Non-Contact Ultrasound Diagnostics for the Ceramic Industry

A novel ultrasound sensor can help enable process and quality control across the ceramic industry.

BY FABIAN LÜCKING, PH.D., SENIOR APPLICATION ENGINEER, XARION LASER ACOUSTICS GMBH

From the aerospace to semiconductor industries, technical ceramics are gaining traction in many areas of modern manufacturing. Acoustic emission process control holds great potential for the ceramic industry, but conventional sensors face serious challenges in the field. A non-contact ultrasound sensor was recently introduced that addresses these challenges.

Based on a purely optical detection scheme, the sensor combines true impulse response and high sensitivity. This optical microphone, free of moving parts, is suited for on-line quality control of high-value ceramic processes, as well as precision sound field measurements.

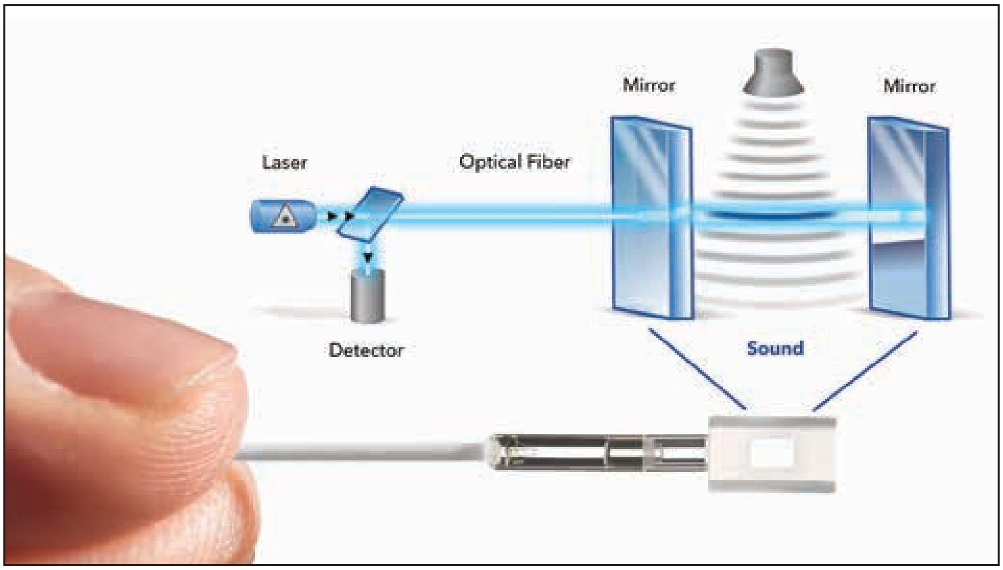

Figure 1 Sensing principle of the optical microphone.

Understanding Acoustic Emission

Process control has long relied on acoustic emission. From worn bearings to cracking parts, structure-borne sound is harnessed across the manufacturing industry to detect equipment faults and ensure product quality. Acoustic signatures span a wide range of frequencies, from the human-audible range up to several megahertz. Like a fingerprint, acoustic signatures carry unique information about their origin.[1] While the whine of a faulty bearing may be heard by an experienced machine operator, the bandwidth of sound emitted by a crack in a brittle material such as glass or ceramic easily exceeds the upper boundary of human perception by a factor of 10 or 20.

Such high-bandwidth vibrations in solids are routinely detected using piezoelectric transducers. These sensors are firmly attached to the machinery or workpiece to allow the detection of ultrasound frequencies up to several megahertz. As structure-borne sound propagates with low attenuation, these sensors do not have to be positioned close to the point of interest.

More often than not, this is a disadvantage. As acoustic emission from all over the workpiece and the machine (and potentially those located next to it) can reach the detector, small signals are easily overlooked. Shielding unwanted acoustic signals is difficult, and arduous computational post-processing is often unavoidable. Things become even more complicated when the workpiece cannot be contacted directly, whether it is too small, too hot, too brittle, moving fast, or part of a continuous feed. In these cases, a non-contact means of acoustic sensing is desired.

Until recently, this was not achievable. Piezoelectric transducers for airborne ultrasound suffer from strongly reduced sensitivity in comparison to their structure-borne counterparts, given the acoustic impedance mismatch between air and the piezo crystal. In addition, due to their highly resonant design, the frequency bandwidth is typically limited to ±10% of the center frequency.

Conventional microphones, in contrast, provide ample sensitivity at low frequencies, but the mass of the membrane limits their use to frequencies below 100 kHz. Air provides almost no attenuation to sound in this range, as anyone working in a busy production environment is well aware of. Therefore, the acoustic fingerprint of a crack is drowned in noise. Manufacturers of high-value technical ceramics have been consequently forced to look for alternative means of quality assurance and testing methods. This often means that parts need to be tested off the production line, incurring extra cost.

Sensing Sound through Light

The new ultrasound sensor circumvents these restrictions, delivering high sensitivity over the entire spectrum of airborne sound. Instead of relying on the sound pressure to physically move a membrane or compress a crystal, it is based on a miniature laser interferometer.[2]

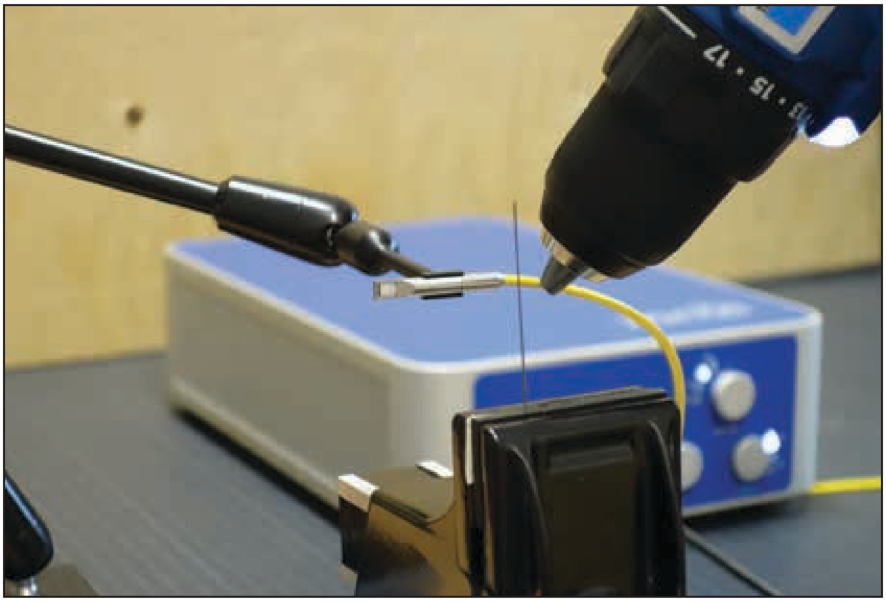

Figure 2 The experimental arrangement.

As shown in Figure 1, a laser is wavelength-locked to the narrow resonance of a so-called Fabry-Pérot etalon, essentially two parallel, partially reflecting mirrors placed a few millimeters apart. The transmission of light through this arrangement depends on the distance between the reflecting surfaces. Only when the optical path is matched precisely to the laser wavelength can the light pass the mirrors unhindered. Any deviation from this resonance condition results in back-reflection of the light toward the source. In this particular sensor, the mirror distance is fixed and the laser actively stabilized, but the length of the air path “seen” by the light depends on the air pressure. Sound is a pressure wave, which causes a modulation of the back-reflected light that is proportional to the instantaneous pressure.

The patented optical microphone is sensitive to frequencies from 10 Hz up to 1 MHz, which means that the sensor delivers true impulse response and does not suffer from ringing. This is particularly important when listening for short events such as cracks in ceramic workpieces.

The sensing element is mounted in a cylindrical capsule of 5 mm diameter and about 40 mm length. The capsule is connected to the signal conditioning unit by an optical fiber, which makes it immune to electromagnetic interference even for large distances to the control unit. The optical microphone can thus be placed close to the device or process under scrutiny, even in tight environments.

Because the attenuation of sound in air strongly increases with frequency,[3] the optical microphone delivers information on the approximate distance of the events it registers. At the same time, noise from adjacent machinery is strongly suppressed, ensuring dependable detection in the region of interest. Thanks to its miniature sensitive volume of less than 1 mm^3, the sensor lends itself to true spatial sound-field characterization.

Tiny Cracks Make Waves

Technical ceramics exhibit exceptional mechanical properties, including heat resistance, hardness and strength-to-weight ratio. While these properties are coveted for myriad applications, they also pose a challenge to the manufacturing process. The brittleness

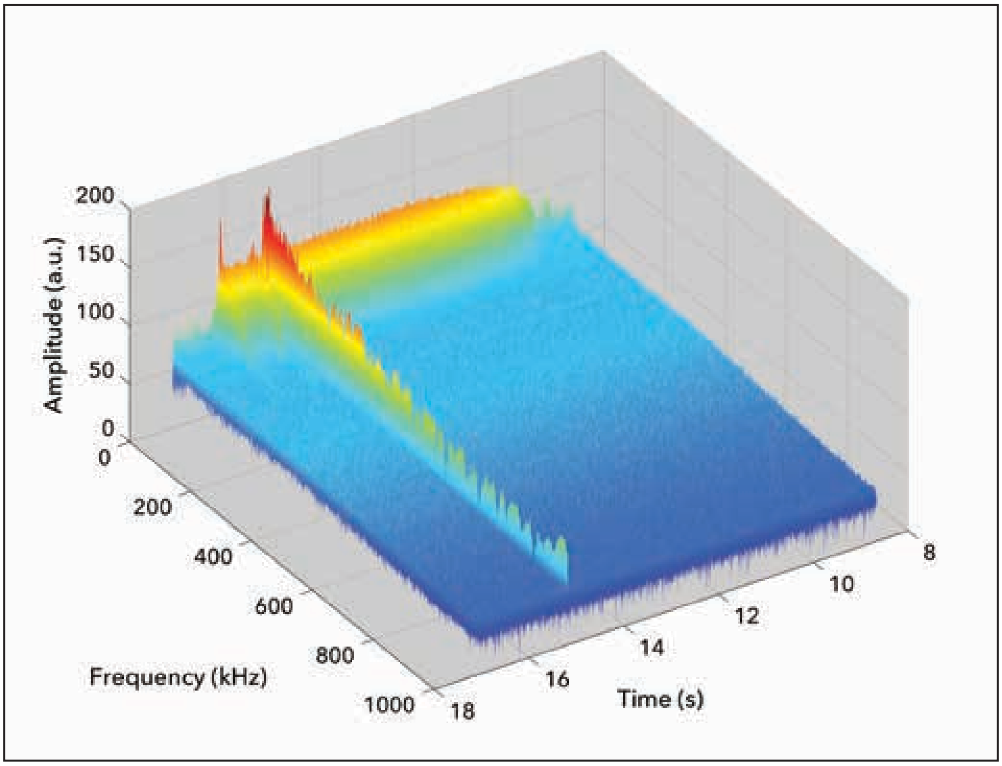

Figure 3 3D spectrogram of the sound recorded emitted during the experiment. While the drill noise falls off rapidly above 100 kHz, the fracture of the pencil lead near the 15 sec mark emits an acoustic shock front that spans the entire measurement range.

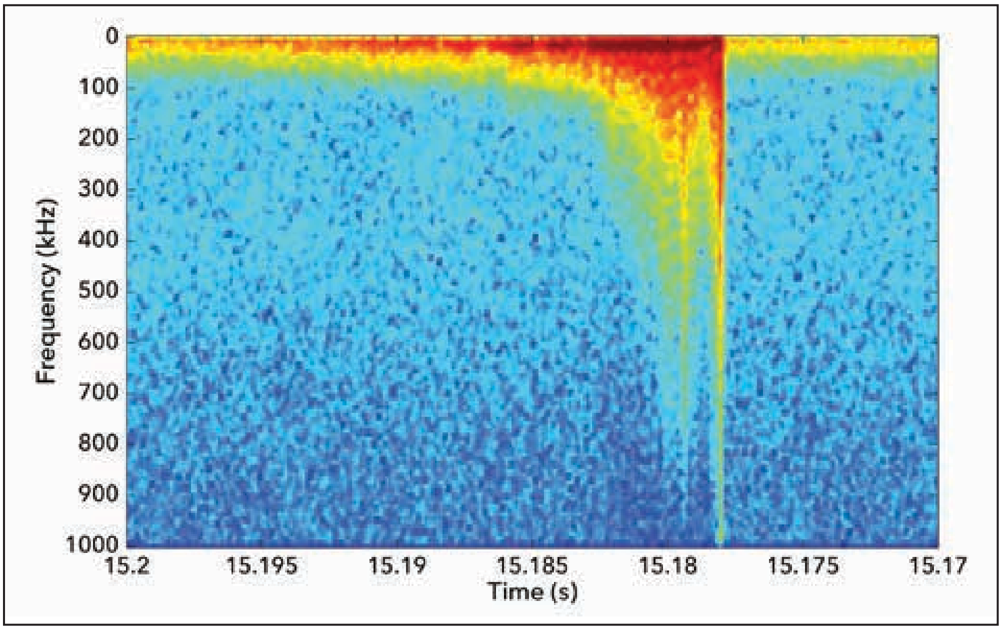

Figure 4 Detailed view of the fracture ultrasound emission taken from the same dataset.

of these materials makes them prone to catastrophic failure during processing. Neuralgic points for a workpiece to fail include temperature gradients, machining, or their integration into a non-ceramic part of an assembly.

An on-line system to detect that a problem has occurred is highly desirable, as it saves time during testing and may even provide a means of process control. Imaging techniques (including thermal methods) may be employed, but they quickly reach their limits for parts with complex geometry or small parts in high volumes. The advent of additive manufacturing techniques to the field of ceramics is bound to aggravate these problems.[4]

The situation is similar for compound parts incorporating ceramic elements. A metal coating, for example, may easily mask structural defects to optical detection, calling for a 100% inspection using time-consuming techniques such as X-ray computer tomography. Non-contact ultrasound surveillance provides an attractive alternative. Instead of examining the part off-line, it identifies defects by their acoustic fingerprint in the line, right when they occur.

A simple demonstration of the capabilities of the optical microphone is shown in Figure 2 (p. 23). A pencil lead is fixed to a holder, while the optical microphone is placed 10 cm away. An electronic power drill is operated right next to the holder to simulate significant acoustic and electromagnetic background noise. The optical microphone output is digitized and displayed in the form of a spectrogram (see Figure 3). Modern computers are capable of performing these steps in real time.

When mechanical force is applied, the pencil lead breaks, emitting a tiny “snap” noise. While barely audible to a human in quiet conditions, the pencil lead cracking is entirely impossible

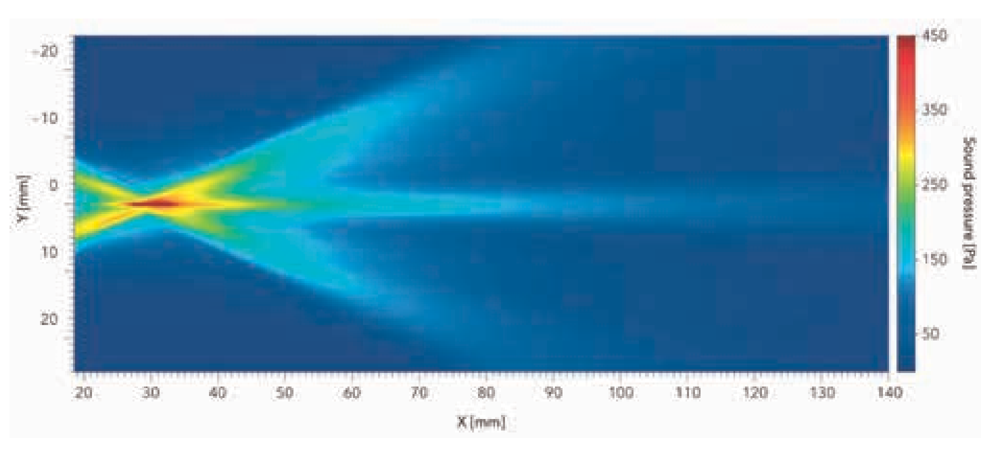

Figure 5 Two-dimensional cross-section of the sound field of a focused ultrasound transducer.

to perceive with the drill running nearby. However, the optical microphone allows us to reach beyond the human perception, and things look different in the ultrasound.

The noise of the drill (generated from its power supply, the gearbox and bearings) is loud, but does not extend further than 100 kHz. The apparently tiny pencil break, in contrast, is revealed to be a continuum of frequencies, exceeding 1 MHz. In time domain, this corresponds to a rise time of the sound pressure in the sub-microsecond regime.

Figure 4 shows a detailed view of the fracture event. Note that the reverberation time declines with rising frequency, which is due to the absorption of high-frequency ultrasound in air. This effect enables the resolution of closely spaced events such as the multi-peak structure seen here. The same structure becomes increasingly hard to detect at lower frequencies.

Although only a tiny fraction of the mechanical energy of the fracture is transformed into airborne sound, it is emitted in the form of a momentary shock-like wave that provides rich information about the material failure. This behavior is characteristic of high-modulus materials such as technical ceramics, glass or carbon fiber composites. In all such materials, similar signals are obtained upon fracture. They can be clearly distinguished from background noise, machinery or handling noise from workpiece carriers. As a result, structural failure of high-value components during machining or manufacturing is readily detectable by the optical microphone in a non-contact, on-line fashion.

Sound Made Visible

A prominent category of functional ceramics is piezoelectric materials, such as lead zirconate titanate (PZT). The majority of ultrasound devices are based on this class of materials; from distance sensors and medical ultrasound probes to level meters and microelectronic components, piezoelectric ultrasound transducers are ubiquitous. Although most of these devices are produced in huge quantities, some of their properties are surprisingly hard to measure. Particularly when looking at air-coupled transducers, even a precise measurement of the radiated frequency becomes non-trivial; there is simply no broad-band sensor for airborne ultrasound.

Choosing another narrow-band sensor as the receiver does not solve the problem, as its sensitivity over frequency is again unknown. Consequently, a multitude of measurements with different receivers is necessary to lower the uncertainty. In contrast, a measurement with the optical microphone precisely determines the radiated frequency at once. In addition, the sensor can be calibrated to provide absolute, instantaneous sound pressure readings.

The spatial characteristics of a piezoelectric ultrasound source are of particular interest in array-type and focused transducers. Measuring the sound field of such a source is hampered by the lack of receivers with small aperture and high sensitivity. In the case of the optical microphone, the spatial resolution is set by the laser beam width rather than geometrical factors. With its sensing volume of about 1 mm³ and its small dimensions, merely scanning the sensor across the volume of interest yields a true sound field measurement.

Figure 5 shows a planar cross-section of a focused transducer output, recorded with the optical microphone mounted in an automated 3D scanning device. The focus position and diameter can be determined precisely.

Harnessing Airborne Signals

The growing demand for novel materials and tightening quality requirements pose an industry-wide challenge. *In-situ*, in-process monitoring and quality control are becoming a necessity.

Acoustic methods, especially those focusing on the ultrasound range, offer opportunities for on-line detection of manufacturing defects. The circumstances of ceramic manufacturing, machining and assembly make solutions that rely on structure-borne sound complicated to implement. A novel optical microphone paves the way for non-contact, airborne signals to be harnessed instead.

For more information, contact the author at f.luecking@xarion.com or visit www.xarion.com.

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