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OPTICAL DETECTION OF ACOUSTIC EMISSION SIGNALS

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ABSTRACT

Piezoelectric transducers, long used in the generation and detection of ultrasonic waves, have more recently become the detector of choice for acoustic emission signals. Optical probing methods, however, have several important advantages for acoustic emission studies: (1) they have an inherent broad frequency response, free from mechanical resonances, (2) they do not interfere with the acoustic waves, (3) since the focused optical beam diameters are typically only a few hundredths of a millimeter, optical methods can probe very close to a crack or a twin, (4) they can probe internally in transparent media, and (5) they can be used over a very wide temperature range. In this paper we compare the response of an optical probe with that of a commercial acoustic emission transducer. Since the optical probe is a detector of acoustic emission and not only measures acoustic emission amplitudes, but also determine the quantitative response of the piezoelectric transducer to known acoustic disturbances of various kinds over a range of frequencies. We include measurements of real acoustic emission from twinning in two metals and stress corrosion cracking in steel.

Introduction

Elastic waves are commonly used for the non-destructive evaluation of materials and structures. One method employs transducer generated pulses of ultrasonic waves which are directed into the material and sensed either by the same transducer (pulse-echo) or by a separate transducer located at another point on the specimen (pitch-catch). By timing the return of the various echoes, we can determine the location of flaws. By monitoring the attenuation of the ultrasonic waves, we can determine changes in the microstructure of the material. Reception of the ultrasonic signals in this method is easy because with periodic signals of simple waveform, the required bandwidths are narrow and the echo return repetitive.

A second method involves the passive reception of naturally generated bursts of elastic waves called acoustic emission. Acoustic emission signals may be characteristic of the generating mechanism, twinning, crack propagation, or dislocation motion and thus very informative. Such emission is known to increase dramatically prior to failure of the material -- hence its importance. However, because acoustic emission arises at unknown locations, at random times, and with an unanticipated waveform involving a relatively broad range of frequencies, it is much more difficult to detect than the ultrasonic pulses used for the first method.

Although optical methods have been shown to be invaluable for the detection of ultrasonic waves of all kinds, they have not been applied to the detection of acoustic emission bursts until now. Several optical techniques such as the knife-edge technique, diffraction technique, and differential interferometry are unsuitable for various reasons. In this paper we describe an optical method which does work, and which has important advantages.

In Section II of the paper we briefly describe the instrumentation, show how it may be absolutely calibrated, and indicate the minimum disturbance amplitudes that we can measure. In Section III we demonstrate the similarity of optically detected and piezoelectrically detected signals when they are sensed under similar conditions. In Section IV we illustrate one of the several advantages of optical probing by showing waveforms obtained within a half millimeter of a crack.

Instrumentation

The optical probe used in our experiments is a modified Michelson interferometer having a stabilized optical path difference. As shown in Fig. 1, an expanded, collimated laser beam is incident from the left on a beam splitter. Light reflected downward is focused on a mirror at P and provides the reference path. Light transmitted by the beam splitter is focused on the specimen surface. Two returning beams, reference and sample, are recollimated and superimposed above the beam splitter where they form (ideally) a single, uniform interference fringe. The light focused on a photodetector, D, generates a photocurrent having both low frequency and high frequency components. The low frequency components, 0 to about 1 KHz, which result from room vibrations and atmospheric disturbances, drive the stabilization circuit. This circuit translates the mirror mounted on the piezoelectric drive in such a way as to maintain a quiescent optical phase difference \( \pi/2 \pm 2\pi n \) between the reference and sample beams. Since the maximum sensitivity to small high frequency signals, the signal frequencies, typically 10 KHz to 1 MHz, are amplified, displayed on the oscilloscope, and generally recorded on video tape as well.

The interferometer is calibrated by substituting for the specimen a second piezoelectrically
driven mirror. This unit, driven at its resonant frequency, approximately 140 kHz, by a variable RF voltage of sufficient amplitude provides a large, controlled sinusoidal mirror displacement, \( \delta = \delta_0 \cos(\omega t) \) where \( \delta_0 \) is the amplitude and \( \omega \) is the RF radian frequency. For a displacement from the quiescent \( \pi/2 \) phase difference, the photocurrent is given by

\[
\text{i}_{\text{photo}} = (\alpha P_t/2) [1 - \sin(4\pi/\lambda)].
\]  

(1)

In this expression, \( \alpha \) is the sensitivity of the photodetector (amps/watt optical power), \( P_t \) is the laser beam power, and \( \lambda \) is the optical wavelength. The amplifier output voltage for a sinusoidal disturbance is then

\[
V_{\text{out}} = K \sin[(4\pi/\lambda) \delta_0 \cos(\omega t)].
\]  

(2)

For sufficiently large disturbances, the peak-to-peak output voltage is \( 2K \delta_0 \sin(\pi/2) \) so that we have the required constant for absolute calibration. The minimum disturbance amplitude needed to give this voltage, \( V_{\text{cal}} \), is evidently

\[
4\pi\delta_0/\lambda = \pi/2 \quad \text{or} \quad \delta_0 = \lambda/8 = 791 \text{A}.
\]  

(3)

The waveform corresponding to this displacement is shown in Fig. 2; it is in excellent agreement with the theoretical curve given by Eq. 2. Having determined the constant \( 2K \), we now consider small signals, and thus approximate \( \sin x \) by \( x \) in Eq. 2. Solving for the instantaneous displacement, we obtain

\[
\delta = (\lambda/2\pi) V_{\text{out}}/V_{\text{cal}}.
\]  

(4)

The minimum detectable displacement \( \delta_{\text{min}} \) is easily calculated theoretically by observing that the noise level is determined by the shot current in the photodetector generated by the constant power \( P_t/2 \), the first term in Eq. 1. We find

\[
\delta_{\text{min}} = (2eB/\alpha)^{1/2},
\]  

(5)

where \( e \) is the charge on the electron and \( B \) the amplifier bandwidth. For our instrument, \( B = 1 \text{ kHz} \), \( P_t = 1 \text{ mW} \), and \( \alpha = 0.4 \text{ amp/watt} \), and we find that \( \delta_{\text{min}} = 0.04 \text{ A} \). The actual measured minimum detectable amplitude is about 1/2 A.

For piezoelectric sensing we used a commercial piezoelectric acoustic emission transducer having a broad frequency response centered at 500 kHz. The signals detected by both the optical system and the piezoelectric transducer were fed through identical adjustable band-limiting filters for our comparisons. In the twinning experiments we set the bandpass at 10 kHz to 500 kHz, and in the stress corrosion experiments we used 10 kHz to 1 MHz. In addition, we used two identical video tape recorders to obtain a permanent record of the signals which we could later play back through the oscilloscope at any desired sweep speed or voltage gain. The audio portions of the two tapes were used to identify the particular events as seen on the oscilloscope used as a monitor during the recording process. We are thus able to compare the same event as detected by the two sensors.

**Twinning Experiments - Optical System Tests**

Our optical probe was first tested by sensing a variety of simulated acoustic emission signals. We also made a comparison with piezoelectrically sensed signals and found acceptable agreement. After these tests, we made a study of twinning in four different metals in which we detected the acoustic emission signals both optically and piezoelectrically at the same time. As shown in Fig. 3, the specimens were held in a clamp which was mounted on the interferometer base. The specimens were 6 1/4 x 25 mm and were about 150 mm long. They were mechanically polished on one surface. The piezoelectric and optical sensors were arranged directly opposite each other across the narrow dimension of the specimen. Not shown in the figure is a special clamp which held the piezoelectric transducer on the specimen and allowed the optical probing beam to be focused directly opposite on the mechanically polished surface of the specimen.

Twinning emissions were generated by bending the specimen rather rapidly against the clamp. The signals passed between the aluminum clamping blocks and were detected by both sensors. Because the two sensors were close together and symmetrically placed, we assumed that the signals detected would be very similar, though they would probably differ somewhat in their high-frequency components for which the specimen thickness is of the order of an acoustic wavelength or more.

Figure 4 shows a typical twinning event generated in a cadmium specimen. The upper trace shows the piezoelectric waveform; the lower one, the optical waveform. The sweep speed for the two traces was 50 \( \mu \text{sec/div} \). The amplitude of the elastic disturbance is seen to build up rather rapidly in the first 50 \( \mu \text{sec} \) or so and then slowly decay in an oscillatory way which suggests specimen resonances. In any case, it is clear that the piezoelectric and optical waveforms are very much alike. The signal from the optical sensor is superimposed on the piezoelectric signal and is absent in the optical signal may correspond to one of the strong resonant frequencies of the piezoelectric transducer. (We have not yet measured these frequencies when the transducer is loaded by being in contact with the specimen surface.)

Typical acoustic emission amplitudes measured from direct oscilloscope photographs in the range 1 to 20A. (Amplitudes as recorded on the video tape recorder were more difficult to determine, since the VTR gain was somewhat uncertain, and many signals were either lost in tape noise or were clipped when the video became saturated.)

Figure 5 shows an interesting double twin signal in indium displayed at a sweep speed of
verified the general belief that acoustic emission waveforms are highly dependent on the location of the sensor, and accordingly show the usefulness of optical probes in being able to probe very locally, an impossibility with other types of probes, either piezoelectric or capacitive. We have determined that typical acoustic emission amplitudes lie in the range 1-20A in many cases.

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References

Figure 1. Stabilized optical path interferometer. Stabilizer removes low frequency, 0-1 kHz, disturbances; the high frequency signals, >10 kHz, are amplified and recorded.

Figure 2. Experimental calibration curve corresponding to \( h_0 = \lambda/8 \). The vertical gain is 2 volts/div; sweep speed 2 \( \mu \)sec/div. The calibration frequency was 140 kHz, and \( V_{\text{cal}} = 7.7 \) volts.

Figure 3. Mounting of specimens for twinning experiments to verify the performance of the optical and piezoelectric sensors.

Figure 4. Acoustic emission in cadmium due to twinning. The sweep speed is 50 \( \mu \)sec/div. The upper trace is the piezoelectric signal, the lower trace the optical signal.

Figure 5. Double twin in indium; sweep speed 500 \( \mu \)sec/div. The upper trace is the piezoelectric signal, the lower trace optical.

Figure 6. Arrangement of probes for study of E4340 steel specimens subjected to stress corrosion cracking. Here the optical probe was positioned along the crack.
Figure 7. Two acoustic emission bursts in E4340 steel which occurred about a second apart. The two upper traces are for the first event, the lower two for the second event. The piezoelectric sensor on the specimen side gave the PIEZO traces, the optical sensor along the crack gave the OPT traces. Note the similarity of the two PIEZO traces and the similarity of the two OPT traces. The large differences between the piezo and optical traces results from sensor location. The sharp initial spike (see arrows) in the OPT traces is not recorded by the piezoelectric sensor only about 20 mm distant.