ON CRACK CLOSURE IN FATIGUE CRACK GROWTH

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The nature and the significance of fatigue crack closure are discussed. It is concluded that although a continuum type of plasticity-induced closure can occur under plane stress conditions, under plane strain conditions plasticity-induced closure can occur only upon the application of an overload. Roughness-induced and oxidation-induced closure are both of significance in the near-threshold region. Examples of the use of closure concepts to explain phenomena such as anomalous crack growth, overload effects, and notch size effects are given.

INTRODUCTION

Ever since Elber's discovery (1,2) of crack closure during fatigue crack growth there has been considerable interest in both the nature and the significance of the closure process. Initially crack closure was related to a residual stretch of material in the wake of a growing crack, with contact of this stretched material being made above the minimum load of the cycle to bring about the crack closure phenomenon. More recently, as reviewed by Suresh and Ritchie (3) and by Gerberich (4), a number of additional processes are now recognized as also contributing to the crack closure process. The growing list now includes:

(1) Plasticity-induced closure

(2) Roughness-induced closure brought about by the mismatch of peaks and valleys on opposing sides of

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the fracture surface especially near threshold,
(3) Oxide-induced closure due to the formation of thick oxide films on the fracture surfaces. The thickness of these oxide films may be enhanced by fretting due to the rubbing of the fracture surfaces, and this in turn may lead to the formation of debris particles on the fracture surface which also contribute to crack closure. The presence of a viscous liquid within the crack may also prevent the crack surfaces from coming together.
(4) Transformation-induced closure due to a stress-induced phase transformation at the crack tip which involves an increase in volume and which leads to enhanced closure in the wake of the crack tip.
(4) Ligament-induced closure which occurs in certain two-phase alloys wherein one phase is more susceptible to cracking, thereby leaving behind the crack tip ligaments which initially keep the crack from fully opening before they rupture, and later gives rise to a form of roughness-induced closure after they have ruptured.
(5) In addition to these forms of closure another type of closure occurs on reduction of the mean stress level as with a reduction in ΔK at a constant R or on reduction in R at constant ΔK.

An important feature of the crack closure process is that no matter which specific controlling closure mechanisms may be operative, only the range of K above the crack opening level provides the driving force for crack advance. This driving force was designated as Keff by Elber, and was introduced by him to explain the influence of mean stress and overloads on the rate of fatigue crack growth. In addition to the topics treated by Elber, other aspects of the fatigue crack growth process are now known to be also influenced by closure, and a more complete listing of the various topics is as follows:

(a) The effect of R-ratio on the rate of fatigue crack growth
(b) The retardation in the rate of fatigue crack growth following an overload
(c) The fatigue notch-size effect and fatigue notch sensitivity
(d) Transient crack growth phenomena associated with changes in R or ΔK, and
(e) The so-called anomalous fatigue crack growth behavior of short cracks

In the remainder of this paper examples will be given to illustrate the relative importance of the various closure processes in understanding the phenomena listed under (a) to (e) above.

PLASTICITY-INDUCED CLOSURE

The residual stretch of material in the wake of the crack tip associated with plasticity-induced closure is generally viewed as a continuum process related to the size of the plastic zone at the crack tip which is a function of the yield stress and ΔK. Under plane stress conditions one can understand why such a closure process should occur, for in this case there is a lateral contraction of the material in the plastic zone at the crack tip. This lateral contraction results in the transport of material into the subsurface region, and it is this excess of material which gives rise to crack closure in the wake of the crack tip. Under plane strain conditions however the situation is quite different, for now there is no lateral movement of material since the strain in the thickness direction is zero, and therefore there should be no crack closure since there is no additional material behind the crack tip. To emphasize this point, consider a crack growing under constant ΔK conditions completely across a compact specimen. If plasticity induced closure occurred there would have to be an increase in volume of the material over the entire crack surface, but since there is no source for such a volume increase it can be concluded that under plane strain conditions plasticity-induced closure does not occur. This is not to say that closure does not occur under plane strain conditions, but rather that when plane-strain closure is observed under constant amplitude conditions, the source of closure must be some process other than the continuum type of plasticity-induced closure.

To illustrate that plasticity-induced closure is absent under plane strain conditions, consider the results shown in Fig. 1 which were obtained by Minakawa et al. (5). The material tested was a mechanically-alloyed aluminum alloy of a grain size in the sub-micron range. The thickness of the specimens was 6.25 mm, the yield strength 530 MPa, and it is considered that the specimens were tested under essentially plane strain conditions in the near-threshold region. If plasticity-induced closure were occurring under these test conditions we should expect to see an influence of R-ratio on the rate of crack growth. The absence of such an influence provides an experimental verification that plasticity-induced closure does not occur under plane strain conditions. In addition, closure was not detected in these tests.

Under overload testing conditions in plane strain, in contrast to constant amplitude conditions, plasticity-induced closure may occur and influence the retardation process. In fact the results of Matsuoka and Tanaka (6) indicate that in high strength materials the plane strain regions may contribute more to retardation than the surface regions. During the overload material is moved ahead of the crack tip in the plane strain regions as indicated by the blunting of the crack tip. As in the case of plane stress the size of the overload plastic zone is increased, and as the compressive stresses associated with this plastic zone relax when the crack advances, a bump will form on the fracture surface which results in plane strain closure. Such a process has been discussed by Fleck (7). These continuum considerations concerning plane strain may also be applicable near threshold, where plane strain conditions predominate. For example, although Shin and Fleck (8) were unable to detect any change in the crack opening level of a 25.4 mm thick, medium strength steel specimen after it was subjected to a 100% overload near threshold, nevertheless they considered that plasticity-induced crack closure may have contributed to the observed retardation, but with the level of additional closure being below the limit of detection. Certainly at threshold a small change in Keff would be particularly significant because of the high sensitivity of the crack growth rate to ΔKeff in the threshold region.

Under plane stress conditions on the other hand there is ample evidence that plasticity-induced closure does occur under both constant amplitude as well as variable amplitude loading conditions. For example, from the results of Broek and Schivje (9) shown in Fig. 2 it can be inferred that as the specimen thickness is reduced the rate of fatigue crack growth is also reduced due to the increasing importance of the plane stress closure process with decreasing thickness.

A further example due to McEvily and Minakawa (10) is given in Fig. 3 which indicates the effect of an overload on the subsequent rate of fatigue crack growth under constant ΔK conditions. The crack growth behavior of the crack at the surface as well as beneath the surface is shown. The results for the surface region are based upon direct observation of the crack, whereas the results for the sub-surface region are based upon a detailed examination of the fatigue striations present upon the fracture surfaces. It is noted that a pop-in event associated with the overload resulted in a large crack growth increment in the subsurface (plane strain) region, and as a result the shape of the crack front was quite curved immediately following the overload. The blunting of the crack tip by the overload resulted in a decrease in the closure level, and an initial increase in the crack growth rate at the surface.

Measurements of the crack opening levels for the surface region were also obtained with the aid of strain gages mounted on the surface of the specimen. Crack opening levels were obtained for the interior region with the aid of a displacement gage mounted at the crack mouth. The results of the measurements are also shown in Fig. 3. It is noted that in the vicinity of the region of maximum surface retardation the closure level is at a maximum, i.e., the value of ΔK_{eff} is at a minimum. The closure level for the interior is initially reduced below its steady state value and then rises gradually as the crack advances. This initial drop is largely due to the blunting of the crack tip due to the overload, although as the crack advances there may also be a contribution from the heavily stretched surface region which tends to prop open the plane strain portion of the crack front. The cause of the increase in closure in the plane stress surface regions as the crack penetrates the overload plastic zone is due to the fact that the overload induces an increase in the size of the region ahead of the crack tip within which lateral contraction occurs, and within which compressive stresses are consequently developed on unloading. As the crack penetrates this region these compressive stresses are relaxed over the larger overload plastic zone, giving rise to an increase in the extent of the plasticity-induced crack closure level in the wake of the crack and the consequent reduction in ΔK_{eff}.

Vecchio et al. (11) have shown that the extent of retardation following an overload depends upon the ΔK level at which the overload is applied as well as specimen thickness, and a U-shaped plot results if the the number of delay cycles is plotted against the overload plastic zone size divided by the thickness, B, as indicated in Fig.4 for a 100% overload. In this case the overload plastic zone size is defined as $K_{OL}^2/2\pi\sigma_y^2$. We can understand the basis for this U-shape in the following way. Assume that R is zero, and that the rate of crack growth can be expressed as

$$\frac{da}{dN} = A(\Delta K - \Delta K_{TH})^2 \qquad (1)$$

Assume further that Elber´s estimate of the crack opening level for plane stress for R = 0 conditions is applicable under pure plane stress conditions, i.e., Kop is 1/2 of Koverload. However, the specimen is not under pure plane stress because in general the size of the overload plastic zone is less than the specimen thickness, B. To account for thickness effects we assume that the excess crack closure due to the overload can be expressed as

$$\text{Excess Closure} = \frac{K_{OL}}{2}\left[1 - exp\left(-\frac{K_{OL}^2 - \Delta K^2}{2\pi\sigma_y^2 B}\right)\right] \qquad (2)$$

To simplify the analysis assume that the excess closure is constant throughout the overload plastic zone. Under constant ΔK cycling the crack growth rate will then be constant throughout the overload plastic zone, and the number of delay cycles, N_d, involved in traversing this zone will be given as

$$N_d \propto \frac{K_{OL}^2}{\left\{\Delta K - \frac{1}{2}K_{OL}\left[1 - exp\left(-\frac{K_{OL}^2 - \Delta K^2}{2\pi\sigma_y^2 B}\right)\right] - \Delta K_{TH}\right\}^2} - \frac{K_{OL}^2}{(\Delta K - \Delta K_{TH})^2} \qquad (3)$$

This function is plotted in Fig.4 and is observed to have the desired U-shape. This is obviously an overly simplified treatment which emphasizes the importance of the surface regions, but even if plane strain closure were important near threshold a similar rise in the number of delay cycles near threshold is expected because of the aforementioned sensitivity of the fatigue crack growth rate to closure in this region.

ROUGHNESS-INDUCED AND OXIDATION-INDUCED CLOSURE

Under plane strain conditions, as indicated above, plasticity-induced closure in the absence of an overload is not expected to occur. However there is ample evidence particularly in the near threshold region that closure does occur under plane strain conditions. It is now recognized that this closure is due to the mismatch of asperities on the opposing fracture surfaces during unloading, and that Mode II deformation contributes to the development of the asperities and to the mismatch. This type of closure is known as roughness-induced closure. Additionally, if oxide films form which are of significant thickness with respect to the crack tip opening displacement, there will be a further contribution to closure.

The magnitude of roughness-induced closure is dependent on the microstructure and slip mode. In ultra-fine microstructures as in the IN-9021 alloy discussed above, roughness-induced closure was not detected, but this is an exceptional case, and in general roughness-induced closure does occur. For example, in planar glide materials such as high strength aluminum alloys of grain size greater than ten microns, the closure level near threshold may be 80% of Kmax at R=0 as in the case of a 7090-T6 alloy (5). In view of the importance of roughness induced closure some recent work has been directed at the measurement of the surface roughness. For example, Fig.5 shows the effect of roughness on the closure level as a function of the parameter $\bar{H}$, where $\bar{H}$ is the standard mean height deviation, as determined by Hamberg et al. (12). In their study no significant influence of the ΔK level on roughness was found, and Kop was expressed as

$$K_{op} = 1.2\,\bar{H}^{1/3} \tag{4}$$

Roughness determinations have also been made by Park and Fine (13), and by Kemper, Weiss and Stickler (14). It is of interest that in all cases the roughness levels are in the range of 20 microns, a magnitude which is generally much greater than the computed value of the crack tip opening displacement at threshold which is of the order of 0.1 micron.

In the study carried out by Kemper, Weiss and Stickler (14) the influence of mean stress on surface roughness at threshold was investigated, and their results for the aluminum alloy 2024-T3 are shown in Fig. 6 . The variation of Kop as a function of Kmean for this alloy is also shown in Fig. 6, and it is seen that the roughness and Kop follow the same trend with mean stress. It is noted that as the minimum stress enters the compression range both the roughness level as well as the Kop level decrease, but even at the lowest Kmin values the roughness still persists, and Kop remains at a positive value. If we attempt to predict Kop from the roughness values in Fig. 6 for the 2024-T3 alloy using Eq.4 which was established for steels, the value is overestimated by a factor of 3. It is noted that since the elastic modulus for aluminum is 1/3 that of steel the ΔK value needed to obtain a given elastic displacement would be 1/3 that needed for steel which may provide an explanation for the discrepency. Eq. 4 might then be rewritten as

$$K_{op} = 1.2\,\frac{E_{Al}}{E_{Steel}}\,\bar{H}^{1/3} \tag{5}$$

However, further work on this point would be desireable.

The variation of the closure level as a function of ΔK in the near threshold region is shown in Fig.7 for several steels (15). These Kop values were determined in air and in vacuum. In vacuum the Kop level is independent of ΔK near threshold, whereas in air in the less oxidation resistant steels there is a contribution to closure in addition to roughness which is due to the formation of thicker oxide films near threshold which are associated with fretting. At elevated temperatures heavy oxidation of the fracture surfaces has been observed to increase the closure level to a much greater degree as is to be expected (16).

An overload can also contribute to an increase in roughness if the crack branches (deviates) from its normal path during the overload or subsequently in order to bypass the overload zone. Such a deviation has been observed by Lankford and Davidson (17) at the surface of a 6061-T6 aluminum alloy tested at a base ΔK of 10 Mpa$\sqrt{m}$ at R = 0.2 and subjected to an 80% overload. Suresh and Vasudevan (18) observed that even at mid-thickness of a 6.25 mm thick specimen of the aluminum-lithium alloy 2020-T651 tested at a baseline K level of 7.7 Mpa$\sqrt{m}$ and subjected to a 180% overload that crack deviation occurred after the overload. Ventkateswara Rao and Ritchie (19) subjected the aluminum-lithium alloy 2090-T8E41 to overloads and observed that marked surface crack deflection along shear bands occurred, but such crack deflection did not occur in the interior. Shin and Fleck (8) found that for a structural steel the crack did not branch at the surface after an overload. It appears therefore that the tendency for the crack to branch during or after an overload is a function of microstructure and the peak stress intensity reached during the overload. Shin and Fleck (8) also concluded that neither the crack profile at overload nor the fatigue precracking operation prior to the application of the overload have a significant influence on the retardation behavior since both notched as well as pre-cracked specimens exhibited similar delayed retardation behavior after an overload.

SIGNIFICANCE OF CLOSURE

It is clear that crack closure is largely responsible for the R-dependency of the crack growth rate, as well as for overload retardation effects. The acceleration of a crack after an underload can also be understood as being due to a reduction in closure load due to a decrease in roughness as in Fig.6. It is also clear that surface induced roughness will have its greatest influence on the rate of fatigue crack growth under R = 0 loading conditions.

The growth behavior of short cracks from notches is also influenced by crack closure, and in particular by the rate of development of closure in the wake of a newly formed fatigue crack. When the crack first forms there is no closure, but as the crack extends closure develops as indicated in Fig.8 (20)(21). The closure level as a function of crack length can be expressed as

$$K_{op} = (1 - e^{-kl})\, K_{opmax} \tag{6}$$

where l is the length of the crack in millimeters, k is a material constant expressed in reciprocal millimeter units, Kop is the opening level in the transient, and Kopmax is the opening level for the macroscopic crack. For the materials of Fig.8 a wide range of k values were determined as indicated.

As a newly initiated fatigue crack grows through the transition region before closure is fully developed, two opposing influences affect the driving force for crack propagation. One is the increase in crack length which increases the driving force, the other is the increase in closure which decreases the driving force. These tendencies strongly affect the so-called anomalous type of fatigue crack growth behavior shown in Fig.9 which is characterized by growth below the macroscopic threshold as well as the development of a minimum in crack growth rate at low ΔK values. This behavior can be understood in terms of the development of closure in the wake of the newly formed crack.

ΔKeff can be defined for a material for which the opening level is independent of the ΔK level such as the 9Cr-1Mo alloy as

$$\Delta K_{eff} = \Delta K - (1 - e^{-kl})(K_{opmax} - K_{min}) \tag{7}$$

The rate of fatigue crack growth is assumed to be given by

$$\frac{da}{dN} = A_1 (\Delta K_{eff} - \Delta K_{effth})^2 \tag{8}$$

and this expression can be written with the aid of Eq. 7 as

$$\frac{da}{dN} = A_1 \left[\Delta K - (1 - e^{-kl})(K_{opmax} - K_{min}) - \Delta K_{effth}\right]^2 \tag{9}$$

The curves shown in Fig.9 were calculated based upon Eq. 9 with Kmin equal to zero, and with $A=2\times10^{-7}$ for da/dN in mm/cycle, Kopmax = 2.4 MPa$\sqrt{m}$, and ΔKeffth = 3.2 MPa$\sqrt{m}$. It is noted that a non-propagating crack is predicted to form at the lowest initial stress intensity factor range shown, and in fact this was experimentally observed.

A similar type of analysis has been employed to explain why the shorter the initial length of a crack the higher the initial rate of fatigue crack propagation (22). Short cracks grow more rapidly than long cracks because the rate of increase of ΔK with increase in crack length is larger for short cracks and this effect offsets the increase in closure which is taken to be independent of crack length. The fatigue notch-size effect and fatigue notch sensitivity have also been related to the development of closure making use of the type of analysis indicated above (23). For example, Fig.10 indicates that the stress to propagate a crack from a notch at a constant rate of 10^{-8} mm/cycle passes through a maximum for a small stress raiser as closure develops and the stress intensity factor changes from an initial value on the $\Delta Keffth$ line to a final value on the Kth line. Note that the peak stress required is higher the smaller the size of the initial stress raiser (in this case a circular hole), which accounts for the notch size effect. If the initial stress is below this maximum a non-propagating crack may form as demonstrated by El Haddad et al. (24). It also follows that the smaller the effects of closure the higher the fatigue notch sensitivity will be.

The effect on the rate of crack growth of a reduction in R at constant ΔK is shown in Fig.11 (25). The transient in growth is associated with crack closure close to the crack tip which develops on reduction of mean stress associated with the reduction in R. During the transient the closure level is gradually reduced as indicated with corresponding increase in the rate of crack growth.

However, despite the success of crack closure concepts in dealing with phenomena such as those described above, we end on a word of caution , for as indicated in Fig.12 (26), there is a region to the left of the Keff line wherein the continuum, linear-elastic approach is unable to deal with the analysis of crack propagation, and further modification is necessary in order to treat crack growth behavior in this regime.

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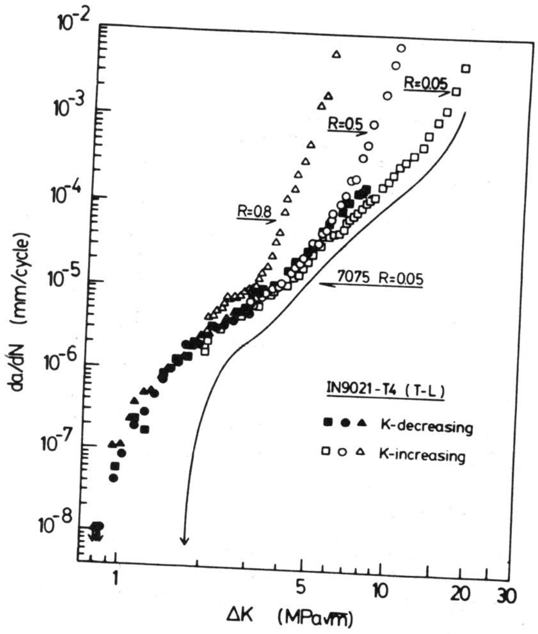

Figure 1 Fatigue crack growth behavior of IN9021-T4 at three R ratios. A curve for the aluminum alloy 7075-T6 is shown for comparison. After Minakawa et al. (5).

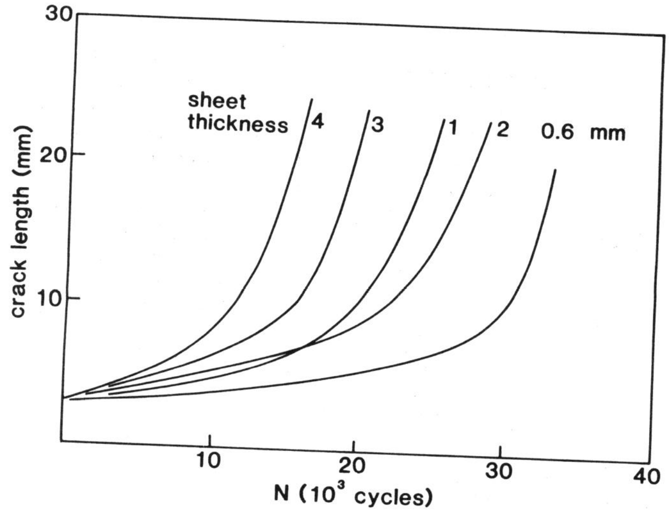

Figure 2 The influence of thickness on fatigue crack propagation in 2024-T3 aluminum alloy. After Broek and Schivje (9).

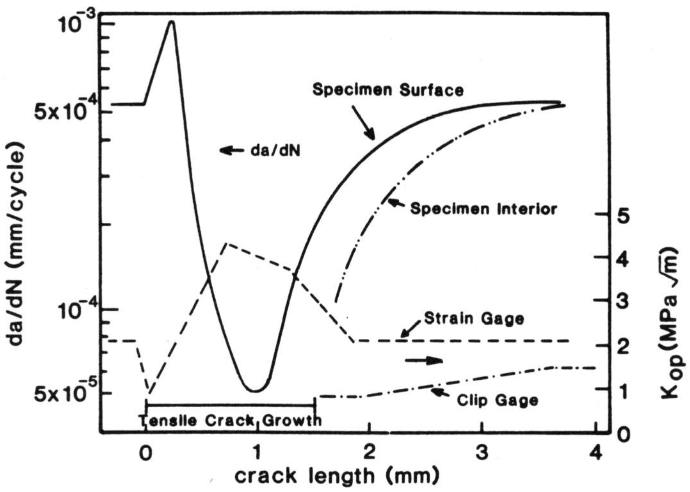

Figure 3 Fatigue crack growth behavior of the aluminum alloy 2219-T87 after a 100% overload. Baseline $\Delta K = 16$ MPa$\sqrt{m}$. The crack opening behavior is also shown. After McEvily and Minakawa (10).

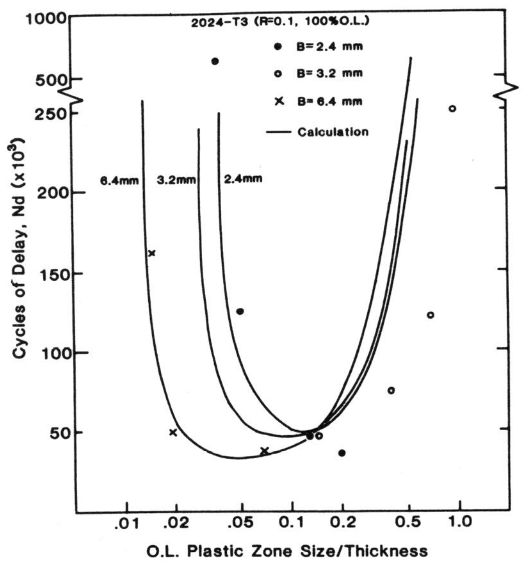

Figure 4 A comparison of the predicted and experimentally determined number of delay cycles after an overload. Experimental results due to Vecchio et al. (11).

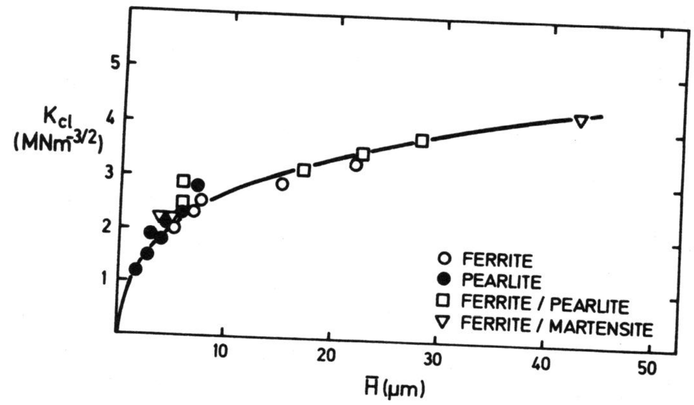

Figure 5 The crack closure stress intensity as a function of fatigue fracture surfavce roughness, $\bar{H}$. After Hamberg et al. (12).

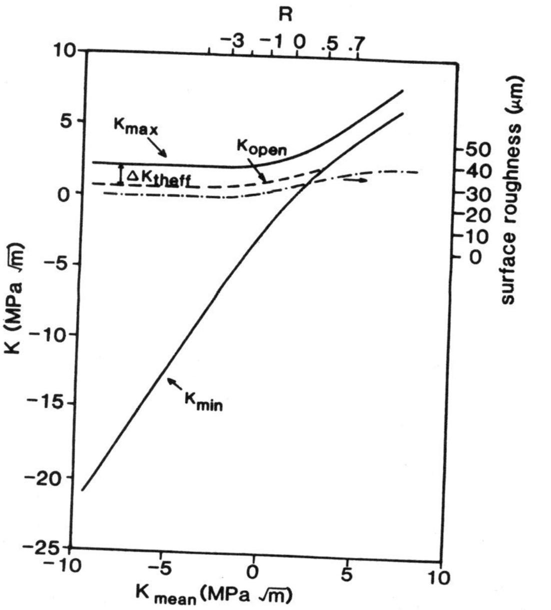

Figure 6 Variation of the Kop level and roughness level with mean stress at threshold for the aluminum alloy 2024-T3. After Kemper et al. (14).

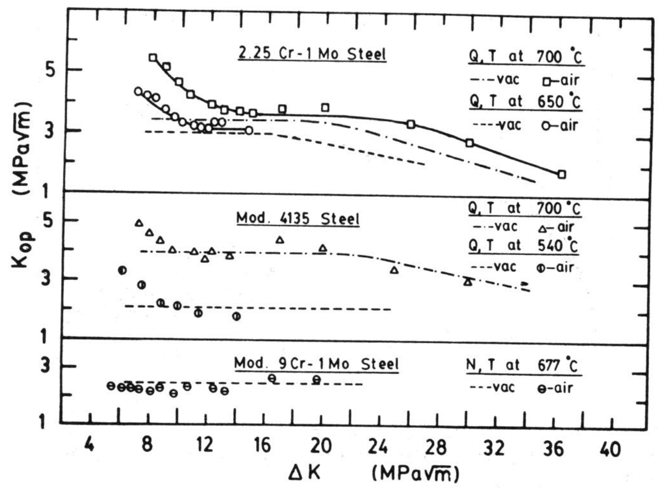

Figure 7 **A** comparison of Kop levels determined in air **and in vacuum** for several steels. After Zhu et al. (15).

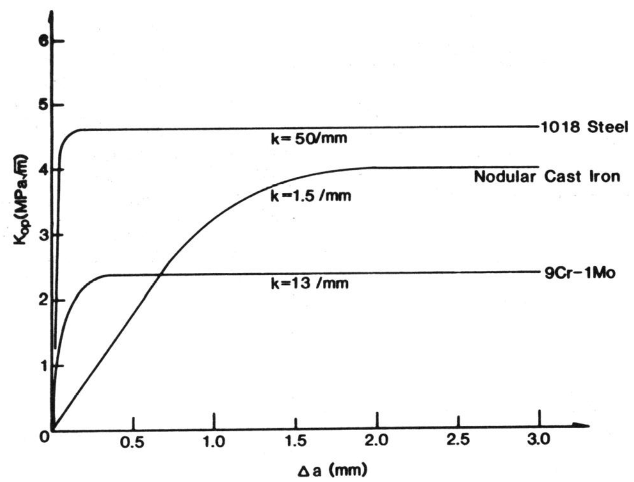

Figure 8 The dependance of Kop on crack length, Δa, for nodular cast iron (after Clement et al. (21), and for two steels (after McEvily and Minakawa (20). The parameter k relates to the rate of closure development, see text.

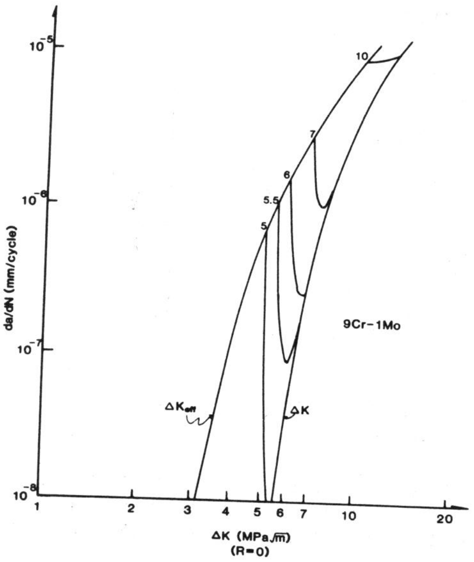

Figure 9 Short crack growth behavior in a 9Cr-1Mo alloy based upon Eq. 9.

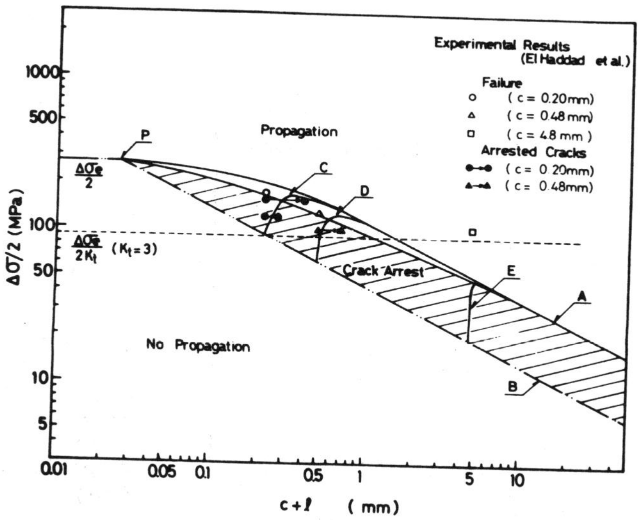

Figure 10 Curves C, D, and E show the stress amplitude required to propagate a crack from holes of different radii at a rate of 10^{-8} mm per cycle in medium strength steel. After McEvily and Minakawa (23). Experimental data due to El Haddad et al. (24).

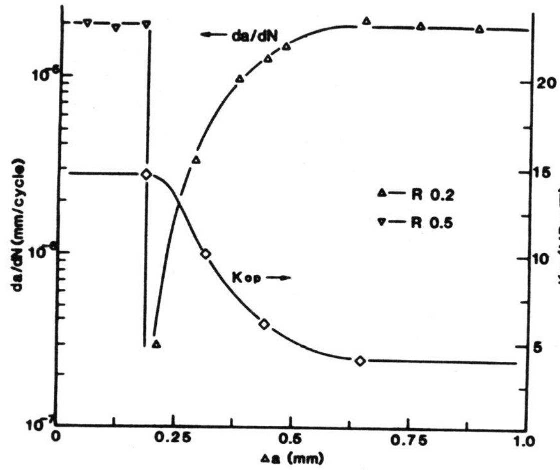

Figure 11 Variation of the opening load in the transient region, and the corresponding crack growth rate after decrease in R from 0.5 to 0.2. After McEvily and Yang (25).

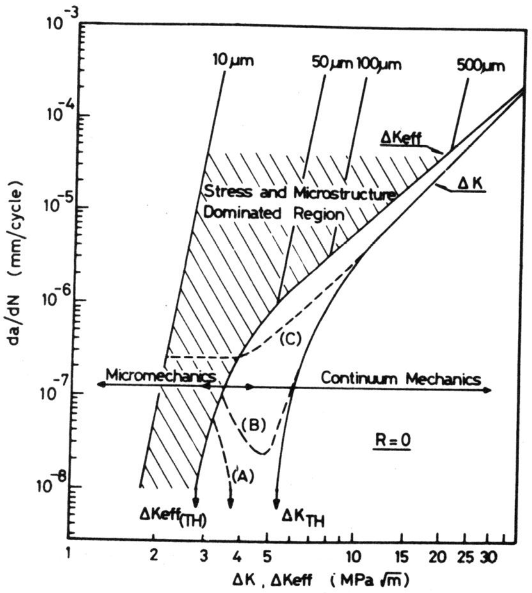

Figure 12 Rate of fatigue crack growth as a function of K. Continuum mechanics approach applicable to right of ΔKeff line. After McEvily et al. (26).