Deducing Mechanical Properties due to Interfaces From Their Acoustical Response

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ABSTRACT

The ultrasonic interrogation of a partially contacting interface provides details on the contact topology. In this paper ultrasonic information is used to deduce important mechanical properties of structures containing fatigue cracks and of diffusion bonds as specific examples of such interfaces. The information is sufficient to determine the residual stress distribution in the wake of the fatigue crack. These residual stresses produce a stress intensity factor which, in part, shields the crack from the externally applied stress intensity range and thus affects the fatigue crack propagation rate. For diffusion bonds in materials of low ductility, the information appears to be sufficient to determine the bond strength in uniaxial tension.

KEYWORDS

Acoustics; bond strength; contact topology; crack tip shielding; diffusion bonds; fatigue cracks; interfaces.

I. INTRODUCTION

The importance of interfaces has long been recognized in chemistry and physics and a variety of instruments for experimental studies is now available. In contrast, research on the effects of interfaces on mechanical properties lags far behind the above efforts. A notable exception is the work by Bowden and Tabor (1986) and Kendall and Tabor (1971) on friction and lubrication. They concluded that it is important to know the "real area of contact" and that "under the intense pressure at the localized points of contact, plastic deformation and flow occur until the area of contact is sufficiently great to support the load." Thus a quantitative description of the contacts is necessary to improve our understanding of the mechanical effects of such interfaces.

Our interest in this area was triggered by a series of similar problems. The first one deals with the contact of the two fracture surfaces in the wake of a crack. This contact, or crack closure (Elber, 1972), appears to have an effect on fatigue crack propagation. In our investigations, using acoustics, it became apparent that a contacting interface not only transmits and reflects but also diffracts an acoustic wave (Thompson et al., 1989). The importance of this diffraction in combination with transmission and reflection is briefly described in Section II. The application of the results to the derivation of mechanical effects on the driving force on the crack will be discussed in Sections III and IV.

The second problem deals with the quality of diffusion bonds. Ideally, the interface between two pieces of material will disappear if exposed to sufficient time, temperature and pressure conditions leading to mechanical properties close to those of the bulk material. In practice, however, deviations lead to degraded mechanical properties. As before, acoustic measurements (Thompson et al., 1989) provide information on the amount of contact achieved, discussed in Section V. Fractographic analysis of diffusion bonds provides direct information on the contact topology useful in checking the predictions of the acoustic interrogation.

Some of the observations discussed appear to be applicable to numerous other interface problems. For instance, a fatigue crack creates an interface whose contacts vary spatially. Similar spatial variations of the contact, referred to as "kissing bonds," have been found in metal-epoxy-metal interfaces and a variety of solid-solid bonds and coupler-tubing interfaces (Rehbein et al., 1984). In these examples it would be highly desirable to use the geometrical information on contact, provided by acoustics, to deduce effects on strength, both in tension and shear.

II. CONTACT TOPOLOGY

In a companion paper (Thompson et al., 1989) experimental and theoretical efforts to characterize an interface by acoustics in a wavelength regime large with respect to contact separation are briefly described. As a specific example, a fatigue crack growing into a block of material is considered. In this case, the interface is formed in the vicinity of the crack tip by the contact of two crack surfaces. Microscopically, the contact is made by individual asperities which transmit, reflect, and diffract the interrogating acoustic energy. A quasi-static distributed spring model (Baik and Thompson, 1984) describes the strength of the contact leading to a spring constant κ which is mainly a function of contact diameter d and separation C. Furthermore, discrete contacts had to be introduced to account for the large diffracted signals observed (Thompson et al., 1984; Buck et al., 1984) providing an independent measure for C. Knowing κ and C, the average diameter d of the contacting asperities can then be calculated (Buck et al., 1987a). Thus, two independent acoustic measurements are needed to provide a full description of the contact topology.

For acoustic wavelengths large with respect to the contact separation, the solutions of the distributed spring model are in good agreement with those obtained using the exact elastodynamic theory (Angel and Achenbach, 1985a, 1985b). The latter, however, predicts well-defined cusps if the wavelength is equal to the contact separation. Thus, full information on the contact topology may also be deduced from the frequency dependent transmission or reflection coefficient if the latter condition is fulfilled.

Similar efforts to determine the contact topology of diffusion bonded interfaces have been carried out recently (Palmer et al., 1988; Gray et al.,

Table I. Comparison of Contact Topology and Spring Constant of a Fatigue Crack and Diffusion Bonds of Different Qualities.

	Closure region next to crack tip-Al	High quality diffusion bond-Cu	Low quality diffusion bond-Cu
d(μm)	35	148	12
C(μm)	70	150	26
$\kappa(10^8 \frac{MPa}{m})$	5.3	1280	42
A/A_o(%)	25	97	22
κ^*	0.5	135	0.8

1988). Again, the topology of the contacts yields a κ which controls the reflection coefficient. Diffraction measurements are now underway to provide the additional information necessary to determine d and C independently. Due to the nature of a diffusion bond, these quantities can be determined directly. In a destructive test, fracture in general follows the bondline, so that the bonded areas can be clearly distinguished from nonbonded ones, yielding estimates for d and C. These values allow a computation of κ and correlation with the measured reflection coefficient. On the other hand, the model also provides the theoretical correlation between κ and the expected reflection coefficient. Palmer et al. (1988) noted good agreement between experiment and theory.

Table I provides a comparison of d, C, and κ as determined in the closure region of a fatigue crack (Buck et al., 1987a) and on diffusion bonds (Palmer et al., 1988). Also included are the fractional contact area A/A_o and a "normalized" spring constant κ^*, related to κ by

$$\kappa^*(d/C) = C\kappa(1-\nu^2)/E \qquad (1)$$

where E is the Young's modulus and ν is Poisson's ratio. Baik and Thompson (1984) found that κ^* depends on the ratio d/C (or A/A_o) only and not on the material. A comparison of κ^* and A/A_o then shows that their values in the closure region are almost the same as those of a low quality bond. This is important since the values for d and C, which determine κ and κ^*, have been obtained differently. In the case of the fatigue crack, d and C were determined based on transmission and diffraction studies, while fractography provided the data for the diffusion bonds. Yet they yield, for similar A/A_o, about the same normalized spring constant κ^*. This supports the accuracy of the acoustic determinations of C.

III. THE CONTACT PRESSURE

If the geometry of the contacts is known, this information may be used to derive a series of parameters which affect the mechanical properties of the material containing the interface. The first parameter of interest is the contact pressure, σ_o, which is the externally applied stress necessary to hold the two pieces of material together. In case of the fatigue crack, this contact pressure is a residual stress, which is a consequence of the elastic and plastic deformation of the material in front of the crack tip and the mismatch of the two fracture surfaces. During diffusion bonding, σ_o provides the stresses necessary for creep to occur in the contact areas, such that the interface slowly disappears.

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For a real interface and a perfectly plastic material, it is assumed that at any σ_o, the true area of contact is comprised of a large number of equi-area circular contacts (Kendall and Tabor, 197; Haines, 1980) and is proportional to P_m, the "flow pressure", which is about three times the ultimate tensile strength. Based on earlier work by Baik and Thompson (1984), connecting σ_o with the transmission coefficient, it has been shown by Buck et al. (1984) that

$$\sigma_o = \left(\frac{\kappa}{nE}\right)^2 \frac{\pi}{N} P_m \qquad (2)$$

where n ($\approx$2) is a parameter which depends on Poisson's ratio and the specifics of the topography of the contacts. N is the areal contact density, $N = (4/\pi C^2)$. In the case of a fatigue crack, κ was found to be an exponential, $\kappa = \kappa_o \exp(-\beta x)$, where x is the distance to the crack tip. In this case, C appeared not to be a function of x. Consequently, σ_o decreases exponentially with x. Thus the picture of the contact in the closure region and the residual stress distribution for a fatigue crack grown in Al 7075-T651 at constant ΔK appear to be as shown in Fig. 1. The estimated peak value of σ_o is roughly 70% of the yield stress in this material. The results agree well with x-ray diffraction measurements by Welsch et al. (1987) in which the residual stress distribution in type 4140 steel near the crack tip in plane stress was determined. On the other hand, stereo-imaging in the scanning electron microscope (Davidson and Lankford, 1981; Davidson et al., 1983) in combination with a constitutive equation yielded peak stresses about 2.3 to 3.5 times the yield stress. This discrepancy is caused by the differences in spatial resolution and does not affect the following discussion significantly.

IV. CRACK TIP SHIELDING

As an asperity contacts the opposite fracture surface, the contact carries a normal load, P , which produces a stress intensity factor K_{IS} on the crack tip. As long as the contact exists, it "shields" the crack tip from the driving force due to the external load. K_{IS} has been calculated for a crack grown under constant ΔK conditions as described in Section III. An individual contact produces a stress intensity factor, K_{IS}, which is given by (Tada et al., 1973)

$$K_{IS} = \frac{2^{1/2}}{(\pi C)^{3/2}} P_s \frac{1}{[1 + (z/C^2]} \qquad (3)$$

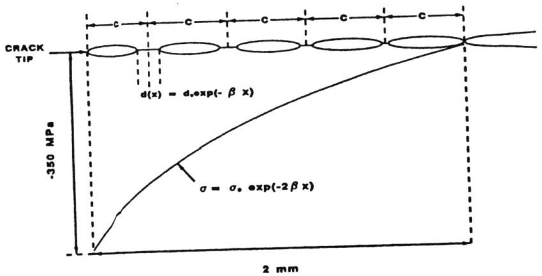

Fig 1. Schematic illustration of asperity contact and resulting residual stress profile.

where C is the nearest distance between the contact and the crack tip, and z is the coordinate along the crack front, as shown in Fig. 2. Assuming a square array of contacts, the superposition of the effects of a row of individual contacts along the crack front yields

$$(dK_I) = \left(\frac{2}{\pi}\right)^{1/2} \frac{(dP)}{BC^{1/2}} \qquad (4)$$

where $(dP/B) = \sigma_o(dx)$ is the load on a unit length of this row of contacts along the crack tip. For the fatigue crack described in Sections II and III, the effects of all contact rows can now be taken into account by an integration over the total closure region. Thus

$$\int_o^{\infty} (dK_I) = K_{sh} = \pi\left(\frac{\kappa_o}{nE}\right)^2 \frac{P_m}{N\beta^{1/2}} \qquad (5)$$

For this fatigue crack we find a numerical value of $K_{sh} \approx 6.8$ MPa $m^{1/2}$ which is about 40% of the cyclic stress intensity range ΔK (at R = 0.1) at which the crack was grown. Thus shielding is a significant fraction of the driving force on the crack. Assuming that the crack propagation rate da/dN is governed by the Paris law, one predicts

$$da/dN = B(\Delta K - K_{sh})^m \qquad (6)$$

if B and m are true materials parameters.

Deviations from a constant ΔK growth condition change the contact topology considerably. For instance, on a fatigue crack (Buck et al., 1987a) grown first at a constant ΔK ($\approx$14 MPa $m^{1/2}$), followed by an overload block (21 cycles) at $2(\Delta K)$ and subsequent cycling at ΔK, the spring stiffness κ not only showed the previously mentioned exponential decay but also an additional contribution to κ in the form of a peak, as shown in Fig. 3a, at a location where the overload was applied. At the time of the measurement the crack tip was roughly 6 mm to the left of the position of the overload region. Thus the effects of the overload are to produce an enhanced transmission. Empirically the data can be expressed by

$$\kappa(x) = \kappa_o e^{-\beta x} + \frac{\kappa_1}{1 + [2(x-\delta)/\gamma]^4} \qquad (7)$$

where δ is the distance between overload region and crack tip and γ ($\approx$ 1 mm) is the width of the overload region with $\kappa_1 \approx 3\times10^8$ MPa m^{-1}. The contribution of this spring stiffness peak to the shielding can be estimated by assuming a strip-like contact so that, from Eq. (4),

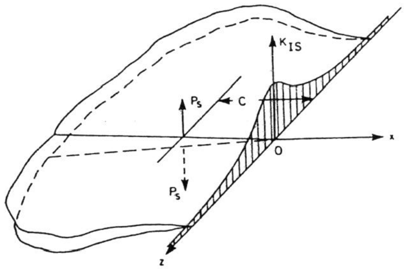

Fig. 2. Shielding stress intensity K_{IS} for a single asperity contact.

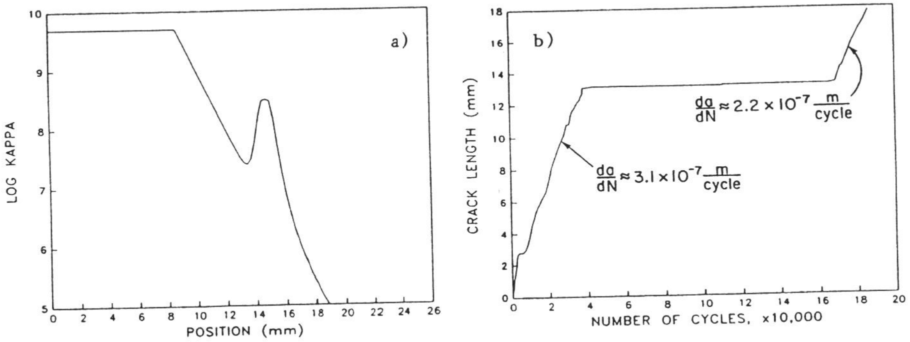

Fig. 3. a) $\kappa(x)$ as a function of x with overload contact. $\kappa(x)$ in MPa
b) Crack length vs. fatigue cycles before and after overload at about 40,000 cycles.

$$K_{ov} \approx \left(\frac{2}{\pi}\right)^{1/2} \sigma_o' \frac{\gamma}{\delta^{1/2}} \tag{8}$$

Assuming a contact pressure $\sigma_o' \approx (\kappa_1/\kappa_o)^2 \sigma_o$, as suggested by Eq. (2) and assuming N = constant, yields $K_{ov} \approx 1.2$ MPa $m^{1/2}$ for a total $K_{sh} \approx 8.0$ MPa $m^{1/2}$. Based on Eq. (6), the crack thus should grow slower than before overload application. Using $m \approx 3$ in the Paris equation, we estimate the growth rate to be about 70% slower. The actual growth data at this point were found to be about 50% slower, as shown in Fig. 3b, indicating satisfactory agreement. However, diffraction experiments will have to confirm the assumptions made.

V. THE STRENGTH OF A DIFFUSION BOND

Inadequate bonding conditions result in a reduction of the fractional bonded area A/A_o. In contrast to the discussions in Section IV, there will be no contact pressure in the finished product since the two pieces of material have, at least in part, grown together. The question is at what tensile stress, e.g., will the bond fail. First experimental results indicate that the "bond strength," here defined as the ultimate engineering stress at which the bond fails in tension, increases with A/A_o, and the spring model appears to apply, as shown by Palmer et al. (1988).

As indicated in Table I. the range of A/A_o achieved varies from low to high. Up to about 80% fractional bonded area the bonds failed (Palmer et al., 1988) with little indication of ductility (strain-to-failure < 1%). Viewing the disbonded areas either as penny-shaped or as circumferential cracks, one may try to employ LEFM to determine the stress intensity factor K_I at which the specimens fail in uniaxial tension. For penny-shaped cracks (Tada et al., 1973)

$$K_I' = \sigma_{bond} [A_o/A] \sqrt{\pi d/2}\, f'(d/C) \sqrt{1-d/C} \tag{9}$$

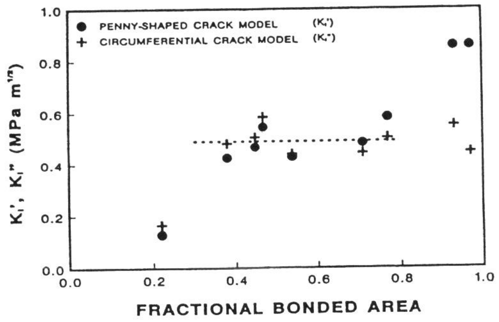

Fig. 4. Stress intensity factors for penny-shaped and circumferential cracks vs. A/A_o.

and for circumferential cracks (Tada et al., 1973)

$$K_I'' = \sigma_{bond} [A_o/A] \sqrt{\pi(C-d)/2}\, f''(d/C) \sqrt{d/C} \tag{10}$$

where f'(d/C) and f"(d/C) depend on A_o/A only and are related to the spring constant κ.

Application of Eqs. (9) and (10) over a large range of A/A_o yields the results shown in Fig. 4. To our surprise, both crack types yield a value $K_I' \approx K_I'' \approx 0.5$ MPa $m^{1/2}$ over a wide range of A/A_o except at the low and high ends. At the low end the model probably becomes inaccurate because the largest disbonds in the distribution dominate the failure. In specimens with large A/A_o, the ductility is quite large (strain-to-failures up to 20%) so that LEFM is clearly no longer valid.

These findings are now under further investigation since it is concluded that the model may indeed be appropriate, even at large A/A_o, for materials with low ductility of the bulk material. On the other hand, for diffusion bonds in materials with high ductility of the bulk material and large A/A_o, plasticity will have to be taken into account. The present results indicate, however, that two acoustic measurements to evaluate the contact geometry and a knowledge of K_I versus A/A_o would allow a calculation of the bond strength, using Eqs. (9) or (10), respectively.

VI. SUMMARY AND CONCLUSIONS

It has been shown that ultrasonic interrogation of a partially contacting interface can provide detailed information on the contact topology at the interface. Discussed are two completely different types of interfaces, fatigue cracks and diffusion bonds. In both cases acoustic response appears to be quite similar.

The discussions focus on deriving parameters which describe the mechanical properties of these interfaces. The geometry of the closure region of a fatigue crack has been characterized in terms of the contact topology yielding the shielding stress intensity factor which reduces the externally applied stress intensity range in fatigue. Overloads enhance the shielding and decrease the crack growth rate in qualitative agreement with the predictions. For diffusion bonds, preliminary results show that almost over the full range of bond qualities investigated a single stress intensity factor determines the bond strength. The observations thus indicate that using this stress intensity factor and performing two acoustic measurements may allow the calculation of the bond strength achieved.

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