DETECTION AND CHARACTERIZATION OF SURFACE CRACKS USING LEAKY RAYLEIGH WAVES

A. Fahr*
Ontario Research Foundation, Mississauga, Ontario, Canada

W.R. Sturrock
Defence Research Establishment, Pacific, Victoria
B.C. Canada

INTRODUCTION

A number of ceramics such as silicon nitride, and zirconia are being considered for high temperature structural applications. The primary problem with these ceramics is their wide fracture strength variability. In consequence, non-destructive evaluation techniques are required to ensure their reliable use. The brittle nature of ceramics inhibits the strain energy release at flaws by plastic deformation. As a result, critical flaw size in these materials is small. For example, flaws in the size range of 20-100 μm are considered as "critical" in silicon nitride for engine applications. Surface cracks are particularly important since they are the major source of failure in ceramics (1). These cracks are generated during machining operations and usually consist of arrays of semi-elliptical cracks with random inclination to the surface, but a preferred alignment parallel to the direction of motion of the abrading particles (2).

This work is concerned with the application of 10-100 MHz frequency leaky Rayleigh waves for the detection and measurement of critical size surface cracks in silicon nitride.

EXPERIMENTAL STUDIES

Material and Standard Cracks

Hot pressed silicon nitride (Norton's NC132) was used in this investigation. Artificial cracks were introduced on polished (1 μm surface finish) surfaces by Knoop indentation technique. Knoop indentation in silicon nitride produces sharp semi-circular cracks which are silimar to those generated during surface machining. The mouth opening

* Presently with the National Aeronautical Establishment, National Research Council of Canada, Ottawa, Canada.
This work was supported by Defence Research Establishment, Pacific, B.C. Canada.

of the crack is less than one fifth of its depth, a, and its surface length is about 2a. The surface length was measured under an optical microscope from which the depth was deduced. Knoop indentations in the depth range of 10 to 400 μm were used as standard cracks.

Flaw Detection Technique

Fig. 1-a shows the basic pulse-echo configuration used for the generation and detection of leaky Rayleigh waves. The flaw detection and measurement system has been described in an earlier publication (3). In this configuration the mode conversion of the incident ultrasonic beam at an angle near the Rayleigh angle, θ_R, results in Rayleigh waves. The Rayleigh angle is given by:

$$\theta_R = \arc\sin \frac{V_W}{V_R}$$

where V_R is the Rayleigh wave velocity in the ceramic and V_W is the ultrasonic velocity in water. The Rayleigh waves reflected by sharp surface discontinuities radiate a portion of their energy back into water at θ_R angle which is received by the transducer. Thus, as the transducer is scanned parallel to the surface of the test material, strong signals from surface flaws are detected. Fig. 1-b shows a typical signal from a 100 μm Knoop indent detected by this technique using a 50 MHz focused transducer.

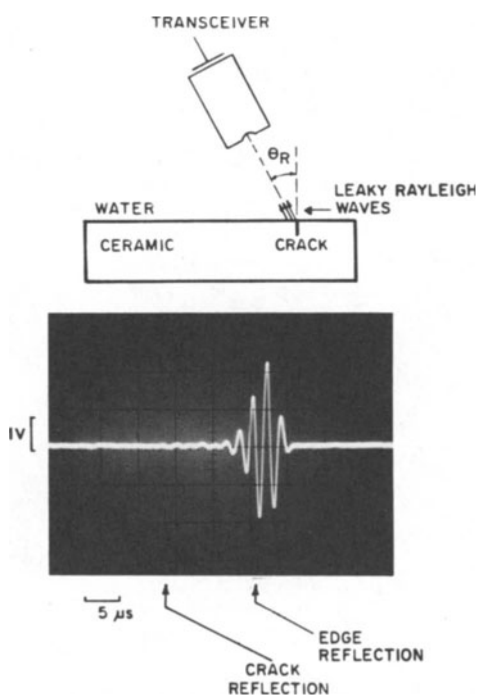

Fig. 1. The testing configuration and a typical signal from a Knoop indentation (100 μm) obtained by 50 MHz leaky Rayleigh waves.

The detectability of surface flaws by leaky Rayleigh waves is dependent on the transducer frequency. This is demonstrated in the experimental results of Fig. 2 which shows the smallest Knoop indentation detectable at different frequencies. This figure indicates that, for the experimental conditions of the present work, a frequency of about 50 MHz is optimum for the detection of flaws as small as 20 μm. This size crack is only about 1/6 of the Rayleigh wavelength in silicon nitride at 50 MHz. Beyond 50 MHz, the detectability tends to level off due to the increase of attenuation losses. Thus, the crack measurements in this investigation were carried out at 50 MHz.

Leaky Rayleigh waves lose their energy rapidly particularly at high frequencies. Thus, only those flaws which are located near the point of incidence of the impinging beam are detected. As a result, resolution of this method is extremely good since reflections from neighbouring flaws or specimen edges do not overlap with the signal from the flaw of interest. The resolution is particularly good when a narrow Rayleigh wave is employed by focusing the incident beam on the surface of the test material using a focused transducer. In our measurements, the beam diameter at focal point is about 500 μm which is larger than the crack sizes investigated.

Overall, the scanning simplicity and the high sensitivity and resolution of leaky Rayleigh waves make this technique a practical and reliable method of testing ceramic parts for surface defects.

Flaw Measurement

(i) Time domain analysis

The measurement of surface cracks in the size range of a=10 to 400 μm by 50 MHz Rayleigh waves (λ_R = 112 μm) cover both the long wavelength

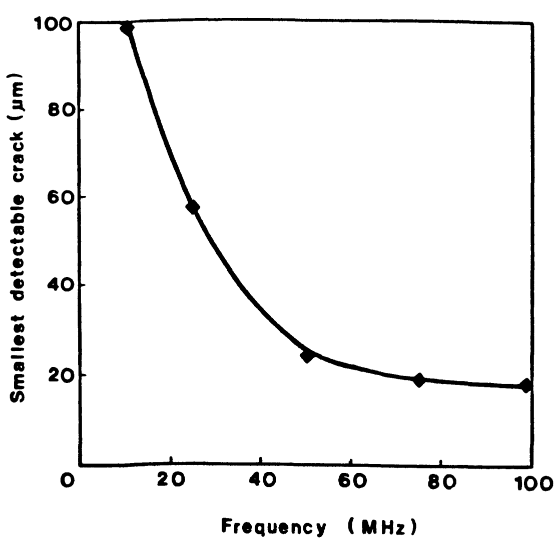

Fig. 2. The detectability of surface cracks in silicon nitride by leaky Rayleigh waves as a function of the frequency.

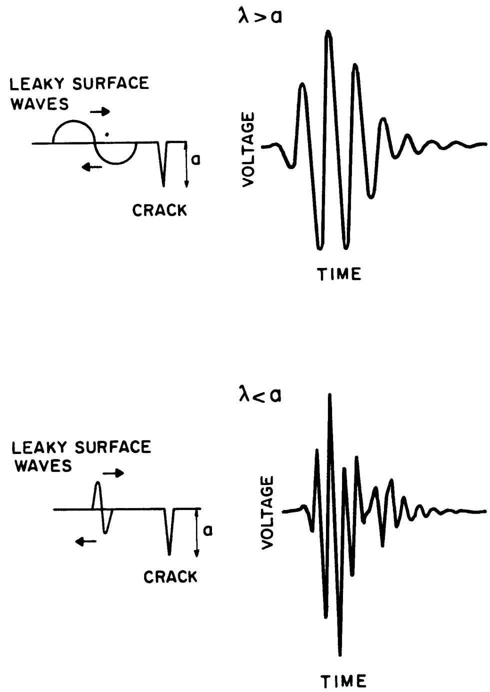

Fig. 3. Typical oscilloscope view of signals from surface cracks by leaky surface waves.

(λ_R>a) and short wavelength regimes (λ_R<a). The typical time domain signals from surface cracks obtained by leaky surface waves under both conditions are illustrated in Fig. 3. In the λ_R>a region, the crack signal is generally a symmetrical group of oscillations whose overall peak-to-peak amplitude increases with increasing the crack size. In the λ_R<a region, on the other hand, the crack signal is more complex and normally consists of more than one group of oscillations. Time domain signals were used to measure the acoustic reflection coefficient, S_{11}, of various size Knoop indentations using:

$$S_{11} = \frac{A_2}{A_1} \quad (1)$$

where A_2 and A_1 are the crack signal and input signal amplitudes at the transducer.

The acoustic reflection coefficient of a crack is dependent on its orientation with respect to the incident Rayleigh beam. This is demonstrated in the experimental results of Fig. 4 obtained for a 100 μm Knoop indentation. Analytical solutions are given by Auld (5) for calculation of the reflection coefficient at oblique angles. Both the analytical and experimental results indicate that as the direction of the crack relative to the Rayleigh beam deviates from normal, the signal from crack face becomes smaller, decreasing the S_{11} value. Thus, for complete characterization of cracks from the reflection coefficient, it is necessary that the specimen be scanned in more than one direction.

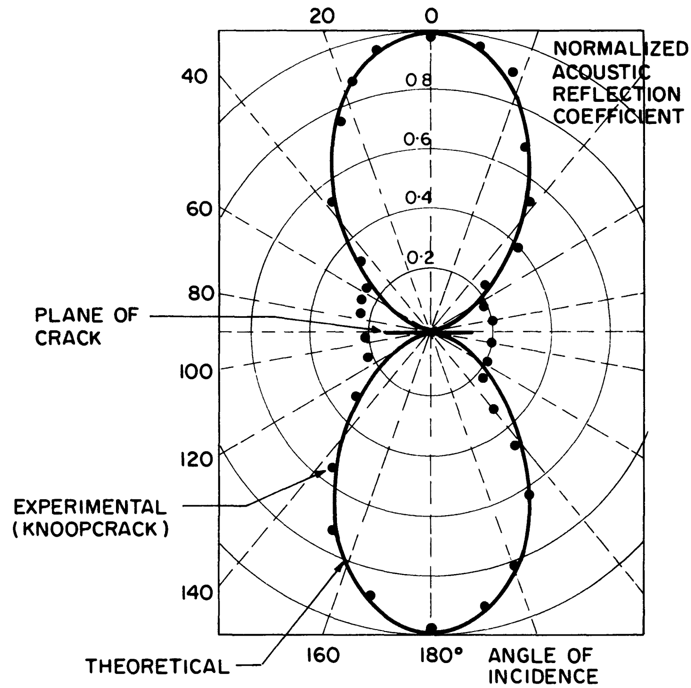

Fig. 4. The analytical and experimental results for leaky Rayleigh wave scattering from a semi-circular surface crack at different orientation.

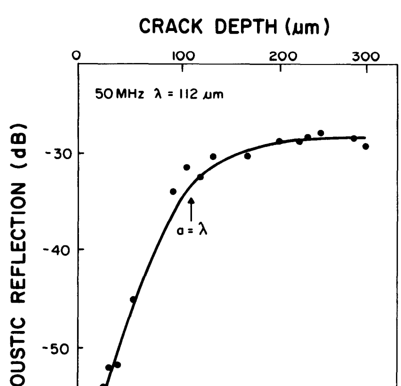

Fig. 5. The signal intensity of different size Knoop indentations obtained by 50 MHz leaky Rayleigh waves.

The maximum reflection occurs when the Rayleigh beam is normal to the plane of the crack. This condition was used to obtain the acoustic reflection versus the normalized crack size, Ka, ($K = \frac{2\pi}{\lambda_R}$). The results are shown in Fig. 5.

Two general regions are quite clear from this figure. First, the rapid increase of the acoustic reflection with crack size in the long wavelength region ($\lambda_R > a$) followed by the slower increase when the crack size exceeds λ_R. This behaviour is predicted by the scattering theory developed by Kino (4) and Auld (5). The application of this theory to a semi-circular crack (6) of depth, a, under normal incident angle results in:

$$S = \alpha \frac{a^3}{\lambda^2} \quad \text{for } \lambda > a \tag{2}$$

$$S = \alpha' \cdot a \quad \text{for } \lambda < a \tag{3}$$

where α and α' are constants which are dependent on the transducer efficiency, width of the beam, test configuration and material under test. The above equations consider only the longitudinal component of the surface wave in the calculation of the reflection coefficient. If, however, both longitudinal and shear components are considered, according to Achenbach and Brind (7), there would be a resonance peak at around Ka=1. The present results are obtained for Ka>2 and thus such a peak was not observed. But resonances due to the interaction from the crack depth with that of the crack face were observed in the frequency spectra of cracks as well as in the S_{11}-Ka diagrams obtained at lower frequencies (3). The resonance effect will be discussed later in this paper.

The above equations can be used for flaw measurement, however, since in silicon nitride we are dealing with flaws smaller than 100 microns in dimension, and this is below the Rayleigh wavelength at 50 MHz operating frequency, only equation 2 is applicable. Under such conditions, the crack size estimation is easily possible by measuring the acoustic reflection of unknown defects relative to a reference defect of a similar type and a depth of about λ_R. From equation 2 we can obtain:

$$a = A^{1/3} a_R \tag{4}$$

for the condition $a < a_R < \lambda_R$

where A is the ratio of the acoustic amplitudes of the unknown defect to that of the reference, a and a_R are the size of the unknown and reference defects, respectively.

(ii) Frequency domain analysis

Fig. 6 shows the frequency spectra of a number of Knoop indentations of different sizes. Two important features are apparent in the frequency domain data. One is the resonance type features which occur periodically at certain frequency intervals depending on the crack size. These resonance peaks become more pronounced when the crack spectrum is deconvolved by a reference spectrum such as that from a sharp edge or a standard crack. Fig. 7 shows the deconvolved spectra of various Knoop cracks.

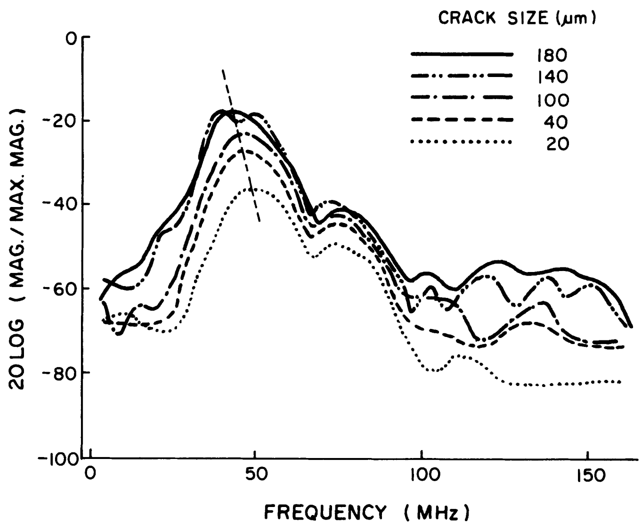

Fig. 6. Frequency spectra of leaky Rayleigh waves from various size cracks.

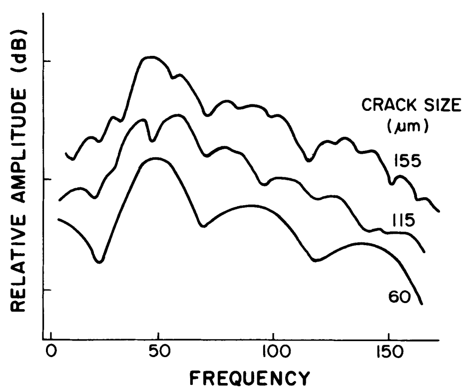

Fig. 7. The deconvolved spectrum of various Knoop indentations by a 100 μm reference crack.

Also the resonance peaks are more clear for cracks oriented at angles other than normal to the direction of the Rayleigh beam (see Fig. 8). This is due to the fact that when the angle of the incident Rayleigh beam deviates from normal, the signal from the crack face becomes smaller while the crack tip signal remains relatively unchanged.

Resonance theory has been developed by Ayter and Auld (8) for half-penny and rectangular shaped 3D cracks which gives:

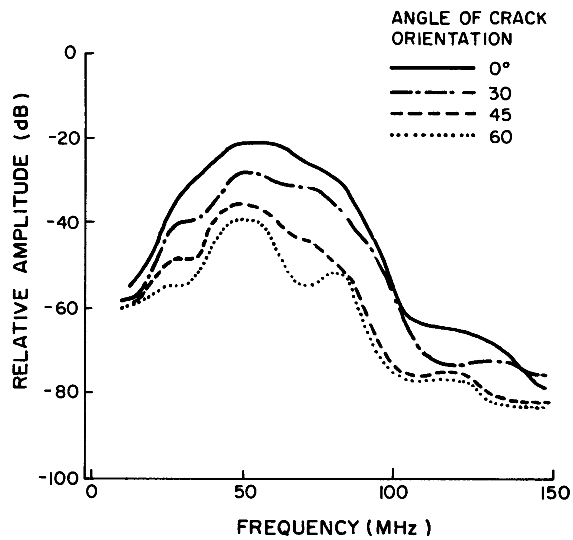

Fig. 8. Frequency spectra of a Knoop crack as the function of the crack orientation.

$$f_a = \frac{nV_R}{2a} \quad (5)$$

for depth resonance and

$$f_\ell = \frac{(2n+1)\ V_R}{4\ell} \quad (6)$$

for length resonance. Where V_R is the Rayleigh velocity, a and ℓ are the depth and the length of the crack, respectively, and n being an integer number. Equations 5 and 6 lead to:

$$a = \frac{V_R}{2\Delta f_a} \quad (7)$$

and

$$\ell = \frac{V_R}{2\Delta f_\ell} \quad (8)$$

where Δf_a and Δf_ℓ are the frequency separation between two consecutive depth or two consecutive length resonances, respectively. The Δf values obtained from Fig. 7 for three different Knoop indentations agree reasonably well with the equation 7. Thus, the minor peaks in the frequency spectra of cracks are believed to be due to the crack depth resonance effect. The resonance excitation of surface cracks in metals by Rayleigh waves has also been investigated experimentally by Domarkas et al (9), Singh and Singh (10) and most recently by Saffari and Bond (11). The former investigators (9) have demonstrated resonance effect both from the depth and the length of cracks. These investigators have shown the feasibility of the use of the resonances in the spectra of the reflected signals to estimate the depth and possibly the length of the defects in metals. The present results demonstrate the validity of the technique for sizing microscopic cracks in ceramics. Furthermore, these results indicate that unlike the conventional acoustic reflection measurement, which is highly dependent on the crack orientation (see Fig. 4), the resonance intervals do not change significantly with the orientation of the crack. Thus, methods based on the spectral analysis are more suitable for crack sizing.

Another important feature in Fig. 6 is the shifting of the frequency spectra towards lower frequencies with increasing the crack size. Similar behaviour has been also observed by Saffari and Bond (11) for larger defects in steel. This can be attributed to the attenuation of the high frequency components of Rayleigh waves with increasing crack size. The frequency shifting can also provide indications about the size of defects.

CONCLUSIONS

Leaky Rayleigh waves can be used effectively to detect and characterize small surface defects in ceramics. The detection of surface cracks in the critical size range of 20-100 μm in silicon nitride is easily possible by 50 MHz leaky Rayleigh waves generated by a focused transducer. The acoustic reflection of cracks can be utilized for size estimation, however, corrections must be made for crack orientation effects. The frequency spectra of the crack signals, on the other hand, contain information which is less dependent on the crack orientation. The peak frequency and the resonance intervals in the frequency spectra are found to be directly related to the size of the cracks.

REFERENCES

1. R.W. Rice, Ceramics for High Performance Applications, Ed. J.J. Burke, A.E. Gorum and R.N. Katz, Brook Hill, Checknut Hill, Mass. 1974.
2. J.J. Mecholsky, S.W. Freiman, and R.W. Rice, J. Amer. Ceram. Soc. 60,116, 1977.
3. A. Fahr, S. Johar, M.K. Murthy, W.R. Sturrock, 1983, Rev. of Prog. in Quant. NDE. 2, 1983, Plenum.
4. G.S. Kino, J. Appl. Phys. 49(6), 3190, 1978.
5. B.A. Auld, Wave Motion 1,3, 1979.
6. B.T. Khuri-Yakub, G.S. Kino, and A.G. Evans, J. Am. Ceram. Soc.63, (1-2), 65, 1980.
7. J.S. Achenbach and R.J. Brind, J. Sound and Vibration, 76(1), 43, 1981.
8. S. Ayter, and B.A. Auld, Proc. DARPA/AFWAL Rev. of Prog. in Quant. NDE, AFWAL-TR-80-4078, 344, 1974.
9. V. Domarkas, B.T. Khuri-Yakub, and G.S. Kino, Appl. Phys. Lett. 33(7), 557, 1978.
10. G.P. Singh, A. Singh, Proc. DARPA/AFWAL Rev. of Prog. in Quant. NDE, AFWAL-TR-81-4080, 443, 1980.
11. N. Saffari, and L.J. Bond, IEEE Ultrasonics Symposium, 1983.

DISCUSSION

G. Kino (Stanford University): Are these cracks you are looking at closed at the top or are they annealed cracks?

A. Fahr: We looked at both annealed cracks and as indented cracks.

G. Kino: Well, then you should see a sharp dip round about K equals 1, which has nothing to do with resonance. It has to do with the shear and longitudinal wave interacting with the crack and cancelling each other out, and that's a very good measure of the depth of the crack. And I somehow don't see that in these curves, so I'm a little lost as to what's going on.

A. Fahr: That's a very good approach to measure the crack depth. However, the values of Ka in our measurements were always above 2, so we did not observe the sharp dip you mentioned.