Acoustic Process Control for Laser Material Processing

Optical microphone as a novel "ear" for industrial manufacturing

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Listening to an industrial process can reveal relevant information. As a complementary approach to optical process surveillance, monitoring the acoustic emissions is a promising alternative. Yet, acoustic detectors have not been extensively established in process control, one reason being their limited frequency bandwidth. Overcoming the disadvantages of existing microphones, a novel laser-based acoustic sensor opens new possibilities in industrial acoustic process monitoring.

Fig. 1 Sensor head connected to an optical fiber: centerpiece of the optical microphone is the miniature Fabry-Pérot etalon shown on the right side of the picture. Sound enters the etalon through the air gap between the mirror surfaces. Small size and robust dimensioning of the glass elements prevent the influence of mechanical vibrations to be below the sensor self-noise throughout the full measurement range.

In order to achieve a cost-effective high-quality production process, automation with minimal down time is required. Manufacturing close to process tolerances can drastically increase yield, but usually requires a close watch on the production quality. This is most elegantly done via in-line, in-process monitoring because potential errors are immediately recognized and corresponding measures can be taken through either a human operator or, in the case of a closed loop, by the machine itself. Process monitoring is of particular importance when a small change in process parameters can signify a considerable loss of quality. This holds for many production processes but is especially true for laser material processing, such as welding, dicing, or additive manufacturing.

Laser process monitoring can be achieved using photodiodes, cameras, spectrometers, pyrometers or charge sensors [1, 2]. Radiation-emitting areas are the plasma plume, the melting zone and the reflected laser beam. All of them deliver diverse process information, distinguishable by their different wavelength. Seam tracking, for example, is based on the projection of structured light and the detection of the reflected fraction. Another example for the use of an auxiliary light source is optical coherence tomography (OCT), an interferometric technique that is using a probe beam to scan the surface, which can generate in-line information about the seam quality or the keyhole depth [3]. Recently, optical coherence tomography has been successfully used to determine the penetration depth correlating it with the measured keyhole depth [4]. Combining different monitoring methods will generate a much more preferable and comprehensive picture of the process.

An alternative method to characterize and monitor an industrial process is to measure its sound and ultrasound emissions. Acoustic process control systems employ contacting and non-contacting acoustical sensors. Contacting systems measure structure-borne process emissions. They work well for many applications but always require a physical contact with the workpiece. In an automated production environment, this is often not possible.

In contrast, state-of-the-art non-contacting acoustic systems make use of airborne sound and ultrasound process emissions. When employing conventional capacitive microphones, these systems struggle with interfer-

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XARION Laser Acoustics GmbH is a young high-tech company, which develops and markets a novel laser-acoustic sensor. The advantages of the transducer refraining from any mechanically moving parts include a linear frequency response and a broad ultrasound frequency detection bandwidth in both air (1 MHz) and liquids (25 MHz). The company is based in Vienna and employs 20 people. The key markets comprise acoustic metrology, industrial process control, non-destructive material testing and medical imaging.

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ence from surrounding industrial noise due to the narrow measuring range of microphones, typically limited to a 100 kHz bandwidth. Experiments have shown that high-frequency airborne ultrasound may be used to monitor keyhole welding [2]. In this approach, a piezoelectric transducer measures the ultrasound emissions during the process. Results show that the emitted ultrasound changes at the transition point from thermal conduction welding to keyhole welding [2]. However, in order to achieve the necessary sensitivity with air-coupled piezoelectric receivers, they need to be designed in a highly resonant way, leading to a so-called coda (prolongation of signal due to ringing, a mechanical resonance) and significant reduction of the frequency bandwidth. A substantial part of the process information is lost due to the limited bandwidth. Furthermore, capacitive and piezoelectric transducers are susceptible to electromagnetic interference. These limitations may serve as a possible explanation as to why acoustic process monitoring is not yet in wide use in industrial production.

The solution would be an air-coupled (and non-contact) acoustic transducer, which is not susceptible to loud background noise. The attributes of this acoustic process monitoring technology should be:

- In-line process monitoring without disturbing or influencing the process
- Easy implementation on existing plants
- Statistical robustness of the measurements. No influence by noise from background or neighboring machines, or from electromagnetic interference
- Resistance to dust, dirt and fluids
- Low cross-sensitivity; parameter-to-be-monitored should be uniquely identifiable.
- A lean amount of data in order to reduce the complexity of the control software.

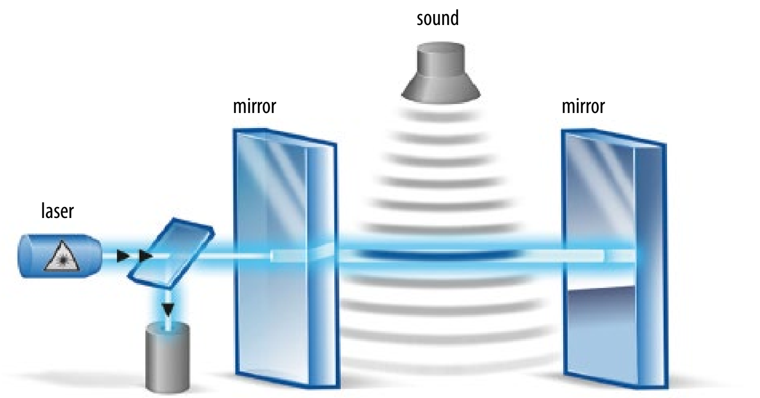

Fig. 2 Principle of operation of the optical microphone. The ultrasonic signal is detected optically by the change of the refractive index within a Fabry-Pérot etalon.

Optical microphone senses ultrasound process emission

The principle of the optical microphone is to directly assess changes in the density of the optical medium. The operational principle is illustrated in Fig 2.

The core of the microphone capsule consists of a Fabry-Pérot cavity, an optical interferometer made of two semi-transmissive mirrors, arranged at a distance matching a multiple of the laser's half wavelength. This leads to constructive interference of the transmitted laser beam. Small changes in the density of the optical medium cause changes in the optical index of refraction and, therefore, in the laser's propagation speed and in its wavelength. Thus, the (fixed) distance between the two mirrors will not satisfy the condition for constructive interference anymore, resulting in a change in the transmitted – and the reflected – laser intensity. This is measured with a photodiode. The use of this multipass interferometer enables both the high sensitivity and the small size of the optical microphone.

If used in acoustic process monitoring, the system consists of two main components:

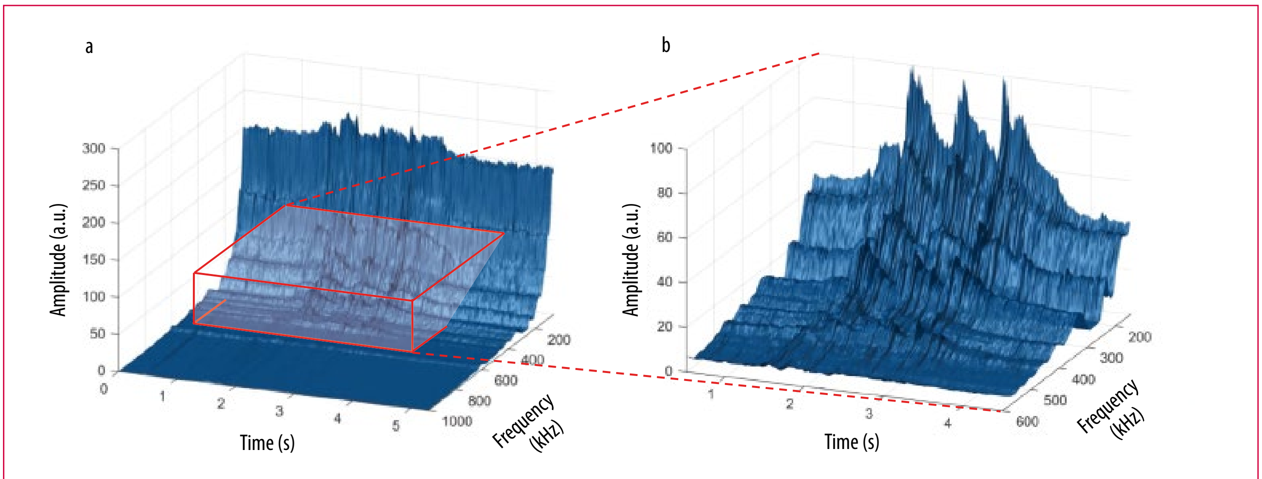

Fig. 3 Acoustic emissions from laser welding. Spectrogram of acoustic emissions during a laser welding process. Crossjet background noise covers the wanted signal for frequencies up to 150 kHz (a). Zooming into the frequency range from 150 kHz to 550 kHz reveals the signature of the laser welding process and shows a sawtooth pattern, characteristic for the monitored laser welding depth (b).

- the acoustic detection system, including the all-optical sensor head and the driver unit comprising laser and detector
- the analog-to-digital converter supporting a high-speed acquisition, the software and a data management system, enabling in-line process control with the measured data

When listening to industrial process emissions, the detection of high ultrasound beyond 100 kHz becomes crucial. Given the fact that the human ear only detects frequencies up to approximately 17 kHz, and many technical ultrasound devices, such as automotive parking aids, operate at a few tens of kHz, airborne acoustic frequencies above 100 kHz are a somewhat exotic field for today's state of the art. Nevertheless, there are four important reasons why the ultra-high frequency range is of relevance to acoustic process monitoring.

First, because significant process information is hidden in the very high ultrasound frequencies.

Second, disturbing background noise usually is of particularly high intensity in the audible acoustic frequency range or the near ultrasound range. In contrast, the space beyond 100 kHz is usually comparatively quiet.

Third, the absorption for high ultrasound frequency in air is substantial and amounts to approx. 15 dB per 10 cm in air (at 1 MHz). This means that simple spatial isolation of machinery can be used rather than acoustic insulation. This allows, for example, a machine inside a hall containing many machines without the need for acoustic insulation from the other machines.

Finally, reverberation time is a function of frequency. Up to 100 kHz, it is virtually impossible to realize reverberation times shorter than 10 ms except in perfect free-field conditions, which is never the case in industrial environments with many acoustically reflective surfaces. As a matter of fact, typical reverberation times for audio frequencies may amount to several hundreds of milliseconds. For the accurate temporal resolution of an industrial process usually consisting of a rapid sequence of acoustic events, it is imperative to monitor ultra-high acoustic frequencies.

The physical principle of the optical microphone leads to outstanding properties compared to a capacitive microphone or a piezoelectric transducer. Without any moving or deformable mechanical parts (such as membranes or deformable crystals) there is no limitation induced by the resonance properties of a mass-spring system. This results in a wide acoustic detection bandwidth of the optical microphone spanning from 5 Hz to 1 MHz in air, and up to 25 MHz in liquids. In addition, because the sensor head is all-optical, strong electromagnetic radiation cannot influence the detection signal.

Emitted ultrasound reveals information about laser weld penetration depth

The optical microphone has been successfully tested in a number of process control settings, such as dynamic fatigue testing, drilling and machining, product inspection, but specifically for various laser manufacturing processes such as dicing, additive manufacturing, and welding. All of these processes were shown to feature broadband ultrasound emissions. The conducted tests show promising results with regards to the extraction of process information from these high-frequency emissions.

Fig. 3 shows a typical dataset from a metal sheet laser welding process. The optical microphone records the acoustic signal, and a real-time data acquisition system processes the data stream and performs a short-time Fourier transform (STFT) of recorded signal segments to construct a spectrogram. It reveals a common situation during laser welding: in the audio-acoustic range and for ultrasound frequencies below 200 kHz, the most prominent feature is the acoustic emission from the crossjet, a strong air blast that protects the weld-

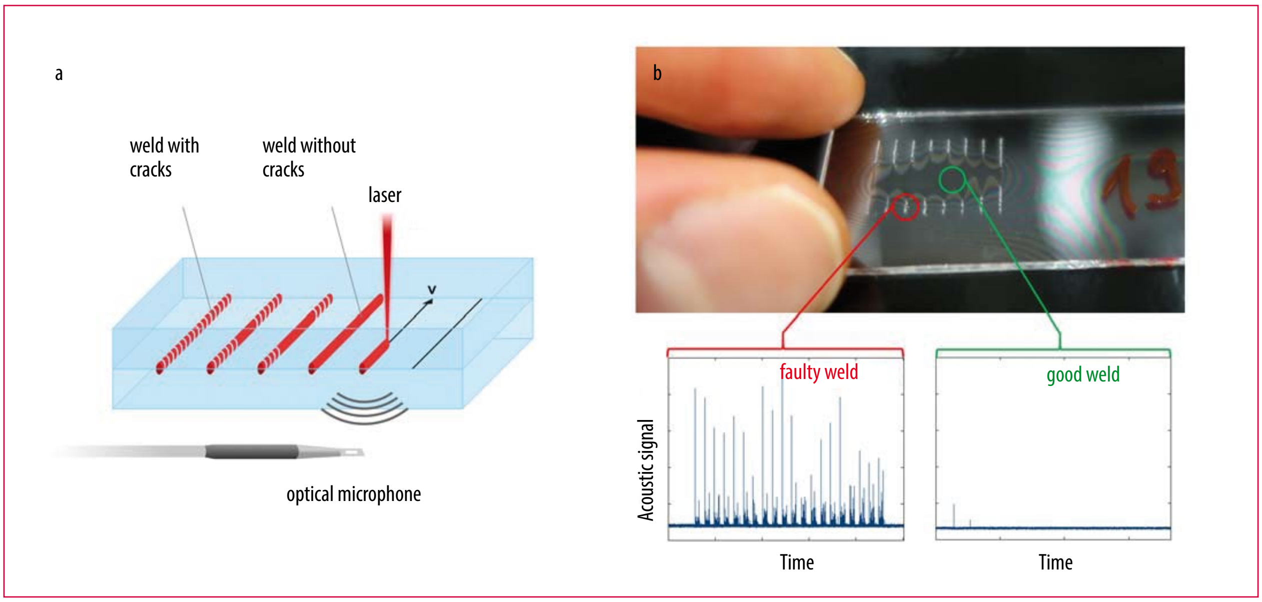

Fig. 4 Crack detection during glass welding. a) Measurement setup. An ultrashort-pulse laser scans over the workpiece to establish a weld. Varying process parameters (pulse energy, focus position, etc.) may lead to cracks in the vicinity of the weld. b) Upper panel: image of workpiece containing good and faulty welds. Lower left panel: in-process acoustic emission from cracks during welding. Lower right panel: acoustic emissions from good weld, scaled to the same amplitude range.

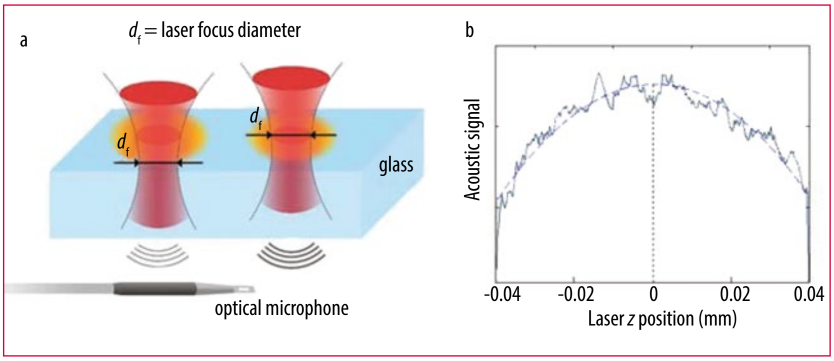

Fig. 5 Monitoring of laser focus position during glass welding. a) Principle. Varying axial displacement of the processing laser during lateral scanning leads to a change of the spot size – and therefore the intensity – at the welding level. b) Measured acoustic signal. The amplitude of the emitted acoustic signal is in excellent approximation a quadratic function of the intensity at the welding level, where the laser light is absorbed. Fitting the signal integrated in the high-frequency region, where acoustic background is mostly absent, allows the determination of the focus position with sub-micron accuracy.

ing optics. While the laser welding process does contribute a signal in this frequency range, its spectrum extends up to 800 kHz. The optical microphone can target these high-frequency emissions for process monitoring (Fig. 3b). This is in contrast to acoustic monitoring of the lower-frequency regime, where the superposition of the signal with crossjet noise makes it hard to extract the details of the process information.

Fig. 3b also demonstrates the correlation between process parameters and the acoustic emission. During the depicted process, the welding penetration depth has been varied. The signal amplitude recorded with the optical microphone is proportional to the penetration depth, featuring a saw-tooth-shaped time dependence, which reproduces the chosen modulation of the welding laser power. In an in-line setting, this data can be used to implement feedback and regulate process parameters in real time.

High-frequency ultrasound for precision monitoring of glass welding

One of the more recent applications of laser welding is its use for glass joining. Glass is a challenging material due to its low thermal conductivity. Uneven heating during laser processing may easily cause stress-induced cracks. Tight control of process parameters is therefore crucial.

In an experimental setup, the optical microphone has been successfully applied to detection of such stress-induced cracks caused by faulty process parameters. A schematic of the measurement setup is shown in Fig. 4a. During the welding process, the laser was scanned over the work piece to generate several straight, parallel welds evenly distributed over the sample surface. Varying process parameters along the path of the detection laser caused areas with faulty welds exhibiting cracks.

Listening with the optical microphone reveals that these cracks are accompanied by short bursts of ultrasound emission (Fig. 4b). Correlating measurement time with the position of the laser spot enables an in-line detection and localization of these cracks. It was found that some cracks were formed several milliseconds after the welding process, which might be due to the cooling of the specimen after the laser beam has passed over it. In addition, the emitted frequency components and the signal duration were observed to be correlated with the crack size. It was found that these differences mainly manifest for ultrasound frequenices beyond 100 kHz.

Sub-micron monitoring of processing laser focal position

Even in well-aligned beam shaping systems for processing lasers, thermal effects and mechanical hysteresis may cause drifts in the focal plane of the laser spot. During processing, such drifts cause a variation in the size of the laser spot at the position of the work piece and therefore changes in the deposited intensity. This effect is especially severe for high-precision processes utilizing small focal spot diameters, such as laser dicing or glass welding processes, where slight changes of energy deposition may cause defects as discussed above. Specifically, deviations of 10 µm can lead to cracks. Hence, checking and readjusting focus at regular intervals is required. Often, this is still accomplished by varying the focus position on a test piece and visual inspection.

Listening to acoustic emissions provides an alternative: using the circumstance that the amplitude of the acoustic signal emitted by the process is proportional to the intensity deposited at the sample surface allows to keep track of the laser's focal plane. With conventional microphones, however, this is extremely challenging: for high-precision laser processing, usually ultrashort-pulse lasers with repetition rates of up to 500 kHz are employed. These lasers cause short, broadband acoustic signals, with most of the energy distributed over frequencies beyond a conventional microphone's detection range.

The optical microphone, on the other hand, can use these emissions to determine focus with surprisingly high accuracy. Fig. 5b shows a measurement in a glass welding setup, where the focal spot has been shifted during processing, and acoustic emissions have been recorded. Maximum signal corresponds to correct focusing. Using the known velocity with which the focus is displaced, one can correlate the relative focal shift with measurement time, resulting in determination of the correct focal position. A sub-µm precision has been experimentally demonstrated.

Since this process can be automated, the optical microphone can help in reducing machine downtimes, and expensive rejects can be minimized.

A novel "ear" for process monitoring

These examples provide a small subset of the optical microphone's applications for industrial process control. They should demonstrate that acoustic process monitoring using high-frequency airborne ultrasound is a potent technique, complementary to established available methods and well suited for evaluating and controlling laser material processing.

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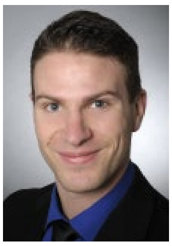
Authors

Balthasar Fischer was born in Switzerland, where he studied physics. He moved to Vienna in 2001 to complete a Tonmeister degree at the University of Music. He received his PhD in photonics from Vienna University of Technology, before joining Philips Sound Solutions as R&D member. In 2012, Balthasar founded Xarion Laser Acoustics, based on his invention, the membrane-free optical microphone. In the course of his career he has won several awards, including the Fehrer Prize and the Leibinger Innovation Award.

Nils Panzer studied mechanical engineering and management at TU München, finishing the Diploma in the field of production technology. Since 2015, he is studying medicine at Medical University of Vienna. He supports Xarion on a project-contracted basis.

Wolfgang Rohringer studied physics at TU Wien. After receiving his PhD in 2014 from the Institute of Atomic and Subatomic Physics, conducting research on probing ultracold quantum gases with integrated fiber optics, he joined a cooperation project between Xarion Laser Acoustics and the Medical University of Vienna as a PostDoc. The project successfully demonstrated photoacoustic microscopy with the optical microphone. Since 2016, he works as a research and development engineer at Xarion.



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