Fatigue Crack Delay and Arrest Due to Single Peak Tensile Overloads

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The effect of single peak overloads on fatigue crack growth was investigated using center crack sheet specimens of 2024-T3 aluminum alloy. The magnitudes of the overload stress intensity values were selected to provide ratios of the overload plastic zone size to the fatigue plastic zone size ($r_o/r_{f\max} = R*$) equal to 5, 10, 15, and 20. To provide a constant fatigue plastic zone size, quasi-constant stress intensity tests were run by means of a load shedding technique. The delaying effect due to a single peak overload was found to increase as the value of $R*$ and consequently as r_o, increased. The higher values of $R*$ were large enough to produce an overload plastic zone that would result in nonpropagating fatigue cracks after 1.5×10^6 cycles. A "zeroing in" technique was used to determine the size of the plastic zone required to arrest a crack at any particular fatigue stress intensity level. From the experimental data, a relationship was developed for approximating the amount of fatigue crack delay incurred due to overloading.

Nomenclature

a = crack length
C = empirically determined constant
c = half crack length
d = geometry factor representing proportion of plane stress and plane strain fracture
E = empirically determined constant
K = stress intensity factor
$K_{\min}$ = minimum stress intensity
$K_{\max}$ = maximum stress intensity
$K_{f\max}$ = maximum stress intensity of fatigue cycle
K_{cr} = critical stress intensity
K_o = overload stress intensity
ΔK = stress intensity range
ΔK_{eff} = effective stress intensity range
N = number of cycles
N_D = number of delay cycles
n = empirically determined constant
$R*$ = ratio of overload plastic zone size to fatigue plastic zone size
$r_{f\max}$ = calculated fatigue plastic zone diameter
r_o = calculated overload plastic zone diameter
r_o' = distance through which delay effects are incurred
r_s = arrest value of r_o
S_1 = crack growth rate prior to overload
σ = stress
σ_{cr} = critical stress
$\sigma_{\min}$ = minimum stress
$\sigma_{\max}$ = maximum stress
$\sigma_{f\max}$ = maximum fatigue stress
σ_{ys} = yield stress

Introduction

UNTIL a little over a century ago, the phenomenon of fatigue fracture played little or no part as a criterion for design, consequently mechanical and structural designs were based almost entirely on static strength of material concepts. But in the mid 19th century, because of ever increasing amounts of vibration and dynamic stress due to such technological advances as the steam engine, it was realized that static strength of material concepts were not sufficient enough to design lasting structures. As fatigue became recognized as a primary cause for service failure, engineers and designers have looked for ways to combat this type of structural damage.

Early investigators[1,2] discovered the techniques of understressing and "coaxing" as methods of extending the fatigue life of laboratory specimens. Due to a number of reasons, these methods proved to be rather impractical in the light of application to mass produced structural elements or complete assemblies. Heywood[3] later showed that the fatigue life of full sized airplane components could be increased by the application of preloads. Heywood's results using preloading techniques were substantiated through work performed by Gerber and Fuchs.[4]

It has been known for some time that a change in crack propagation rate occurs when changing from one level of constant stress amplitude to another of a different, but constant, amplitude. Recent investigations in this area have stimulated research in the area of single peak overloads. Schijve[5,6] found that a single peak overload slowed down crack growth rate considerably. This led to investigations[7,8] which explored the effects of single peak overloads of varying magnitude. Results showed that for a particular value of the crack tip stress parameter, the higher the overload, the greater the increase of fatigue life.

There are a number of proposed explanations of fatigue crack delay phenomenon caused by overloading. Although none of these theories is universally accepted, there are three which are most prominent. One of these explanations involves the crack tip geometry or the "sharpness" of the crack tip during the crack opening portion of each load cycle.[9] It is theorized that during high loading the crack tip is blunt while in low loading the tip remains sharp. Thus, when progressing from a high load level (blunt crack tip geometry) to a lower load level, the low stress concentration factor associated with the blunt crack tip produces a delaying effect when the load is decreased.

Another theory used for explaining the cause of delay is the theory of residual compressive stresses. Due to the high stress

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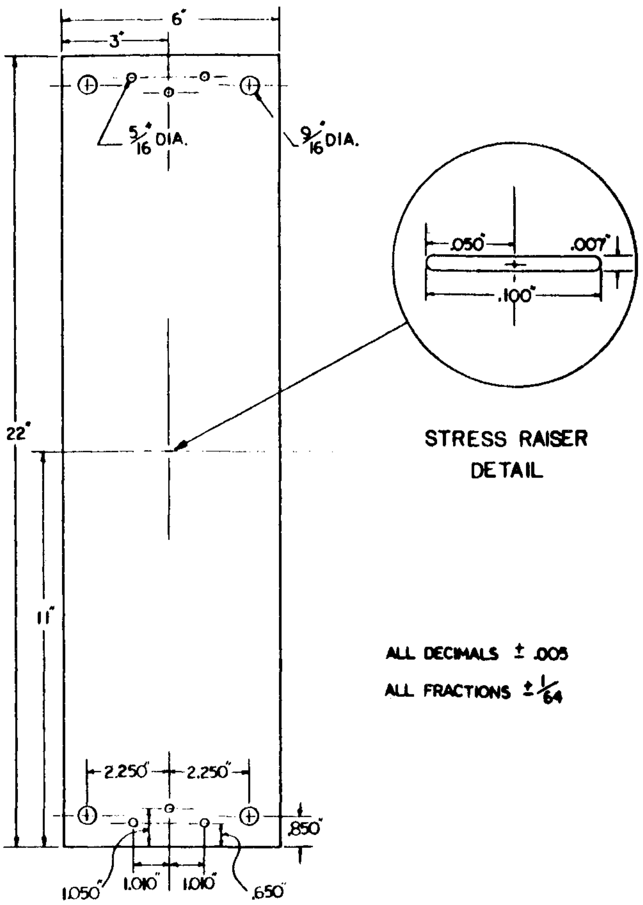

Fig. 1 Tension-tension center crack specimen.

concentration at the tip of the crack, a small region of yielded material or plastic zone exists at the tip of the crack. The residual compressive stresses are formed in the plastic zone. If the plastic zone is made large enough in size due to overloading, the compressive residual stresses will reduce the magnitude of the tensile stresses tending to propagate the crack and delay will occur.

A somewhat different approach is taken by Elber[10] in his crack closure explanation of delay. Elber showed experimentally that a fatigue crack cycled in tensile loading closed before the tensile load had been completely released. He theorizes that residual tensile deformation created in the plastic zone due to the overload acts to decrease the crack opening displacement. As the crack propagates into this region of residual deformation the clamping action created behind the crack tip increases the stress required to open the crack. Thus, an increasingly smaller portion of the tensile loading cycle becomes effective in propagating the crack. Recent investigations[8,11] tend to strongly substantiate this theory.

The objective of this study was to observe and correlate the delay trends due to the application of single peak overloads when applied to constant stress intensity fatigue tests. The effects of various values of a ratio of overload plastic zone size to fatigue plastic zone size were investigated in an attempt to produce complete fatigue crack arrest.

Experimental Investigation

Test Procedure

The center crack specimens used in this investigation were cut from 2024-T3 aluminum alloy sheet stock, 0.10 in. thick. Figure 1 shows a typical specimen with all dimensions. The stress raiser used to initiate the fatigue crack was machined into the specimen by electro-discharge techniques. The stress intensity factor used for this center crack specimen was that for an eccentrically located, transverse crack developed by Isida.[12,13] Since the specimen material was obtained with a mill finish, the area near the stress raiser was polished to a mirror finish to facilitate optically monitoring the length of the crack.

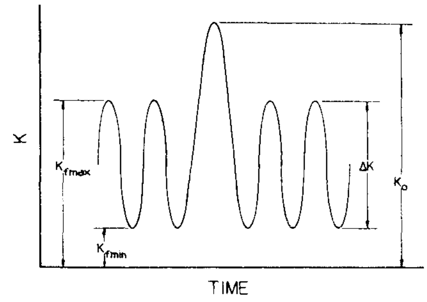

Fig. 2 Typical overload sequence with definition of overload terms.

A 20KIP electro-hydraulic closed loop fatigue test system was used to load the specimens. Crack growth was monitored optically with a Leitz Wezlar microscope (40X) mounted on a Spindler & Hoyer traversing base. A General Radio Strobotac strobe light was used to illuminate the specimen and allow the crack length measurements to be made while the system was running. Tests were carried out in an uncontrolled environment where the relative humidity varied from 39–60% and the temperatures ranged from 70–76°F. Tension–tension sinusoidal loading was applied to the specimens at rates of 15 or 20 cps. In all tests, a constant value of $\sigma_{min}/\sigma_{max} = 0.3$ was maintained. The single peak overloads were applied by means of a triggered output available on the system's function generator. The rates at which the overloads were applied were either 0.015 or 0.020 cps. Figure 2 shows a typical overload sequence. After an overload was applied, the specimen was continuously cycled until the test was completed in order to avoid any detrimental time effects.[14,15]

In order to obtain uniform fatigue plastic zones and constant growth rates, it was necessary to run quasi-constant K tests. This involved monitoring the crack length and decreasing the mean and alternating loads accordingly. Figure 3 is a plot which typifies the load shedding technique. Loads were shed approximately every 0.008–0.010 in. of crack growth.

Testing Program

As von Euw[8] stated, overload plastic zone diameter alone is not a fundamental measure of delay. This is because any overload plastic zone diameter, r_o, corresponding to a K_o for one case can also be a fatigue plastic zone diameter, $r_{f_{max}}$, when the corresponding $K_{f_{max}}$ is equal to the aforementioned K_o. Thus, to enable a correlation to be made with respect to overload

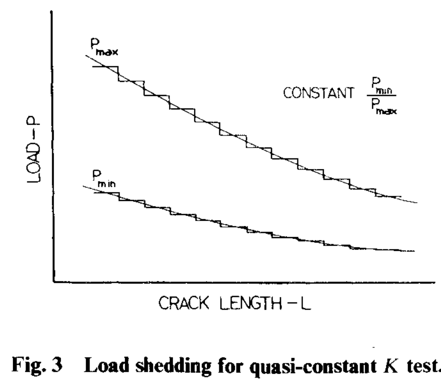

Fig. 3 Load shedding for quasi-constant K test.

Table 1 Delay data obtained from l vs N curves

$K_{f\max}$ ksi (in)$^{1/2}$	K_o ksi (in)$^{1/2}$	S_1 $\times 10^{-5}$ in/cycle	N_D $\times 10^3$ cycles	r_o' in	r_o in	$R*$
6.8	13.7	0.028	120.0	0.0039	0.0067	5.000
	16.8		1,500.0[a]	...	0.0134	10.000
9.9	17.1	0.239	35.0	0.0102	0.0142	5.000
	20.4	0.231	87.5	0.0208	0.0285	10.000
	21.5	0.207	104.0	0.0285	0.0360	12.636
	22.9	0.231	1,500.0[a]	...	0.0427	15.000
	25.8	0.207	1,500.0[a]	...	0.0570	20.000
12.2	19.5	0.300	36.0	0.0266	0.0235	5.000
	23.7	0.393	107.0	0.0335	0.0470	10.000
	26.5	0.393	246.0	0.0217	0.0600	12.755
	28.7	0.358	1,500.0[a]	...	0.0706	15.000
	33.2	0.463	1,500.0[a]	...	0.0941	20.000
14.4	22.3	0.656	9.5	0.0244	0.0400	5.000
	30.6	0.563	398.8	0.0615	0.0800	10.000
	32.4	0.462	278.5	0.0730	0.0900	11.251
	34.6	0.657	749.0	0.1380	0.1021	12.764
	37.5	0.787	1,500.0[a]	...	0.1200	15.000
	43.2	0.433	1,500.0[a]	...	0.1600	20.000
16.7	27.8	0.837	21.0	0.0354	0.0660	5.000
	35.9	0.713	244.0	0.1004	0.1100	8.331
	37.8	0.713	120.0	0.0650	0.1220	10.000
	37.8	0.875	295.0	0.0590	0.1220	10.000
	39.3	0.606	1,500.0[a]	...	0.1320	15.000
	48.1	0.787	1,500.0[a]	...	0.1981	20.000

[a] Indicates test in which arrest occurred.

plastic zones, a nondimensional parameter $R*$ was selected. This is defined as the ratio of overload plastic zone diameter to fatigue plastic zone diameter.

$$R* = r_o / r_{f\max}$$

The diameter of the plastic zone cannot be calculated exactly, however, it is usually approximated using the following expression[16]

$$r = \frac{2}{d\pi}\left(\frac{K}{\sigma_{ys}}\right)^2 \tag{1}$$

where

$d = 2$ for plane stress or
$d = 6$ for plane strain

Since the value of d depends on whether plane stress or plane strain conditions exist at the crack tip, the method used by von Euw[8] for mixed mode conditions was used. In these tests, once a crack was initiated, the system was set at a constant load and the crack was allowed to propagate until specimen fracture occurred. Thus, by measuring along the fracture surface the stress intensity at any particular crack length could be related to the percent shear lip associated with that particular value of stress intensity. Consequently Eq. (1) becomes

$$r = \frac{1}{X(2)+(1-X)(6)}\left(\frac{2}{\pi}\right)\left(\frac{K_{f\max}}{\sigma_{ys}}\right)^2 \tag{2}$$

where $X = \%$ shear lip.

In order to minimize the number of tests needed to determine the overload condition causing complete crack arrest, four initial values of $R*$ were chosen to provide a wide range of overload plastic zones. These values were

$$R* = 5, 10, 15, 20$$

Five levels of fatigue stress intensity, $K_{f\max}$, were chosen for constant K tests. These levels ranged from $K_{f\max} = 6.8$ ksi (in.)$^{1/2}$ to $K_{f\max} = 16.7$ ksi (in.)$^{1/2}$.

As the test program was performed, the higher values of $R*$ produced crack arrest. Additional tests were then run at each constant K level between the highest value of $R*$ which did not cause arrest and the lowest value which did cause arrest to "zero in" on the lowest value of $R*$ which would cause complete crack arrest (see Table 1). Complete arrest was defined to be no measurable crack growth (less than 0.0004 in.) in 1.5×10^6 cycles.

Test Results

The basic data recorded during the fatigue tests were crack length and total number of loading cycles applied. In constant K tests such as those performed in this investigation a plot of crack length vs cycles results in a straight line, the slope representing growth rate. When a positive overload is applied, a delay in the crack growth results. This is illustrated in Fig. 4 which represents a typical crack length vs cycles plot in which an overload has been applied and a period of delay follows.

This plot can provide a number of experimental quantities. The slope of the curve, (S_1), prior to the application of the overload represents the normal, undelayed crack growth rate. The delay period was taken to begin at the point where the

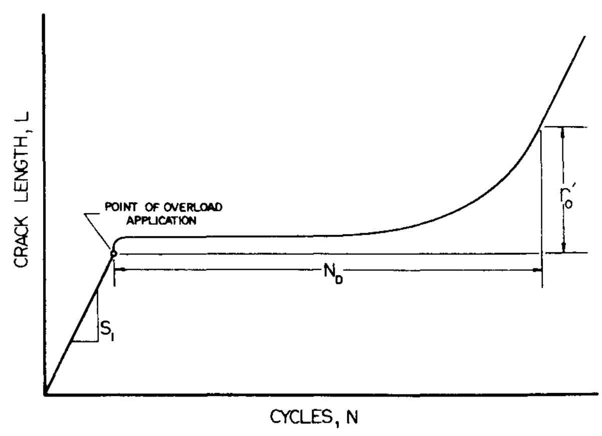

Fig. 4 Typical l vs N curve defining delay terms.

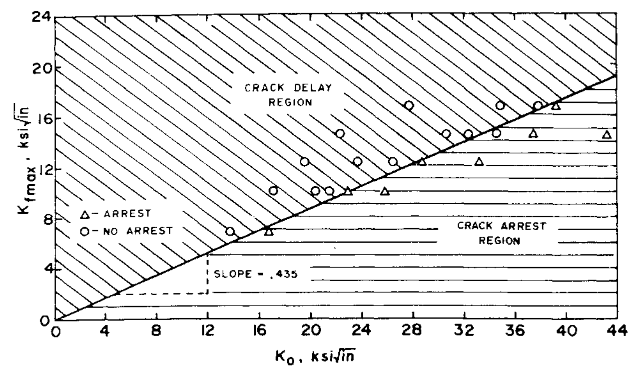

Fig. 5 Division between overloads that produced crack arrest vs crack delay.

overload was applied and assumed to end at the point where the growth rate returned to its value prior to the overload. The horizontal distance, N_D, represents the length of the delay period. It would seem logical that the vertical distance from the point where the overload was applied to the point where the original growth rate returned is the distance, r_o', through which the crack was effected by the overload. Ideally, this distance would represent the calculated overload plastic zone diameter, r_o. These experimentally determined parameters are tabulated in Table 1 along with the corresponding values of $K_{f\max}$, K_o, and r_o.

Figure 5 is a plot of $K_{f\max}$ vs K_o which represents the results of the "zeroing in" process used to determine the values of $R*$ which caused arrest. The results show two separate regions: one in which only delay will occur, while in the other, complete crack arrest will occur. The significance of this will be discussed later.

The growth rates for each constant stress intensity level prior to overloading are plotted in Fig. 6. Elber derived a growth rate equation based on his crack closure model.[10] The equation takes the form

$$da/dN = C[(0.5+0.4R)\Delta K]^n$$

where $C = 5.35\times 10^{-7}$ and $n = 3.62$ when ΔK has the units of psi(in)$^{1/2}$ and da/dN has the units of in/cycle. As can be seen from Fig. 6 the experimental growth rates are in fair agreement with Elber's equation.

Photographs of the surface of specimen OL-4 were taken in order to observe the plastic zone size. Figure 7 is a photograph of the overload plastic zone created by $K_o = 23.7$ ksi (in.)$^{1/2}$. The plastic zone as indicated by the plastic deformation visible on the surface has been outlined in this photograph. The size of this plastic zone corresponds well with both the calculated value and the experimentally measured value, r_o'. It should be noted in Fig. 7 that the fatigue plastic zone increased in size as the crack propagated through the overload plastic zone. This tends to indicate that the plastic zone size is a function of the effective stress, as is the growth rate.

Delay Theory

The large number of nonpropagating cracks produced in the initial test program indicated a trend in what could be considered the critical values of $R*$—those values which caused crack arrest. This was verified through the "zeroing in" process and represented in Fig. 5. The reason crack arrest occurred can be explained by both the crack closure and the residual stress concept in similar manners.

It is generally accepted that if a crack does not open, the tip cannot act as a stress raiser; consequently, the crack will not propagate. In his crack closure model, Elber holds that the premature closing of the crack tip reduces the portion of the load cycle which is effective in propagating the crack. The stress at which the crack actually opens and closes is what Elber

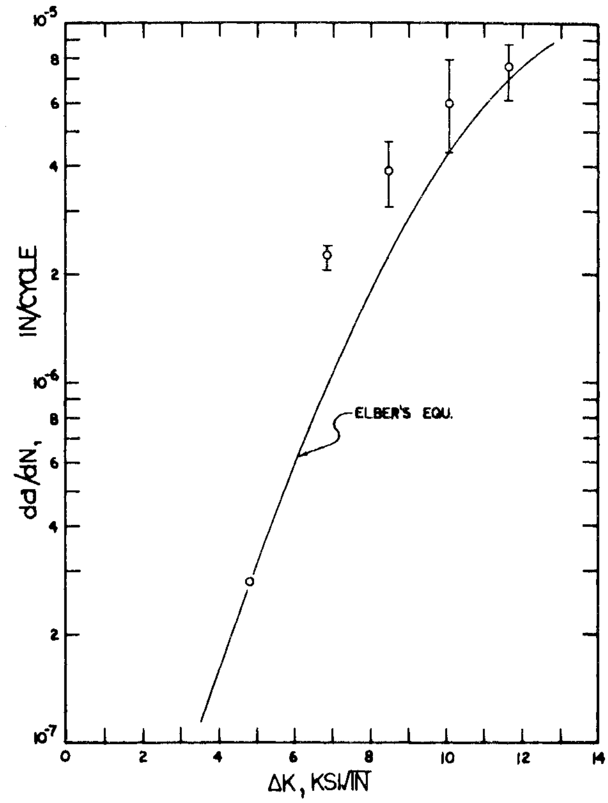

Fig. 6 Comparison of crack growth rates with Elber's equation.

designates as the crack opening stress, S_{op}. Thus, if S_{op} is equal or greater in magnitude than the maximum fatigue stress, the crack will not open and hence, will not propagate.

In considering the residual stress concept as it is proposed by Gerber and Fuchs,[4,17] the same basic process takes place during arrest. If the residual compressive stresses which directly oppose the tensile fatigue stresses are larger in magnitude, the net stress at the crack tip is compressive. Here again crack propagation ceases because the crack tip remains closed. In both models, crack closure and residual stress, there is a "critical stress" which the fatigue stress must exceed in absolute magnitude before the crack can advance. Thus, it would seem reasonable to state that in order for a crack to arrest

$$\sigma_{cr} \geqq \sigma_{f\max}$$

where σ_{cr} is the critical stress. The same idea could be expressed equivalently in the form of stress intensities

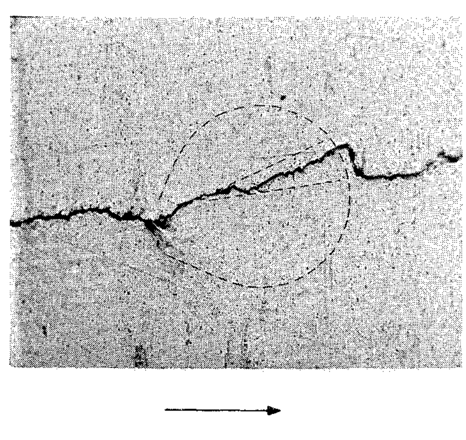

Fig. 7 Appearance of overload plastic zones on specimen surface. (Arrow indicates direction of growth.)

$$K_{cr} \geqq K_{f\max} \tag{3}$$

Both concepts state that the causes of delay, either residual compressive stresses or residual tensile deformations, are a direct consequence of the formation of the overload plastic zone, i.e.

$$K_{cr} = f(K_o) \tag{4}$$

This functional relationship was verified in the present study by experimentally determining the critical values of r_o which just produced crack arrest. These critical values of r_o will be hereafter designated as r_s. Once having determined these values, the critical stress intensity value corresponding to each r_s can be plotted as a function of $K_{f\max}$. This was done in Fig. 5. The functional relationship between K_{cr} and K_o can be obtained from Fig. 5 if we substitute K_{cr} for $K_{f\max}$. From Fig. 5, Eq. (4) becomes

$$K_{cr} = f(K_o) = EK_o \tag{5}$$

where $E = 0.435$.

It was observed during this study, as von Euw did in his work, that immediately following the application of an overload the crack would continue to propagate for a short distance into the enlarged plastic zone at an ever decreasing growth rate until the minimum growth rate was reached. In the tests which resulted in nonpropagating cracks, the growth rate quickly reached its minimum value within the first few hundred cycles immediately following the application of the overload. No measurable crack growth (less than 0.0004 in.) was observed for the remaining 1.4×10^6 plus cycles. It is felt that this is a sound basis for assuming that the magnitude of the critical stress intensity was greater than that of $K_{f\max}$ for the greatest percentage of the test duration.

An average delay growth rate, $da/dN|_D$, can now be defined as the distance through which the delaying action occurs (ideally r_o) divided by the number of cycles of delay. Assuming that the generally accepted form of growth rate equation can also be applied to the average delay growth rate, we obtain

$$da/dN|_D = C(\Delta K)^n \tag{6}$$

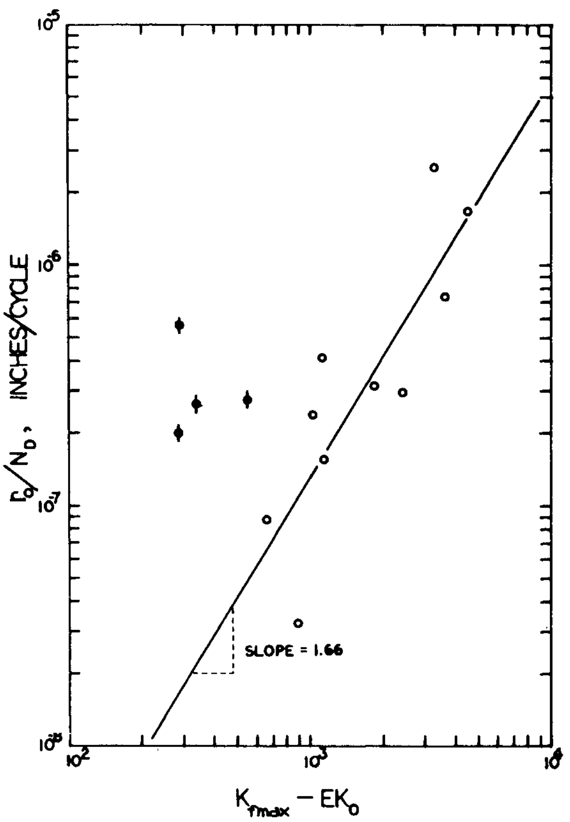

Fig. 8 Average delay growth rate as a function of $K_{f\max} - EK_o$ ($\sigma_{\min}/\sigma_{\max} = 0.3$).

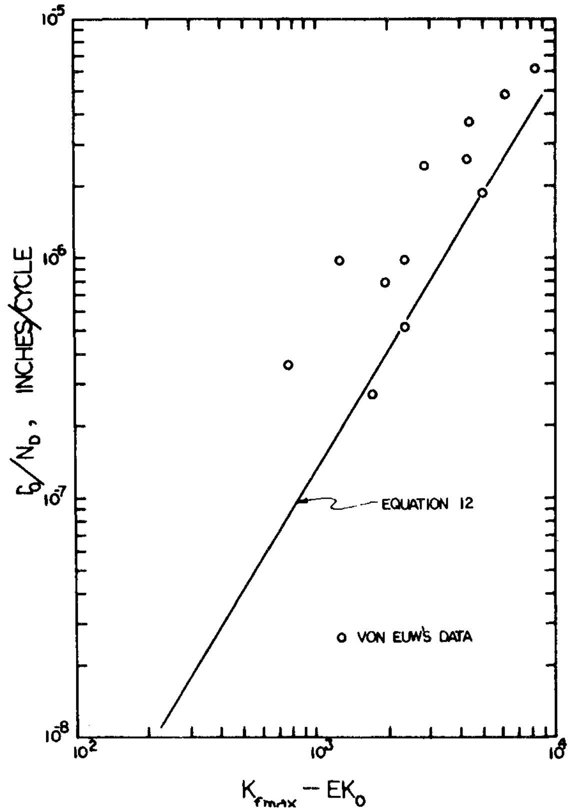

Fig. 9 Comparison of von Euw's data[8] with Eq. (12), ($\sigma_{\min}/\sigma_{\max} = 0$).

Since growth rate occurs only when the crack tip is open, only the portion of the load cycle that is greater in magnitude than K_{cr} will be effective in propagating the crack. From this an effective stress range, as it was termed by Elber, can be defined as

$$\Delta K_{\text{eff}} = K_{f\max} - K_{cr} \tag{7}$$

Subsequently Eq. (6) becomes

$$da/dN|_D = C(\Delta K_{\text{eff}})^n \tag{8}$$

From Eqs. (5) and (7) this becomes

$$da/dN|_D = C(K_{f\max} - EK_o)^n \tag{9}$$

where $E = 0.435$ from Fig. 5.

If $da/dN|_D$ is assumed to be the average growth rate through the overload plastic zone and the growth rate is assumed to be constant in this region (even though we know it isn't) then

$$da/dN|_D = r_o/N_D \tag{10}$$

Equation (9) then becomes

$$N_D = \frac{r_o}{C(K_{f\max} - EK_o)^n} \tag{11}$$

The data should then plot as a straight line on a $\log(r_o/N_D)$ vs $\log(K_{f\max} - EK_o)^n$. This is illustrated in Fig. 8. The constants C and n can be obtained from the graph which gives

$$N_o = \frac{r_o}{1.4 \times 10^{-12}(K_{f\max} - 0.435K_o)^{1.66}} \tag{12}$$

It should be noted that whenever the quantity $(K_{f\max} - EK_o)$ is negative it should be set equal to zero. This is the case where the magnitude of K_{cr} is greater than that of $K_{f\max}$ and the result is infinite delay. Likewise is the case when $K_{cr} = K_{f\max}$. Also it should be noted that Eq. (12) is valid only for $K_o > K_{f\max}$ (for constant amplitude loading K_o would equal $K_{f\max}$ and Eq. (12) would predict a delay effect).

It should be pointed out that as the value of r_o approached the arrest value, r_s, the number of resulting delay cycles, N_D, became very sensitive to slight variations in r_o. The four data points (indicated by a vertical line through the data point) located to the extreme left in Fig. 8 represent the results obtained from values of r_o which lay in the sensitive region near r_s. Since the cracks from which this data was obtained were on the verge of arrest (which would shift these points down significantly) these data points were omitted in fitting the curve to the data. It is felt that the curve as shown is representative of the results.

A comparison of these results with von Euw's data is illustrated in Fig. 9. von Euw's results are for the same material, 2024-T3 aluminum alloy, tested with $\sigma_{min}/\sigma_{max} = 0$ compared to $\sigma_{min}/\sigma_{max} = 0.3$ for this study. As can be seen, the correlation is good. The apparent slight difference in the slope of the data may be due to the difference in the values of $\sigma_{min}/\sigma_{max}$ for the two sets of data.

Conclusions

The major conclusions arrived at in this investigation are as follows:

1) As expected, the number of delay cycles at each constant stress intensity level increases as the value of the plastic zone ratio, $R*$, increases.

2) At each level of constant stress intensity there exists a critical overload plastic zone diameter, r_s. Overload plastic zones with diameters equal or greater than this critical value produce infinite delay (crack arrest).

3) There exists a linear relationship between the fatigue stress intensity and a critical stress intensity which produces crack arrest. Arrest occurs when the maximum fatigue stress intensity is less than or equal to the critical stress intensity.

4) The surface appearance of the fatigue plastic zone when propagating through an overload plastic zone indicates that the diameter of the plastic zone is dependent upon an effective stress intensity range which can be defined as the difference between the maximum fatigue stress intensity and the critical stress intensity.

5) Correlation of growth rates with a relation developed by Elber based on crack closure and effective stress concepts was good.

6) The correlation of the number of cycles of delay with the maximum fatigue stress intensity, overloading plastic zone size and overload stress intensity developed in this study showed good agreement with the experimental results of this study as well as with the results of a previous study by von Euw.

7) The crack arrest phenomena observed in these studies may influence experimental results in studies of the threshold of fatigue crack growth. As the stress intensity is reduced in these studies, the crack arrest may be what is observed rather than a true threshold level.

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