SIMULATION OF CLOSURE: EFFECTS ON CRACK DETECTION PROBABILITY AND STRESS DISTRIBUTIONS

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ABSTRACT

It is well known that partial contact of two rough crack surfaces will lead to transmission of an acoustic signal across the crack, thus giving rise to a reduced probability of detection (POD). To explore the effects and consequences of such partial contact, impression experiments--using small spheres--have been performed to determine the effects of contact area on the amplitude transmitted. The results have been compared with a theory described elsewhere in these Proceedings. Based on the experimental results it will be speculated that the residual stress field responsible for the crack closure may be calculated based on a determination of the size and separation of the contact areas.

INTRODUCTION

In a previous paper,[1] the dynamics of crack closure during fatigue crack propagation has been investigated. From the experimental results obtained, it appeared that localized contact (partial contact) of two rough crack surfaces occurs. Between the contact areas, small voids remain open even if the crack is under zero external load. If a tension load is applied to the crack, the voids become bigger until the crack is fully open. They interfere with a probing ultrasonic wave. Particularly at zero external tensile load a crack of several millimeters in length and depth can become almost undetectable by ultrasonics since the voids may be quite small. Very little is known at present about the dimensions of these voids. Crack opening displacement (COD) measurements[1] on a Al 7075-T6 part-through crack specimen yielded an average height of about 1 to 5 μm. Experiments are now under way[2] to determine the width and distance between these voids. Analysis of pulse-echo data has shown that the transmission coefficient has the form

$$t = \left[1 + (\pi f \rho v/K)^2\right]^{-1/2} \tag{1}$$

where ρ is the density, v is the (longitudinal) sound velocity, f is the frequency and K is a distributed "spring constant" of the layer that makes up the crack (voids and localized contact areas). Using a two-dimensional model,[3] K is given by

$$K = \frac{E}{2\alpha s}\left\{1.071\left(\frac{1}{\alpha}\ln\frac{1}{1-\alpha} - 1\right) + 0.25\alpha - 0.357\alpha^2 + 0.121\alpha^3 - 0.047\alpha^4 + 0.008\alpha^5\right\}^{-1} \tag{2}$$

with $\alpha = \frac{s-w}{s}$

and w = width of the contact area

s = (average) distance between the centers of the contact areas (or, equivalently, the centers of the voids), and

E = Young's modulus of the material.

First measurements[2] have indicated that a frequency analysis of the transmitted signal (Eqn. 1) can yield information on K and therefore on the geometry of the localized contact. In order to improve our understanding of this localized crack closure phenomenon we have performed model experiments in which the geometry of the contact is known. First results, which are reported in the following, indicate that the above concept may not only be fruitful to determine the nature of the ultrasonic wave-crack interaction but may also yield information about the residual stresses that are set up in the wake of the crack tip and which may determine the "closure stress", which is that stress below which partial contact of the fracture surfaces comes about.

EXPERIMENTAL PROCEDURES AND RESULTS

The basic experiment is shown in Fig. 1. Fourteen steel spheres (D = 1.66 mm) were epoxied to a cylindrical steel block in a hexagonal closest packed arrangement. These spheres were then (plastically) pressed into a cylindrical, annealed Al 6061 block. Both blocks contained cavities into which transmitting (T) and receiving (R) 2.5 MHZ PZT transducers were mounted. The signal transmitted was then determined as a function of applied load and/or "projected" area A ($A = 14\pi d^2/4$ with d = diameter of the projected contact area) which was determined under a microscope. Fig. 2 shows the projected area versus applied load relationship and Fig. 3 the transmitted signal amplitude (A_T) as a function of applied load and projected area as obtained in two separate experiments (qualitative differences are due to differences in transducer coupling to the test blocks). As can be seen from

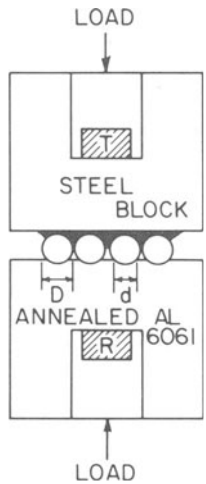

Fig. 1. Experimental set-up.

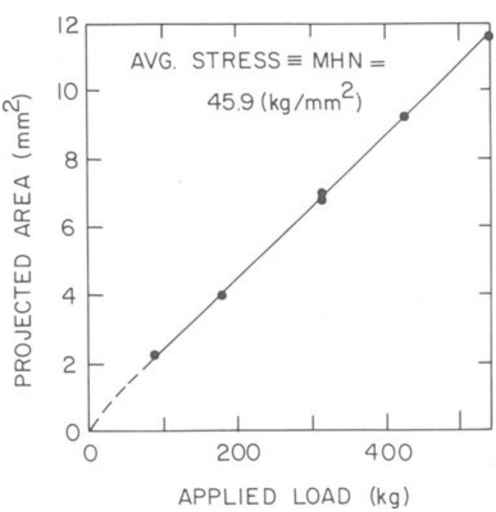

Fig. 2. Projected area versus applied load.

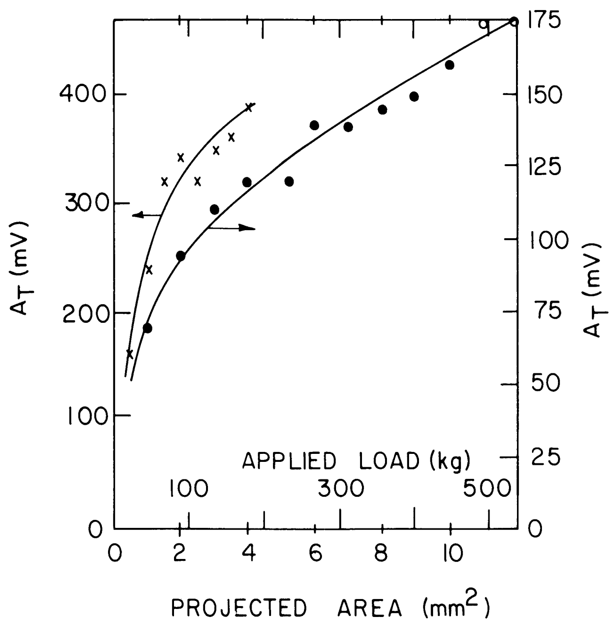

Fig. 3. Transmitted amplitude, A_T, versus applied load and projected area.

Fig. 2, the average stress (applied load over projected area) is basically constant over the total load range (except at small loads where elasticity dominates the contact). Fig. 3 demonstrates that A_T is not simply a linear function of contact area which is not surprising in view of Eqns. 1 and 2.

The above experiments have certain similarities to a "hardness testing" experiment, in which severe plastic deformation is induced in the material under investigation. To obtain an idea about the strain hardening of the annealed Al 6061, we conducted a uniaxial tensile deformation test, the results of which are shown in Fig. 4. It is quite obvious that this material strain hardens strongly and yet the projected area versus applied load results does not indicate any significant effect of the strain hardening. Possible consequences of this observation will be discussed later.

DISCUSSION

In Fig. 5 we have plotted the transmission coefficient, t, as derived from Eqns. 1 and 2, as a function of w/s. We have also

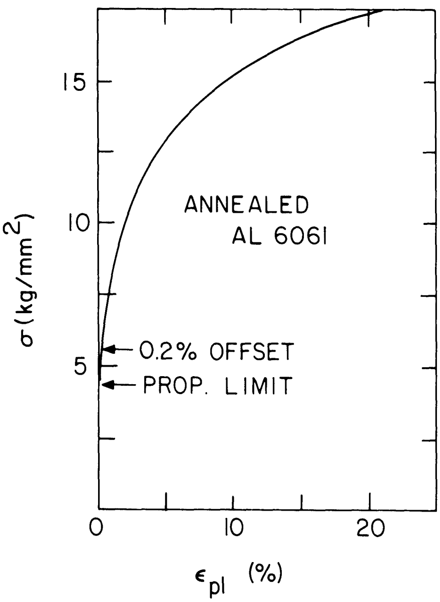

Fig. 4. Stress-strain curve of annealed Al 6061.

replotted the measured values of the normalized transmitted amplitude, A_T (lower curve in Fig. 3), against w/s where w = d, the diameter of the impressions and s = D, the diameter of the spheres. The normalization of A_T was performed at w/s = 0.4. As can be seen from Fig. 5, there is qualitative agreement between theory and experiment. We believe the agreement can be improved in that the theory has been developed for a one-dimensional contact area model, whereas the experiments have been performed for a two-dimensional model. In other words, for the present experimental set-up, K has to be rederived to correspond to the actual situation.

On the other hand, we may make the simple assumption that the probability of detection (POD) in transmission increases with decreasing contact area as

$$POD = (1 - t)\ 100\% \quad . \tag{3}$$

Fig. 5, therefore, also contains information about the functional relation of POD versus w/s.

The observation that the projected area versus applied load is basically constant (see Fig. 2) led us to an interesting

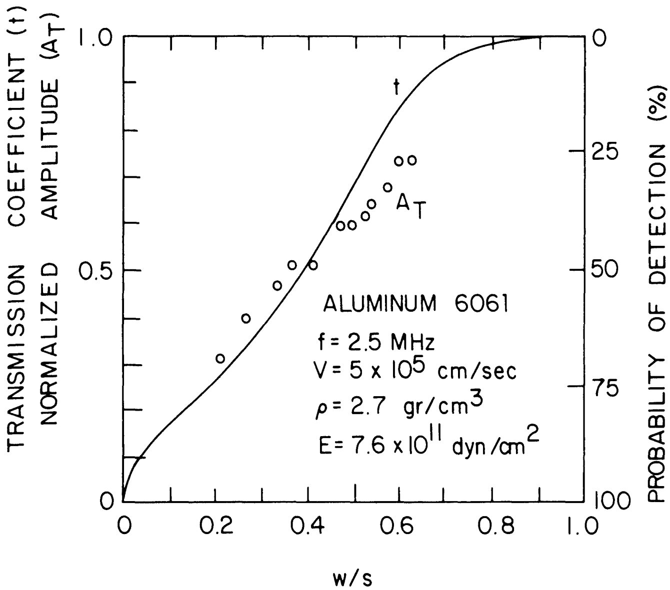

Fig. 5. Transmission coefficient (theory), normalized amplitude in transmission (experiments) and probability of detection versus amount of contact.

speculation. As indicated in Fig. 2, the average stress over the projected indentation area was constant (45.9 kg/mm^2). This stress is the definition of the "Meyer hardness number", MHN. In contrast, the "Brinell hardness number", BHN, is defined by applied load over the actual contact area between sphere and the investigated material. As shown in Fig. 6, BHN decreases with increasing d/D, whereas MHN remains basically constant.[4] At small d/D, BHN = MHN and at d/D = 1.0 (half the sphere is pressed into the tested material), BHN = 1/2 MHN. The change of BHN with contact area thus is strictly a geometrical effect. In contrast, MHN does not depend on geometry and, as shown in Figs. 2 and 4, MHN also does not depend on the state of strain hardening. Applying now the MHN concept to a fatigue crack, we may develop the following picture. Assume, as shown in the lower part of Fig. 7, that there is a crack with partial contact. Let us also assume that the contact width (w) and the average distance (s) between the contact areas changes with distance away from the crack tip. Each contact area then carries a stress that is equal to the MHN of the material, even if the material has undergone severe plastic deformation during fatigue crack propagation. Using a stress concentration factor, appropriate to the contact geometry, we will then

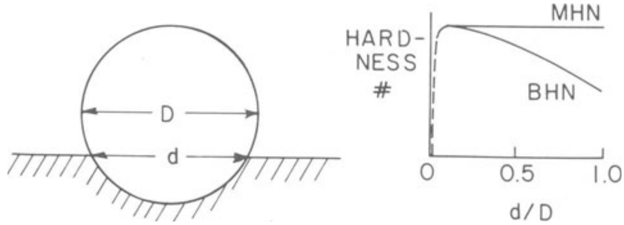

Fig. 6. MHN and BHN as a function of d/D.

be able to estimate the "residual stress", $\sigma_{residual}$, in a sheet of material which is parallel to the fracture surface. Suppose, e.g., that $w_1 > w_2 > w_3$ and $s_1 \approx s_2$, the residual stress will drop off as schematically shown in the top part of Fig. 7 for two different contact geometries.

SUMMARY

The experiments, discussed above, have been designed to help us understand the nature of partial contact of fatigue cracks and its effects on the probability of crack detection which could lead to an erroneous crack sizing and remaining life prediction of a component.[5] With certain experimental modifications, it should also be possible to simulate the angular dependence of the transmitted acoustic energy and to relate the results to the distance between the contacts.[2] In addition it seems possible that the acoustic measurement of partial contact may lead to a quantitative description of the residual stresses in the wake of a crack. These residual stresses have to be overcome to open the crack fully and thus are related to the crack closure or crack opening stress[6] which is a quantity that affects the driving force on a fatigue crack strongly.[5]

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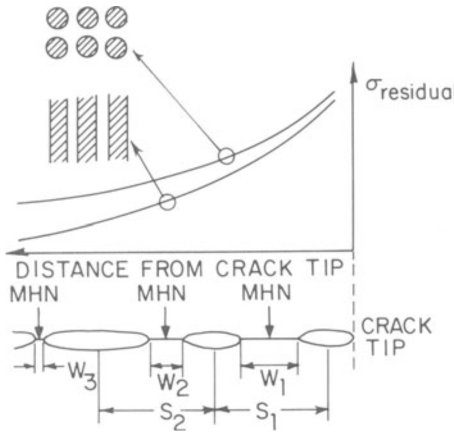

Fig. 7. The probable residual stress distribution in the wake of a crack tip, based on localized contact models.

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