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Characterization of Surface-Breaking Defects in Metals with the Use of Laser-Generated Ultrasound [and Discussion]

J. A. Cooper, R. J. Dewhurst, S. B. Palmer, R. B. Thompson, L. J. Bond, H. N. G. Wadley and R. E. Green

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Characterization of surface-breaking defects in metals with the use of laser-generated ultrasound

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The interaction of ultrasound with surface-breaking slots has been used to characterize the slots, with laser generation of ultrasound providing the short-duration Rayleigh pulses used as the probe. Defect depth has been measured in the range 0.3–5.0 mm. Analysis has shown that surface echoes reflected from the defect have two major components. The first arises from direct reflection of a Rayleigh pulse from the top of the defect, whereas the second arises from a shear pulse originating from the bottom of the defect which mode-converts to a Rayleigh pulse on reaching the metal's surface at the critical angle. This interpretation offers a diagnostic technique for measuring defect depths.

Introduction

There is a growing awareness that laser technology now offers new possibilities in ultrasonic non-destructive testing. Some advantages of the use of lasers have already been reported (see, for example, Scruby *et al.* 1982; Birnbaum & White 1984; Monchalin 1984). In the case of laser generation of ultrasound, the short duration of the excitation pulse, typically in the range 10–40 ns, leads to short-duration surface acoustic pulses. Such pulses contain a substantial amount of the total acoustic energy generated by the laser. It is therefore expected that these pulses will play an important role in new laser-based NDT techniques.

Most of the surface acoustic energy is contained in the Rayleigh pulse, which may be used to probe surface breaking slots in metals. The presence of such defects can be detected by using a pulse–echo method or a pulse–transmission method. In the first method, the presence of a crack is detected by a reflection from the crack, and in the second method by a reduction in the transmitted signal amplitude since the pulse is partly or wholly blocked by the crack according to its depth relative to the depth of Rayleigh-pulse penetration. In the case of a laser-based pulse–echo method, a unique acoustic source configuration can be adopted to achieve radar-like scans of the metal's surface (see, for example, Aindow *et al.* 1982). It was shown that by using a cylindrical lens to focus the laser beam into a line on the metal's surface, short-duration Rayleigh pulses were generated having a highly directional nature. Their directionality was seen to consist of two pulses propagating away from, and broadside to the acoustic line source. In the far field, their beam spread was *ca.* 15°. By having a detector coincident with the centre of the line source, echo returns from boundaries and defects were measured. If the cylindrical lens was then rotated through small angles between successive laser pulses, a two-dimensional echo scan was gradually built up (see, for example, Aindow *et al.* 1983). The process was analogous to sonar and radar techniques, producing a visualization of surface features that showed the position and extent of surface breaking cracks.

As well as detecting the presence of a surface defect, a Rayleigh pulse interaction with a slot

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provides information about the depth of the slot. Acoustic spectroscopy has been used for this purpose (see, for example, Burger 1981). We have examined this technique experimentally for the case of a laser-generated acoustic Rayleigh pulse. Results we present show that although there is frequency information which relates to the slot depth, data from laser-generated acoustic measurements can be conveniently evaluated in the time domain. Morgan (1974) attempted to relate time dependent features occurring in the reflected pulse to the discontinuities of the corners at the top and bottom of a slot. However, the broadband Rayleigh transducer did not provide a sufficiently brief pulse to separate out the expected echoes from a 1.4 mm deep slot. Further work, (see, for example, Lidington *et al.* 1975), used a short-pulse surface-wave probe operating at 2.5 MHz to investigate the echoes from the slot top and base to estimate depths from 2 mm to 30 mm in steel. More recently, studies have been carried out on surface pulse interactions with metal slots by using one type of laser to generate acoustic pulses and another laser interferometer to record reflected or transmitted pulses (see, for example, Nadeau *et al.* 1984).

In experiments reported here, analysis on artificial slots in aluminium has been carried out for slot depths of 0.3–5 mm, a region representing the origin and early growth stages of the majority of fatigue failures.

EXPERIMENTS AND RESULTS

An experimental arrangement, shown in figure 1, was used to study the interaction of a laser-generated Rayleigh pulse with an artificial surface-breaking crack. A large aluminium block, measuring typically 150 mm × 80 mm × 40 mm contained a milled slot acting as the crack. A laser pulse from a Nd–YAG Q-switched laser, with typically 20 mJ of energy in 30 ns pulse duration, was partly focused onto the surface on one side of the slot. By using a small amount of grease at the incident point, a short-duration Rayleigh pulse was generated, which travelled to the slot. Its features were measured with a ball capacitance transducer. This transducer was placed about 2 μm above the surface of the metal and responded to

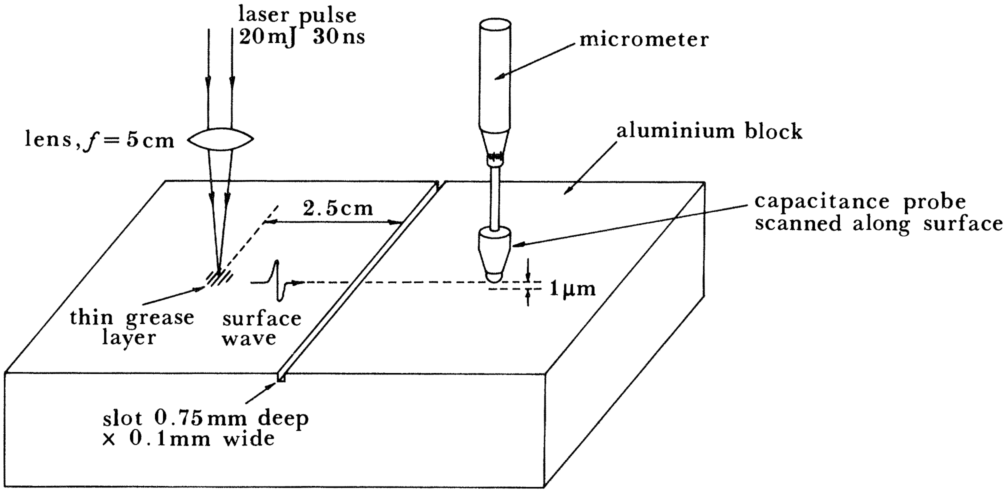

FIGURE 1. Experimental arrangement for investigating the interaction of laser-generated Rayleigh pulses with surface-breaking slots.

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displacements normal to the surface. It had a broadband frequency response extending from 2 kHz to 5 MHz. The signal from this probe was fed through a charge amplifier (bandwidth 10 MHz) before being converted to a digital waveform using a Tektronix 7912 AD digitizer, linked to a Tektronix CP4165 minicomputer. Each waveform, representing the surface displacement, consisted of 512 data points and was stored by the computer for later signal processing. Synchronous external triggering was obtained from a fast response silicon photodiode which monitored the Q-switched laser pulse.

Figure 2*a* shows the ultrasonic waveform recorded by the detector when it was placed on the same side of the slot as the acoustic source, i.e. a pulse–echo measurement; figure 2*b* shows a transmitted waveform. The frequency components of the various waveforms were obtained by performing a numerical fast Fourier transform (FFT). In the case of the incident and reflected pulses, figure 2*a*, the waveform was split into separate parts before carrying out the FFT. A comparison of the various frequency components is shown in figure 3. Figure 3*a* compares the spectrum of the incident pulse with that of the reflected waveform. Below 2 MHz, frequency components in the reflected spectrum are significantly reduced in amplitude. This frequency

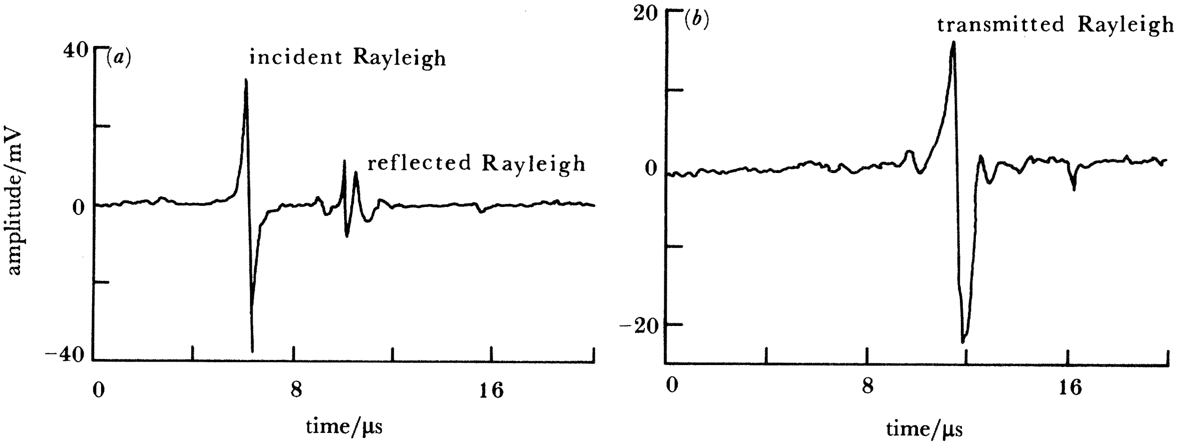

FIGURE 2. The interaction of a laser-generated Rayleigh pulse with a 0.75 mm deep surface slot as an aluminium block. The separation between source and slot was 25 mm. In (*a*) the detector–slot separation was 6 mm. In (*b*) the detector–slot separation was 10 mm on the other side from the source.

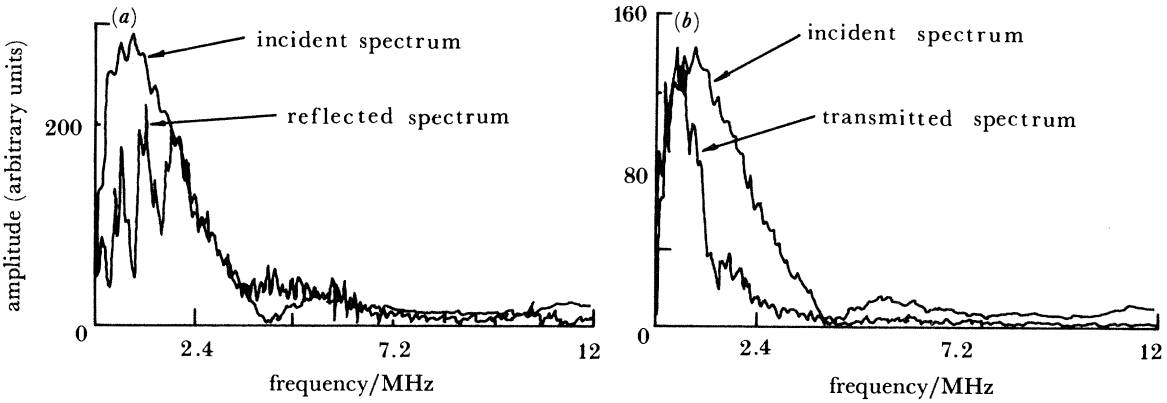

FIGURE 3. (*a*, *b*) A comparison of the frequency components in the incident, reflected and transmitted Rayleigh pulses for a 0.75 mm deep slot.

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corresponds to a Rayleigh wavelength of 1.5 mm, or about twice the depth of the slot. This is consistent with the fact that Rayleigh waves of this wavelength and less should be substantially reflected by the side-wall of the crack. Conversely, in figure 3*b* the incident and transmitted pulse spectra are compared. This time, high-frequency components are attenuated with the attenuation becoming rapid at about 1 MHz. This frequency corresponds to a Rayleigh wavelength of 3 mm, and confirms that long wavelength components with a penetration significantly greater than the depth of the slot continue across the surface with little interaction. Previous authors (e.g. Viktorov 1967; Achenbach *et al.* 1980; Hirao & Fukuoka 1982; Yew *et al.* 1984) have attempted to analyse Rayleigh-wave or Rayleigh-pulse interactions in terms of frequency, but detailed interpretation is in practice difficult.

However, figure 2*a* shows that features of the slot-interaction process were also evident in the time domain and further investigations were carried out without recourse to frequency analysis. Experiments were carried out with the detector on the same side of the slot as the laser source. Pulse echoes from the slot consisted of two peaks which were separated by a fixed time duration. These peaks were related to the slot interaction. Slot depths from 0.3 to 5 mm were investigated by using this arrangement and figure 4 shows the waveforms for six of the slot depths for the same source–detector–slot distance. The separation between the two peaks in the reflected pulse clearly increases with slot depth. For a slot depth of 0.3 mm, the first and second peaks in the reflected pulse were just resolved, whereas for slot depths greater than 5 mm the amplitude of the second feature became less than the noise in the waveform on a single shot basis. All these acoustic waveforms were recorded for the case of a slot normal to the direction of the incident acoustic pulse. Further experiments showed that double-peak Rayleigh reflections were still evident when both the laser source and detector were angularly displaced from the normal by as much as 70°.

DISCUSSION

There is so far no theory that has fully described the waveforms presented in figure 4. However, some interpretation is possible.

For a slot of 1 mm depth, the time delay between the reflected peaks was consistent with the time delay between a Rayleigh pulse directly reflected from the top of the slot and another which continued to travel down the slot before reflection at the bottom. From this possible interaction process, and by using the known Rayleigh velocity in aluminium of 2900 $\mathrm{ms^{-1}}$, it was possible to acoustically determine the slot depth of 1.03 ± 0.09 mm, which is in good agreement with the depth measured by a mechanical gauge of 1.0 ± 0.1 mm. Unfortunately, over a range of slot depths the agreement was poor, figure 5. Experimental points did not follow the theoretical line with an expected slope of 1.

Further investigations were carried out with laser-generated Rayleigh pulses interacting with a down-step, an up-step and corners (see, for example, Cooper 1985). These were the component features which make up a slot. By way of example, figure 6*a* shows one form of experimental arrangement used to explore 90° corners, and figure 6*b* shows a set of detector waveforms as the detector moved from the corner in 3 mm increments between each laser shot. All the waveforms confirm that from such a geometry, a strong Rayleigh pulse is transmitted around the corner. It is also interesting to see on the traces evidence of longitudinal and shear pulses coming directly from the laser source. Similar experiments with the detector on the same

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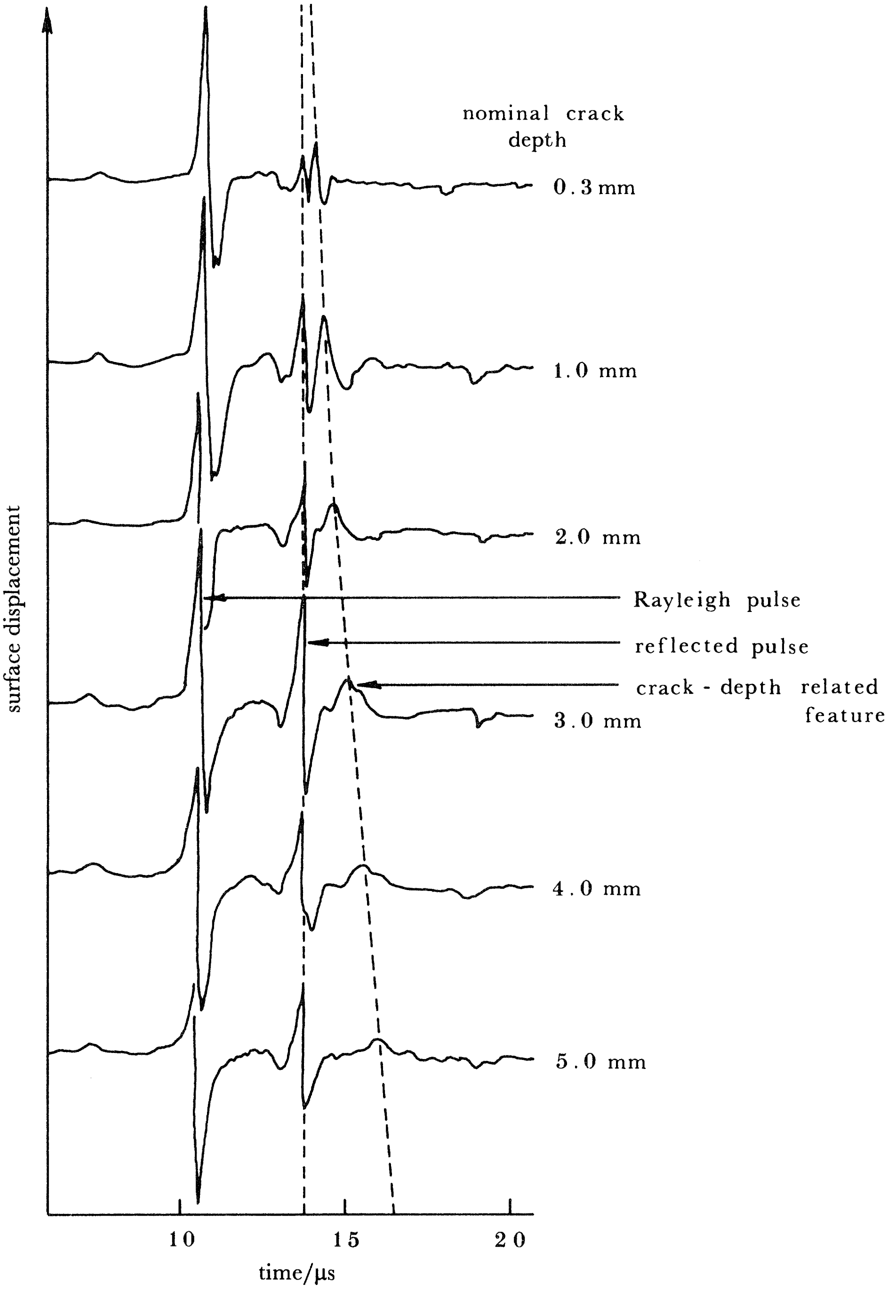

FIGURE 4. Laser-generated acoustic waveforms, showing the variation of the second reflected peak with slot depth.

surface as the laser source showed that the reflected Rayleigh pulse from a 90° corner consisted of just one peak, as expected, and had the same polarity as the incident pulse. In contrast, when the laser source and capacitance detector were arranged on the same surface of a sample leading to a 270° corner, no significant Rayleigh pulse was reflected. Since a 270° corner represents the geometry at the bottom of a slot, we conclude that no Rayleigh pulse of significant amplitude can be reflected at the bottom of surface breaking slots.

The second peak observed in slot-depth measurements must therefore arise from other

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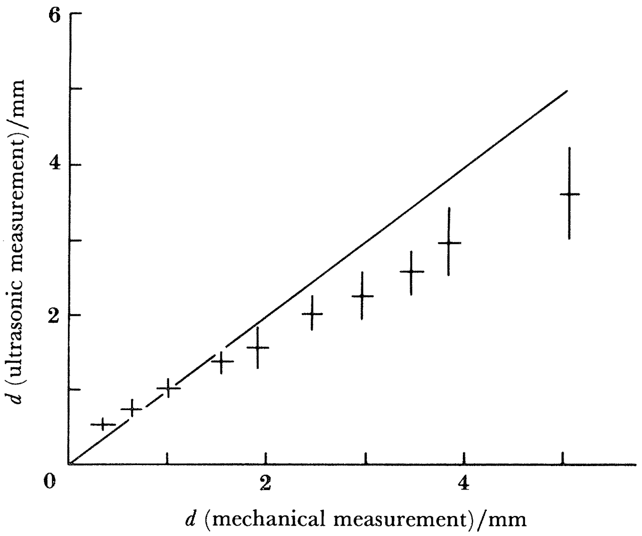

FIGURE 5. A comparison of mechanical and ultrasonic measurements to determine slot depths.

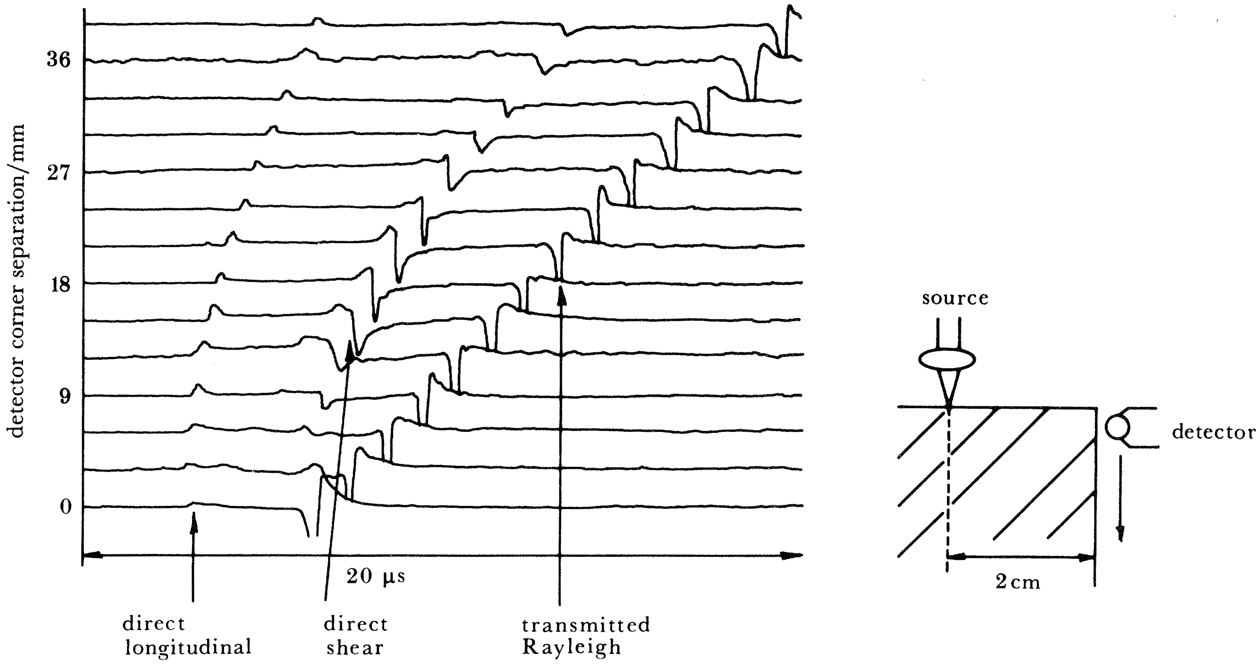

FIGURE 6. Detection of laser-generated acoustic waveforms around a 90° corner, showing the transmission of a Rayleigh pulse.

physical processes. Computer simulations of acoustic surface waves interacting with surface discontinuities have been developed (see, for example, Bond 1979). They suggested that strong mode conversion takes place at a 270° corner, surface-wave energy being converted to bulk shear-wave energy. Similar processes have been observed previously (see, for example, Reinhardt & Daly 1970). We therefore propose that a back-scattered component of this shear wave arrives at the metal surface at the critical angle and is again mode-converted into a

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surface wave. This surface wave produces the second peak observed in the experimental scans. The interaction mechanism is shown schematically in figure 7. Our experimental evidence has shown that the first peak in the reflected Rayleigh pulse, RR, arises from an interaction with the top corner of the slot. A transmitted component travels down the side wall and is mode-converted at the tip mainly into shear pulse energy. Some fraction travels back to the surface where it is mode-converted again at some angle, to another Rayleigh component, producing the second peak, RS. It is known that in aluminium, $\theta_c \approx 30°$, and it has been demonstrated that for angles greater than this, a surface Rayleigh pulse appears from a buried source (see, for example, Pekeris *et al.* 1957).

This model was examined by re-evaluating the data shown in figure 5. For a given slot depth, d, as shown in figure 7, the time delay, Δt, between the two peaks of the reflected Rayleigh pulse is given by

$$\Delta t = \frac{d}{v_r} + \frac{d}{v_s \cos\theta_c} - \frac{d\tan\theta_c}{v_r}, \tag{1}$$

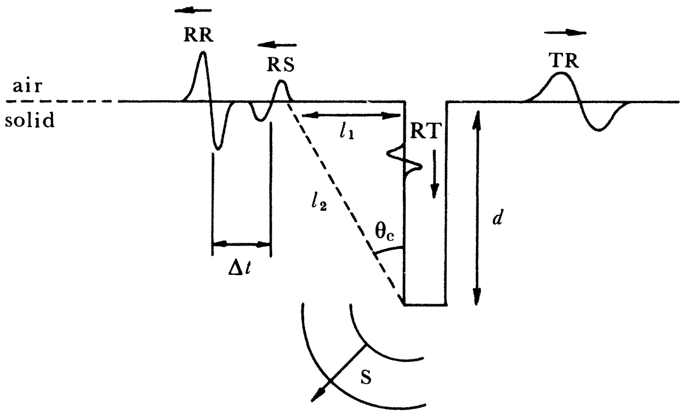

FIGURE 7. Physical processes involved when an incident Rayleigh pulse interacts with a slot to produce reflected and transmitted surface pulses.

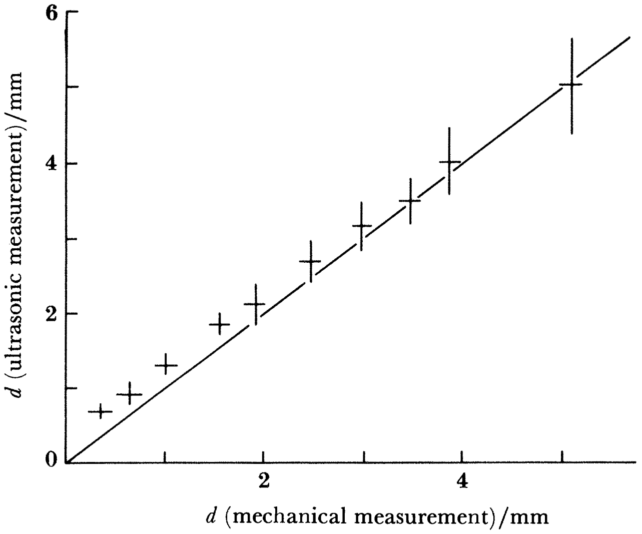

FIGURE 8. A comparison of mechanical and ultrasonic measurements to determine slot depth. Ultrasonic measurements were based on a 'Rayleigh–shear–Rayleigh' interaction.

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where v_r and v_s are the Rayleigh- and shear-wave velocities respectively. By substituting $\theta_c = 30°$ for aluminium, (1) was rearranged so that the depth, d, could be evaluated. That is,

$$d = \frac{\sqrt{3}\,\Delta t\, v_r\, v_s}{(\sqrt{3}-1)\, v_s + 2v_r}. \tag{2}$$

Results are shown in figure 8, with the solid line showing the expected gradient of 1. Overall agreement was now good for slot depths greater than 2 mm. For shallower slots, systematic deviations from the straight line were thought to be associated with the difficulty in mechanically measuring slots with corners which have a finite radius of curvature.

Conclusions

From the short time duration, acoustic Rayleigh pulses that can be produced by laser-generated ultrasound, distinctive pulse–echoes are seen from artificial slots acting as surface breaking cracks. The pulse–echo consists of two peaks, one of which arises from reflection at the top of the slot, the other arising from interaction with the bottom of the slot. Experiments have shown that reflection from the bottom is not due to direct Rayleigh pulse reflection, but is instead due to a shear-wave pulse which is mode-converted on returning to the surface into a secondary Rayleigh pulse. Artificial crack depths in the range 0.3–5 mm have been measured.

The presence of two peaks in pulse–echoes has since been observed in real cracks. It is therefore proposed that by using pulsed repetition-rate lasers to perform radar-like scans of a metal's surface, it is feasible to not only locate a surface-breaking crack but also measure its depth.

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Discussion

R. B. Thompson (*Ames Laboratory, Iowa State University, Ames, Iowa, U.S.A.*). Dr Dewhurst described the generation of a Rayleigh wave reflected from a crack in terms of a critical angle

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effect, whereby a shear wave, diffracted backwards and upwards from the crack tip, is converted to a Rayleigh wave at the part surface. Plane-wave theories would not predict that such a conversion would take place. Can he comment further on the mechanism?

R. J. Dewhurst. When we have measured the velocities of the first reflected peak and the second reflected peak, they have both been found to travel at the Rayleigh-wave velocity (within experimental errors). Our model has been partly based on this fact, and on the other experimental evidence presented here. There is a need to develop a full theoretical understanding.

L. J. Bond (*London Centre for Marine Technology*, *University College London*, *Torrington Place*, *London WC1E 7JE. U.K.*). My first comment is to correct what I am sure must have been a slip of the tongue. The interaction of pulsed Rayleigh waves with sharp 90° corners. (a $\frac{1}{4}$ space) and with sharp 270° corners (a $\frac{3}{4}$ space) are both frequency *independent* and *not* frequency dependent as stated.

My second comment concerns the state of available theory for pulsed Rayleigh-wave interactions with corners, steps and slots, including the determination of reflection and transmission coefficients. A range of studies has been performed in seismology, ultrasonics and for SAW electronics, which established basic descriptions of such systems by the early 1970s. In our own studies we have used explicit finite-difference methods supported by experimental measurements on pulsed Rayleigh waves in the 1–15 MHz range since 1974, and the results obtained are in good agreement with the available data from other groups (Bond 1978, 1979).

Regarding the basic coefficients for interactions with isolated corners on aluminium alloy test blocks (Poisson's ratio, $\sigma = 0.34$): for $\frac{1}{4}$ space the reflection coefficient is 0.47 ± 0.05, the transmission coefficient is 0.59 ± 0.05 and the percentage of energy mode-converted is 44%; for $\frac{3}{4}$ space these values are 0.11 ± 0.03, 0.23 ± 0.03 and 94%, respectively.

In our work the models give full two-dimensional numerical visualizations of the wave fields which enable the time development to be followed and also the extraction of 'RF' signals at selected points which can be used to give the frequency domain data (Bond 1978, 1979; Bond & Blake 1983; Georgiou & Bond 1985). A final point, in relation to several of yesterday's talks which considered leaky Rayleigh waves in acoustic microscopes. We have now extended our models and experiments to consider immersion systems including leaky Rayleigh waves and the interaction with both surface and near-surface features (Saffari & Bond 1983, 1985).

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R. J. Dewhurst. In answer to Dr Bond's first comment, perhaps we have a misunderstanding. Experimentally, corners are not necessarily sharp. Therefore in the case of laser-generated Rayleigh pulses, have a wide frequency spectrum, some frequency dependence might be expected. This has already been pointed out by Viktorov (1967).

Second, we agree that there is a large body of theory which discusses Rayleigh-wave interactions with corners, steps and slots. Unfortunately, we are not aware of any paper which predicts reflected waveforms from slots which have amplitude envelopes as presented in this paper.

H. N. G. Wadley (*A*163, *Materials Building* 223, *NBS*, *Gaithersburg*, *Maryland*, *U.S.A.*). I believe examination of the paper by Pekeris & Lifson (1957) will reveal the origin of the second signal component in Dr Dewhurst's reflected waveforms. A buried source of shear waves may node convert at the surface creating longitudinal, shear and Rayleigh waves. In particular, the possibility exists of a critically refracted longitudinal wave (Head wave) accounting for your signal.

R. J. Dewhurst. I think this is something we should examine in future work.

R. E. Green (*Center for Nondestructive Evaluation*, *The Johns Hopkins University*, *Baltimore*, *Maryland*, *U.S.A.*). In response to discussion between a number of members of the audience and the speaker, relative to whether or not his experimental observations are actually caused by an acoustical critical-angle phenomenon, I would like to point out that the classical method of treating critical angles in homogeneous, isotropic media is not applicable to real, inhomogeneous, anisotropic materials.

First, in anisotropic materials it is the direction of the energy-flux vector and not the propagation vector which must be considered in any critical-angle calculation. Because the direction of this energy-flux vector varies considerably with crystallographic orientation as well as with wave-mode (quasi-longitudinal or quasi-transverse) classical calculations ignoring this behaviour are in error.

Secondly, all real materials attenuate (absorb and scatter) the ultrasonic waves passing through them and this attenuation of the waves is not taken into account in the classical theory. Marked differences in critical-angle behaviour can occur depending on the type and degree of attenuation present. Thus, in defence of the speaker, I contend that his experimental results are most likely to be correct and the members of the audience who contest them on classical theoretical grounds are in error.