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Applications of Laser Light Probes to Quantitative Sensing Stress Waves

Abstract
The recent development of laser light probes for stress wave measurements has aided our understanding of acoustic emission and ultrasonic signals by allowing quantitative measurements of stress waveforms. This paper reports on applications of the laser interferometer probe for surface detection of stress waves and the laser transmission probe for sensing of stress waves inside transparent materials. Laser light probes were used to characterize ultrasonic and acoustic emission transducers’ response in a realistic configuration, with transducers in actual contact with a solid. Laser light probes also were applied in directly detecting acoustic emission due to stress corrosion cracking in 7039 aluminum and crazing of Plexiglass. The results of the laser light probe measurements indicate that conventional piezoelectric transducers, although adequate for many ultrasonic pulse inspection tests, are severely limited as stress pulse sensors for acoustic emission measurements. The acoustic emission signals measured by the laser light probe showed a pulse-like waveform which has not been previously recorded by conventional piezoelectric acoustic emission sensors.

Keywords
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Disciplines
Materials Science and Engineering
APPLICATIONS OF LASER LIGHT PROBES TO
QUANTITATIVE SENSING OF STRESS WAVES

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ABSTRACT

The recent development of laser light probes for stress wave measurements has aided our understanding of acoustic emission and ultrasonic signals by allowing quantitative measurements of stress waveforms. This paper reports on applications of the laser interferometer probe for surface detection of stress waves and the laser transmission probe for sensing of stress waves inside transparent materials. Laser light probes were used to characterize ultrasonic and acoustic emission transducers' response in a realistic configuration, with transducers in actual contact with a solid. Laser light probes also were applied in directly detecting acoustic emission due to stress corrosion cracking in 7039 aluminum and crazing of Plexiglas. The results of the laser light probe measurements indicate that conventional piezoelectric transducers, although adequate for many ultrasonic pulse inspection tests, are severely limited as stress pulse sensors for acoustic emission measurements. The acoustic emission signals measured by the laser light probe showed a pulse-like waveform which has not been previously recorded by conventional piezoelectric acoustic emission sensors.

INTRODUCTION

In almost all industrial applications, conventional piezoelectric transducers are used to detect acoustic emission and ultrasonic transients in solid materials. As the demand for accuracy and reproducibility of nondestructive tests and inspection methods increases, the limitations of electromechanical devices such as piezoelectric transducers are becoming more noticeable and must be specified.

Industrial piezoelectric ultrasonic transducers (see Fig. 3) are complex structures of layered active and passive elements, packaged into a small unit which is coupled to the workpiece by a variety of impedance matching fluids. Because of the contact with the test piece, such devices inadvertently mechanically load the contact surface and thus change the test piece behavior. Also, the need for coupling agents between transducer and contact surface introduces the problem of reliable test repeatability. However, these problems are only secondary to the strong need for industry-wide calibration and standardized comparison of different ultrasonic and acoustic emission transducer units.

To be able to address some of the above-mentioned problems, an experimental system was developed that utilizes laser light probes to measure stress waves in solids. The combination of laser probes with digital signal capture and computer data processing enabled accurate evaluation and analysis of the piezoelectric transducers' response. Figure 1 is a schematic representation of a whole test system that allowed ultrasonic or acoustic emission signals to be measured simultaneously by laser probe and piezoelectric sensor.

Two types of laser light probes were used to measure a physically identifiable parameter associated with stress wave propagation. A laser transmission probe sensitive to material density changes was used to measure bulk ultrasonic waves inside transparent test specimens and a laser interferometer probe was used to measure the normal surface displacement produced by propagating ultrasonic waves. The performance of these laser light probes was described in other publications.1,2 However, it is important to note that a laser probe sensor does not alter the stress waves, produce no change in mechanical boundary conditions, and has no intrinsic frequency-response limitations. Thus, the simultaneous use of optical probes and conventional piezoelectric transducers enabled direct signal comparison and critical evaluation of the performance limitations exhibited by piezoelectric sensing devices.

ULTRASONIC TRANSDUCER CALIBRATION
AND CHARACTERIZATION

Ultrasonic transducers mounted on the face of a transparent cube test block (such as Plexiglas) were evaluated using a laser transmission probe. By scanning the YZ plane, this arrangement allowed the pointwise measurements of the stress pulse waveform, relative pulse intensity, and arrival time at all test block locations. These measurements were then used to indicate the transducers' beam profile (near field [NF] and far field [FF]) as well as any regions of anomalous nodal lines or high intensities. The three dark photographs in Fig. 2 are indicative of the signals measured at the three different test block locations. The top trace is the signal from the piezoelectric inspection transducer and the bottom trace is due to the signal sensed by the laser transmission probe. Note that the laser probe centered on the block shows the first-signal-arrival-time delay of 1/4 of the total time necessary for the pulse reflection to return to the transmitting transducer. Thus, the centered laser probe sees stress waves twice as often as the surface mounted transducer and
nicely illustrates a phase shift between a transmitted and a reflected ultrasonic stress wave packet. The off-centre signal sample by the laser transmission probe is used to demonstrate a spread of the stress wave packet. The signal observed by the laser probe became significant only after a time delay; a few reflections of the ultrasonic pulse allowed significant widening of the original stress wave packet.

Beam intensity asymmetry of an ultrasonic inspection transducer is demonstrated by a four-waveform sample taken across the transducer main beam. Transducers with such asymmetric beam intensities are not desirable and can be very troublesome when used for ultrasonic inspection. These characteristics sometimes develop only when a transducer is in contact with a solid and cannot be seen with conventional liquid-immersion transducer-beam profile measuring methods.

In general, surface laser interferometer probe measurements agree with transmission probe indications. The transducer and laser interferometer probe signals shown in Fig. 2 are compared in frequency domain. The power spectra of the two sensors simultaneously measuring the same stress wave are similar except for an unavoidable harmonic peak around 3 MHz for the piezoelectric transducers.

**ACOUSTIC EMISSION TRANSDUCER CHARACTERIZATION**

The response and accuracy of waveform measurements by conventional piezoelectric transducers degrades when complicated waveforms, such as acoustic emissions, are encountered. Figure 3 illustrates the test block arrangement used to evaluate acoustic emission transducers. As reported in other publications, this design (1,2,3) utilizes a glass capillary fracture as a repeatable stress wave pulse. The stress wave signals generated by this arrangement have been analyzed theoretically and confirmed experimentally. For this purpose, the test block was used as a stress signal source and measured by a laser interferometer probe. The response of a typical piezoelectric acoustic emission transducer to the same stimulus is also shown. The difference in the signals observed is more easily explained by a power spectra plot of the signals from the two measurements. The transducer power spectrum peaks at 175 kHz, which was the resonant frequency of the piezoelectric element. Thus, the complexity of the acoustic emission transducer signal output mostly is characteristic of the piezoelectric element and sensor design, thereby masking the true stress waveform signal present in the test block.

**ACOUSTIC EMISSION MEASUREMENTS USING LASER INTERFEROMETER PROBES**

The laser interferometer probe can be used to sense and characterize stress waves directly. It is especially useful for complex signals such as those encountered in acoustic emissions due to cracking in metals or crazing of polymers. Acoustic emissions were generated by initiating stress corrosion cracking using dilute sodium chloride solution on a self-loaded, double-cantilever beam specimen made from 7039 aluminum alloy. The observed, fast rise time, pulse-like waveforms suggested that acoustic emission from stress corrosion cracking is due to catastrophic, microscopic fracture events inside the growing crack. It should be noted that these signals have not been observed by conventional acoustic emission methods.

Similar in form, but much slower in time (on the order of milliseconds), are acoustic emissions due to polymer crazing. The crazing of Plexiglass, induced on the surface of a bend-loaded test bar, generated a complex acoustic emission signal lasting a few milliseconds. The complexity of this signal (4) was identified to have been generated by reflections of stress waves at a boundary of the specimen and subsequent constructive or destructive interference of the waves at the location of the laser interferometer probe. The experimental work on polymer crazing is still in progress and should aid our understanding of the dynamics of the failure mechanisms in polymer materials under load.

**SUMMARY**

By utilizing laser light probes, it is now possible to accurately sense the true ultrasonic signal waveform in solid materials. Therefore, laser probes can be used to critically evaluate piezoelectric transducer response.

In multi-frequency, complex, stress wave signal measurements such as acoustic emissions, laser light probes can measure stress waveforms not observable by piezoelectric devices, which exhibit resonance-like behavior.

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**REFERENCES**

1. B.B. Djordjevic, R.E. Green, Jr., "High speed digital capture of acoustic emission and ultrasonic transients as detected with optical laser beam probes," Proc. Ultrasonic Int. 79 Conf., Graz, Austria (May 1979) 82-87.
ABSTRACT

The recent development of the laser interferometer probe and laser beam transmission probe has allowed quantitative measurements of stress waves in solids. These laser probes were used to evaluate and calibrate ultrasonic inspection transducers and conventional piezoelectric acoustic emission sensors. The laser interferometer probe was used for stress waveform measurements of complex multi-frequency acoustic emission signals due to cracking in metals and crazing of polymers. Thus, although adequate for many ultrasonic pulse inspection tests, conventional piezoelectric transducers are severely limited as stress pulse sensors for acoustic emission signals.
ULTRASONIC TRANSDUCER CHARACTERIZATION AND CALIBRATION BY LASER LIGHT PROBES

1. Transducer can be evaluated while actually in contact with a solid.
2. Beam profile and ultrasonic stress waveform are measured in bulk and on the surface.
3. The true frequency characteristics of the device are determined.
4. Absolute calibrations can be achieved.

FIGURE 2
ACOUSTIC EMISSION TRANSDUCER CHARACTERIZATION USING LASER INTERFEROMETER PROBE

1. Transducer's response to complex stress waveforms encountered in acoustic emission work can be evaluated.

2. Inadequacies of conventional piezoelectric acoustic emission sensors are demonstrated.

Conclusions:

- THE ACOUSTIC EMISSION TRANSDUCER DOES NOT RESPOND TO STRESS WAVEFORM RESOLVED WITH INTERFEROMETER PROBE.
- ACOUSTIC EMISSION TRANSDUCER SIGNAL OUTPUT IS MOSTLY CHARACTERISTIC OF THE PIEZOELECTRIC ELEMENT AND SENSOR DESIGN.

FIGURE 3
ACOUSTIC EMISSION MEASUREMENTS USING LASER INTERFEROMETER PROBES

STRESS CORROSION CRACKING 7039 AL

EXPERIMENTAL ARRANGEMENT FOR MEASUREMENTS OF ACOUSTIC EMISSIONS DUE TO CRAZING OF POLYMERS (After Djordjevic, Murphy et al.)

ACOUSTIC EMISSION SIGNALS

100 USEC TIME RECORD

25 USEC TIME RECORD

Figure 4
A NOVEL DETECTOR ARRAY FOR INDUSTRIAL X-RAY TOMOGRAPHY*

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ABSTRACT

We are attempting to construct a simple tomographic instrument. The instrument is intended for development and evaluation of a novel x-ray sensitive detector array, which will permit a line resolution of less than 1 mm. The system can be constructed as an array of 500 to 1000 detectors suitable for energies in excess of 1 MeV. Each individual detector can be addressed separately and sequentially by means of a scanning light beam. A prototype consisting of 40 elements has been built and its performance evaluated. Details of its construction and the results of its performance will be presented.

INTRODUCTION

Present CAT equipment is designed specifically for medical use, where the object to be examined consists primarily of low atomic number (Z) elements. This is generally not suitable for samples which consist of high Z elements. One of the reasons is that the detector will not be effective for the high energy photons which have to be used to penetrate the sample.

The work to be described here deals with a new type detector system which can be constructed as a linear array, and which is suitable for x-ray energies in excess of 1 MeV.

DESCRIPTION OF THE NEW DETECTOR

The first stage of the detector system consists of a linear array of small narrow scintillators, which can be envisioned as a stack of thin (0.5 - 1 mm) scintillators (CsI, GSO), each scintillator representing a separate detector. This is depicted in Fig. 1. The width w can be several times the thickness t. The depth dimension d is chosen so that the scintillator will absorb say 90% of the radiation.

The second stage of the x-ray detection system is a converter which uses amorphous selenium to convert light or x-ray photons into electron-hole pairs. For visible light, the quantum conversion efficiency is one electron per photon. It has, therefore, a 10x higher quantum efficiency as compared with the first stage of a photomultiplier. However, the converter does not have internal amplification and requires a low noise, high gain amplifier to further process the signal. The proposed converter can be constructed in such a way that only one such amplifier is required for the whole scintillator array. This is accomplished by use of light activated switches. The principle of operation of the proposed converter will be discussed with reference to Fig. 2.

*Work supported by the Energy Laboratory of the University of Houston.
Basically the converter consists of a substrate onto which are deposited narrow interdigitated electrodes $E$. Each of the electrodes represents a separate detector. On top of the electrodes are two separate but adjacently located narrow selenium strips, running perpendicular to the electrodes. One of the selenium strips, $W$, is designed to record (write the photon image) the other, $R$, to read the recorded image. Both selenium layers have a semi-transparent conductor $E_1$ and $E_2$ on the surface. In the dark, each detector element of the device can be represented as two capacitors in series. One of the interdigitated electrodes $E$ serves as the center electrode. All detector elements are connected in parallel by means of the surface electrodes. When, in the absence of light, a voltage is applied across the two surface electrodes, a voltage will develop across each of the selenium layers, which is inversely proportional to its capacitance. Directing a light beam on the $R$ layer effectively short-circuits it, thus the applied voltage is now found across the $W$ layer. This condition is maintained when the light beam is turned off. Photons from the scintillators which are directed to the $W$ layer will generate charge carries which results in a voltage drop in each of the affected interdigitated electrodes. This voltage modulation across the detector system can subsequently be read by sequentially illuminating the $R$ surface with a scanning light beam. The output is a video signal. In practice, the scintillator can act as the substrate and the two selenium layers can be deposited on top of each other separated by the interdigitated electrodes. Such a geometry is illustrated in Fig. 3.

Another possible geometry is shown in Fig. 4, where separate "Write" selenium layers are located between the stacked scintillators. Here, each scintillator channel is coated on one side with a reflective coating, and on the other side with the three layers $E_1$, $W$, and $E$.

Photons, generated within each channel enters (through $E_1$) into the active selenium layer as long as the angle of incidence does not exceed the critical angle (ray 1). The reflector on the opposite side of the selenium reflects the light, which otherwise would have escaped, back onto the selenium surface (ray 3). The light (ray 2) which is totally reflected by the scintillator interface, $E$, tends to escape from the surface perpendicular to the selenium surface. Some of this may still be captured by shaping these surfaces as shown in Fig. 4 (ray 4).

When the photosensitive $W$ layer is much larger than the thickness of the scintillator, the area of the selenium which receives light due to x-ray photons is quite localized. By subdividing the electrode $E$, in the depth direction of the x-ray is being absorbed. Since the depth distribution of the absorption is closely related to the x-ray energy, the various subelectrodes of the channels exhibit a different energy response. This method is similar to the technique used by Kaplan et al (Nucl. Inst. Meth. 106, 397, 1973) in the split electrode xenon detector.