ON CRACK CLOSURE AND CRACK TIP SHIELDING DURING FATIGUE CRACK GROWTH

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INTRODUCTION

Fatigue crack growth can be strongly influenced by crack closure, i. e., the contacting of the opposing faces of a fatigue crack above the minimum load in a loading cycle. This crack closure shields the crack tip from the full stress field, but different views are held regarding the extent of this shielding. The type of closure, whether it be plasticity-induced, or roughness-induced may also play a role. According to Elber, who considered plasticity-induced closure, the crack is effectively closed as soon as the first detectable closure is developed in the wake of the crack tip. However, Otto Buck and his colleagues, who used ultrasonic waves to investigate crack closure, have been in the forefront of those who claim that the crack tip continues to close even after the first closure contacts have been made, thereby leading to a lesser degree of shielding than in Elber's view. The purpose of the present paper is to review the extensive work in the area highlighting the ultrasonic approaches as well as the current state of the art concerning crack closure, and to discuss the various views concerning the extent of shielding provided by crack closure.

In the 1970s when Elber [1,2] first conceived of the concept of crack closure Otto Buck and his co-workers [3-11] were using ultrasonic approaches to follow fatigue crack growth in structural alloys. The ultrasonic signatures clearly showed direct evidence for crack closure and the continuing closing of the crack as the load was reduced after closure was first observed. Fatigue crack growth ahead of the propagating crack is dominated by the cyclic plastic deformation that occurs ahead of the propagating crack. The mechanics of the crack opening is such that a crack is not completely open under a tensile load unless a critical crack closure stress is exceeded. The crack closure phenomenon has the effect of reducing crack propagation rate by reduction of the range in stress intensity,

$$\Delta K = K_{max} - K_{min}, \text{ [12]} \qquad (1)$$

to what is defined as the effective range in stress intensity,

$$\Delta K_{eff} = K_{max} - K_{clos} \text{ [1,2]} \qquad (2)$$

The definition of cyclic crack closure stress intensity factor, K_{clos}, and the effective range in stress intensity can becomes an important factor in the assessment of crack growth processes. It is then used to define aspects of the influence of other factors such as environment, load ratio, maximum load and load spectra on fatigue crack growth. The an important role[10,11].

In the following the results of a wide range of experimental results and models are presented to try to describe the history and to establish the state of art of the crack closure concept THAT was extended to the study of fatigue in short cracks where it has an effect of closure on fatigue crack growth behavior. The regimes investigated will

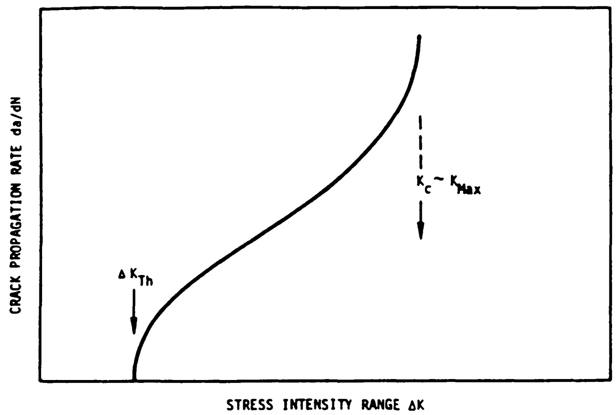

Figure 1. Typical dependence of crack propagation rate upon stress intensity range [8].

be related to the fatigue crack growth representation where crack growth rate per cycle, da/dN, has a sigmoidal shape, Fig. 1[8], when log-log plotted against stress intensity range, ΔK. The extensive literature on the mechanical and finite element modeling of crack closure will not be discussed.

CRACK CLOSURE CONCEPT AND MEASUREMENT

Elber [1,2] first introduced the effective stress intensity range, ΔK_{eff}. Crack closure under tensile loads is expected when the fracture surfaces touch and the stress singularity is eliminated on the low load portion of the fatigue cycle. The definition of Keff is illustrated schematically in Fig 2 [8] where apparent crack length is plotted as a function of instantaneous cyclic load. Po is the "crack closure load." For an applied load less than Po the crack tip is closed. The effective stress intensity range of ΔK_{eff} is then defined to be K(Pmax) - K(Po). Crack growth is then only influenced by loads in excess of Po.

The regime of plastic strains developed near a crack tip is schematically illustrated in Fig. 3 (8). The regions of RF and RR are the forward and reverse plastic zones, respectively, and the region marked δ_o is the residual material on the crack surface that

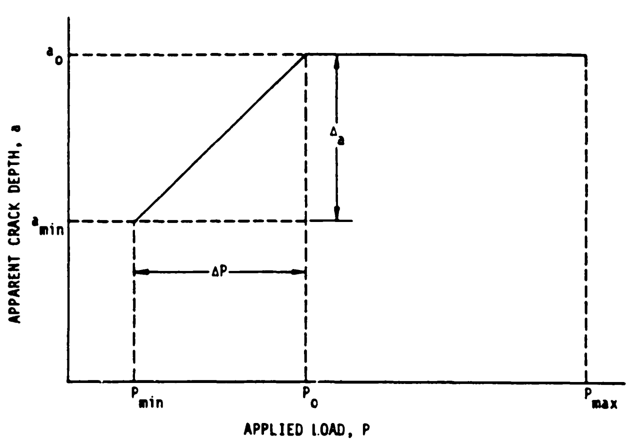

Figure 2. Apparent crack depth as a function of applied load from P_{min} to P_{max}. Crack is closed for loads less than P_o[8].

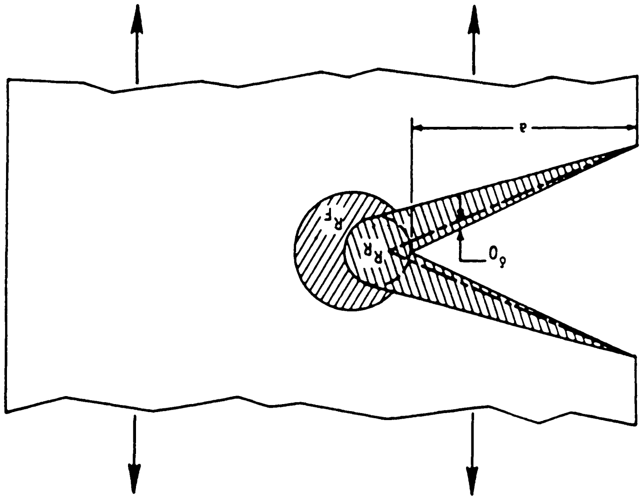

Figure 3. Representation of near crack tip deformation zones and residual strain. R_F and R_R are forward and reverse yielding zones [8].

results in the closure taking place at the low loads in a tensile loading condition. There is a variety of effects that lead to this residual "strain", and the magnitude is different for the various contributions. Depending on the loading conditions and the environment that the load is applied in, the material that leads to closure can come from the rms of the surface (probably crack tip plasticity produced) from an oxide formed on the surface, from wear/fretting powder produced by the fatigue cycling (in particular at low ΔK) from Mode II displacements and from the actual introduction of dislocations during the deformation.

Buck and co-workers have found that ultrasonic techniques are effective as an approach to measuring the crack growth closure effect. Elber's approach was to use a displacement(strain) gauge directly in front of the crack tip. Others have use the clip on gage at the mouth tip of a compact tension specimen to record the load displacement The ultrasonics has the advantage of giving additional information other then Po. Another approach to probe closure was using electrical resistivity [14] where the path length changed as the crack closed, reducing the resistivity measured from the crack origin. This did have the disadvantage when a resistive oxide was present that the change would not be observed. The ultrasonic measurements were made on both part through crack (PTC) specimens [3,4] using surface wave techniques and with the compact tension (CT) specimen geometry using bulk acoustic waves, Fig. 4[8]. The determination of the crack closure load is when the received acoustic signal starts to change. This crack closure load, Po, is not uniquely defined and is one of the difficulties in interpreting the data for all approaches used. A significant aspect to the lack of a clear definition of Po is that you are dealing with a surface operating in plain stress and an interior of the crack tip operating in plane strain condition that often results in a curved crack front and with much greater closure at the surface [15-17]. Extrapolation of the two segments of the experimental curves is used to define Po. Another aspect of this phenomena is described as diffraction of the acoustic wave by the crack tip and asperities [9].

One other factor that impacts the acoustic closure signal measurement is the acoustic energy transmitted through a rough surface. To characterize this [9]) Buck and co-workers made up blocks of aluminum with controlled roughness and determined the energy transmitted vs applied stress for a wide range of surface roughness using a solid block as the reference signal. It was clearly shown that a reasonable load must be applied to get the transmission thereby resulting in a less then well defined external load for initial load transfer contact. Use of these results ended with a model defining the integrated load acoustic energy transfer for a given roughness of a crack surface.

Another aspect of the acoustic probing of the fatigue crack growth behavior is the impact of environment on the crack growth rate. In a study of Al 2024 where the fatigue

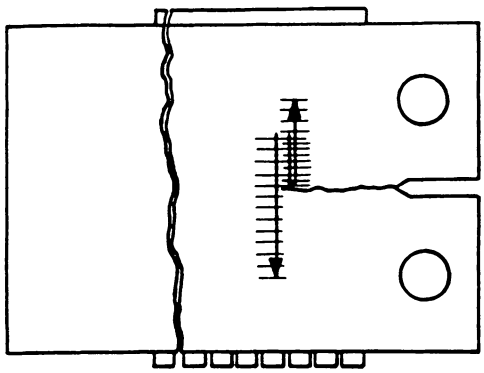

Figure 4. Sketch of bulk wave generator-detector on a compact tension, CT, specimen used to determine crack closure [8].

crack growth was run in dry nitrogen and moist air (~50%RH) a large increase in fatigue crack growth rate was observed. Similar results were observed in Al 7075 [7]. When the data was plotted in terms of the crack closure load and the resultant ΔK_{eff} the data was reduced to one curve. This result has not been universally obtained [27]. What this implied was that the environment reduced the roughness of the surface by reducing the amount of plasticity before failure, but that the mechanics of the crack growth were the same. The reduced plasticity could be a result of surface chemical reaction, so it physically separates at a much lower strain the environment is introduced directly into the specimen during forward and reverse yield cycling by a "dislocation sweep-in" mechanisms resulting in reduced local ductility. Studies of the impact of hydrogen on the crack closure in nickel base alloys could not be explained in terms of ΔK_{eff} but were associated with a change in the fracture mode from transgraular to intergranular,.

Overload and Shielding Effects Related to Crack Closure

The influence of overloads on the constant amplitude loading fatigue crack growth rate have been studied by many investigators. The introduction of a single overload or multiple overloads results in a significant reduction or delay of the crack growth. The acoustic measurements by Buck and co-workers [7] showed that the crack did not fully open under subsequent loading. They explained this behavior by the increased δ_0 due to the larger plastic zone associated with the overload. This explanation has been challenged by McEvily and co-workers [15-18]where he demonstrates that there are two crack opening loads and that the upper one is only associated with the plane stress region near the surface of the sample. When the surface layer of material is removed from a specimen much thicker then the plastic zone the retardation effect in the plane strain region is almost totally removed. The removal of the plain stress plastic zone from the surface by either machining or by EDM eliminates the upper crack closure level. This evidence and other results [15-17] leads to the conclusion that the primary cause of crack growth decay is due to the surface plane stress overload zone and not associated with the majority of the crack front that for a thick specimen is in plane strain.

It should be noted that in all cases described to now there is crack tip shielding, defined as the reduction in the nature and magnitude of the stress intensity factor due to a physical interference from the elastic solution. Asperities are described in the terms of shielding by Buck et.al. [13]. Many other shielding contributions are defined throughout the literature [15-23].

LOADING BELOW CLOSURE LOAD

Other investigators have also considered the load range below Kop may be of significance in propagating a fatigue crack. A number of investigators have found that underloading can crush the asperities and reduce the roughness level and thereby increase Keff so that an arrested crack may begin to propagate again. Such experiments were carried out by Zaiken and Ritchie [20] for example, who also found that Kop values were indeed reduced following the compression underload. Zaiken and Ritchie [20] on 7070 Al and Yu [22] on 2090 Al-Li alloys grew cracks down to the threshold at R = 0.05, and in one case R = 0.7, and then subjected them to a single compression overload. The compression acted to crush the asperities, and the arrested threshold cracks then started to propagate again until they rearrested once a new steady-state closure wake zone had been established. Concurrent with these transient growth-rate measurements closure values show that Kcl values were indeed reduced following the compression overload.

CRACK CLOSURE AND SHORT CRACKS

Another aspect of the impact of crack closure on fatigue studied by Buck and co-workers was the importance of closure on the crack advance of sub-grainsize short cracks [10,11, 24,25]. In this case they clearly showed that closure exists and works in a manner similar to large cracks until the crack approaches a grain boundary which reduces further growth. They also describe a model for coalescence of multicracks that then become the primary crack that induces the fatigue failure. Initiation sites were at an intermetallic in an aluminum allow showing the crack at the surface. These observations were made directly in samples fatigued in an SEM. The crack opening of the crack after growth when the load was removed supported the presence of plasticity induced crack opening at the crack tip and the corresponding crack closure.

SUMMARY

This paper has discussed a broad range of experimental results relating crack closure to fatigue crack growth behavior. It is clear that some of the pioneering research in this area was done by Otto Buck. His many contributions to the field will have an impact for a long period of time.

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