attenuation of an acoustic 2-MHz signal in air is in the order of 640 dB/m.[6]

In the following cases, several applications are discussed. In all setups, the sensor's analog electrical output is fed into a high-speed data acquisition and analysis system, which performs real-time FFT calculation and spectral display of the airborne process emission.

Laser Metal Deposition (LMD)

A common problem in LMD processes is the formation of cracks due to thermal stress. Those cracks can occur within the processing time but also several minutes afterwards. The robot-based LMD process, wire- or powder-fed, allows for maintaining of constant measurement distance. The advantage of an air-coupled acoustic system mounted to the robot head is the possibility of analyzing signals from the laser-material interaction as well as material behavior after lasing. An example of a measurement setup with a corresponding acoustic signature is shown in Figure 2.

As crack signals tend to be broadband in frequency, a high pass filter can be applied to safely detect crack occurrence in- and post-process without disturbance from production noise. In this setup, a filter of 350 kHz to 1 MHz was applied, which showed the strongest correlation to crack counts from non-destructive testing methods of X-ray imaging and

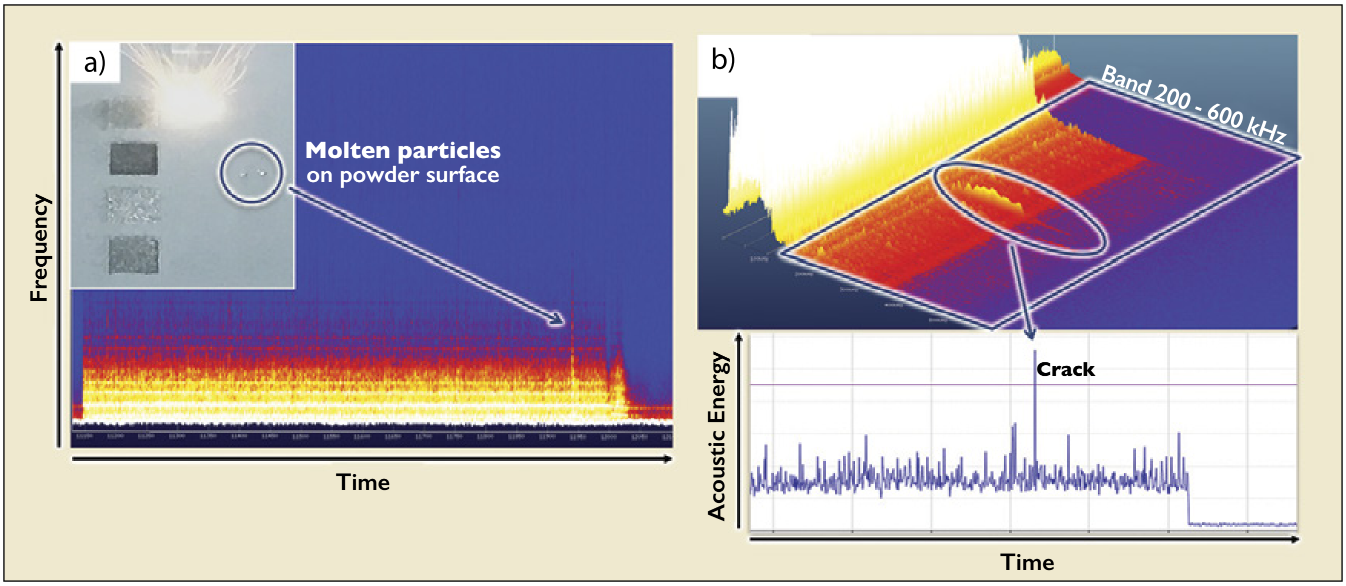

Figure 4. Two examples of short-term, broadband acoustic anomalies related to a) molten debris on the powder bed and b) cracking during the PBF process.

eddy current testing, as further described in reference [7].

Powder Bed Fusion (PBF)

To pick up the ultrasound emission during a PBF process, the optical microphone was positioned inside the build chamber, approximately 30 cm from the build plate, as shown in Figure 1b. A typical acoustic process signature is depicted in Figure 3, which also demonstrates the advantage of high frequency ultrasound analysis, namely the absence of reverberation, which in the lower frequency regime can ‘smear’ the signal and, subsequently, the superior temporal resolution of process events.

In contrast to the LMD setup, PBF employs mirror galvanometers to direct the process laser across the powder bed. This procedure causes distance- and frequency-dependent attenuation of the airborne signal, which follows a known relationship and thus can be taken into account if the laser coordinates are simultaneously tracked. In many cases it is also not necessary to maintain a constant signal ground level, e.g. for detection of short-term spectral anomalies. Two examples of these are presented in Figure 4: Figure 4a shows a broadband peak in the spectrogram originating from a laser pass over a molten particle on the powder and Figure 4b shows a crack signal in the 3D-spectrogram view (upper) and the respective 2D-energy curve (lower) integrated over a frequency band of 200-600 kHz.

Wire Arc Additive Manufacturing (WAAM)

A similar setup as in LMD can be applied for WAAM processes (Figure 5). The signature of the acoustic signal differs strongly, even though it is also broadband up to 600 kHz. Main phenomena are the droplet formation cycle (distinct blocks appearing roughly every 10 ms), a tonal signal related to the arc modulation rate (here: 80 kHz) and broadband process emission, related to metal evaporation.

Two of the most critical parameters for the process are the stability of the arc and the formation cycle. To monitor the former, a narrow bandpass filter may be applied to the modulation frequency and its higher harmonics, and for the latter, an FFT analysis may be performed on the high-pass filtered time signal, in order to calculate the comparatively slow droplet rate free from background noise.

Conclusion

Through the availability of a membrane-free, broadband microphone for highest ultrasound frequencies, previously inaccessible information can now be harnessed and utilized to monitor acoustic process phenomena in real-time. Future developments involve the application of triangulation so that sound origins can be localized to further facilitate operators, process engineers and machine manufacturers to spot potential defects. Moreover, the inclusion of onboard AI methods that lend themselves to acoustic data streams and facilitate the advancement of the technology towards more complex, industrial monitoring applications, is targeted.

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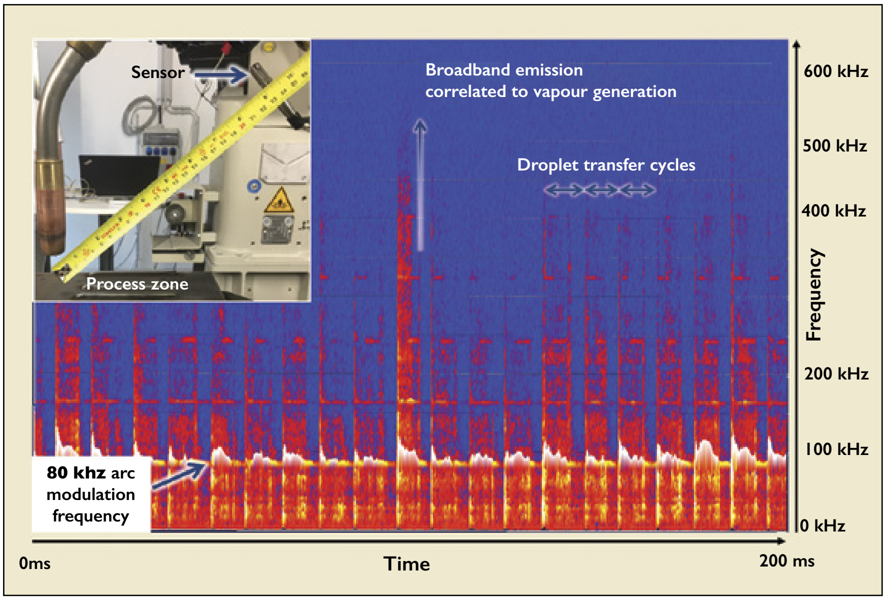

Figure 5. Positioning of the Optical Microphone in the Wire Arc AM process (inlay) and the corresponding acoustic signature of a 200 ms process section.

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Acknowledgment

The authors gratefully acknowledge the support from AIMEN Technology Centre (Spain) and Damon Northeast (Renishaw plc).

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