ASAT

MILITARY TECHNICAL COLLEGE

CAIRO - EGYPT

1 # FATIGUE CRACK CLOSURE IN ALUMINIUM ALLOYS

2 ## UNDER VARIABLE-AMPLITUDE LOADS

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4 ABSTRACT

During fatigue crack propagation,residual deformations are built up in front of the crack tip and left behind the propagating crack. As a result of these residual deformations the crack will close(at least partly) during unloading. At zero load the presence of these deformations excersises residual compressive stresses in the wake of the crack normal to the fractured surfaces. The load at which the crack closes is therefore tensile rather than zero or compressive. This phenomenon is reffered to as **crack closure.**

The main objective of this study is to correlate fatigue crack growth rates with crack closure under different types of loadings: Constant-amplitude with two different cycle ratio R,($R=\sigma_{min}/\sigma_{max}$), Programmed block loading and A single tensile overload.

The incidence of crack closure is examined and the concept of equivalent constant-amplitude is applied. The delayed crack growth retardation after a single overload cycle is interpreted using crack closure concept. Aspects covered include microscopic and fractographic observations confirming the crack closure to provide the fatigue striations on the surfaces ruptured by cyclic loads.

Materials used in this study are two Aluminium alloys,widely used in aeronautical structures: 2124T351 (AU4G1) and 2618AT851(AU2GN). Several interaction effects might be explained by changes in the crack closure levels due to variable amplitude loads.

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INTRODUCTION

Crack closure was first observed by Elber [1] and has been used to correlate crack growth behaviour under constant-amplitude loadings [2-4]. It is a significant factor in causing load-interaction effects on crack growth rates(retardation and/or acceleration) under variable -amplitude loads. Furnee [5] showed that crack closure should predominately occur near the free surface and to a much lesser extent at the interior of the material. Mc Evily [6] found that peak load introduced a significant crack growth delay. He then reduced the thickness of the specimen immidiately after the peak load and a much smaller delay occured. Elber [7] introduced successfully the equivalent constant-amplitude concept,based on the crack closure phenomena, to replace random load spectra in both analysis and tests. Different techniques are used to measure the crack closure load level,these techniques include: Elber's gauge[1],Schmidt'gauge [8],Photography[9],Laser interferometry[10],Electrical potential [11],Ultra sonic[12] and Photoelasticity[13]. Pelloux [14] measured the crack closure by electrophractography,using high resolution fractography to correlate closure and striation spacings. He pointed out that higher closure developing after overloads was found to be a suitable explaination for crack growth retardation. Bathias [15] showed that the fracture micromorphologie corresponding to the retardation phases are different at mid thickness and near edges of tested specimens;this might suggest a poorer closure at mid-thickness than near edges reflecting smaller delay for thicker specimens. Schijve [16] surveyed the different published formula to determine the crack opening(closure) stress level as a function of cycle stress ratio R. Originally Elber [1] proposed for 2024T3 Aluminium alloy tested under constant-amplitude loading:

$$U = \Delta\sigma_{eff}/\Delta\sigma = \Delta K_{eff}/\Delta K = 0.5+0.4\ R$$

Where

U is the stress variation effectiveness factor, $\Delta\sigma_{eff} = \sigma_{max} - \sigma_{op}$, $\Delta\sigma = \sigma_{max} - \sigma_{min}$ and corresponding ΔK is the stress intensity factor range. Consequently $\Delta K_{eff} = U.\Delta K$ is suggested to replace ΔK in Paris relation [17]:

$da/dN = C(\Delta K)^m$,describing the crack growth rate as function of material's constants C and m;and stress intensity factor range. the complex nature of factors contributing to crack closure makes a pure quantative theoritical study of the phenomenon very difficult. Therefore crack closure is generally studied experimentally. This research contributes to provide additional phenomenological crack growth behaviour of the two Aluminium alloys specimens subjected to:

1. Constant-amplitude loads of two different R ratio
2. Variable -amplitude loadings in a form of simple flight load simulation(programmed blocks).
3. A single tensile overload cycle introduced during a constant-amplitude sequence.

The developed concepts are based on physical aspects of damage .

TEST PROGRAM

The test program was designed so that the crack growth under the two different R ratios (0.01 and 0.63) would enable us to determine the crack growth rate curve $da/dN = C(\Delta K)^m$ as a single curve independent of the applied load ratio. The simple flight load simulation was designed so that block loads types C/n would represent disturbed flights in which the load cycle A (R=0.01) represents the Ground-Air-Ground cycle(G.A.G.) and n load cycles of B (R=0.63) would represent flight disturbing loads (Gust,Manoeuvre...etc.). n takes values 2,3,6,25 and 69. The sigle tensile overload test was run for τ = 2,where the original constant-amplitude sequence was of R=0.01. In all the three cases,crack closure was monitored and contiuously determined using same technique applied by Elber [1].
The patterns and loading values for the test program are given in Fig. 1

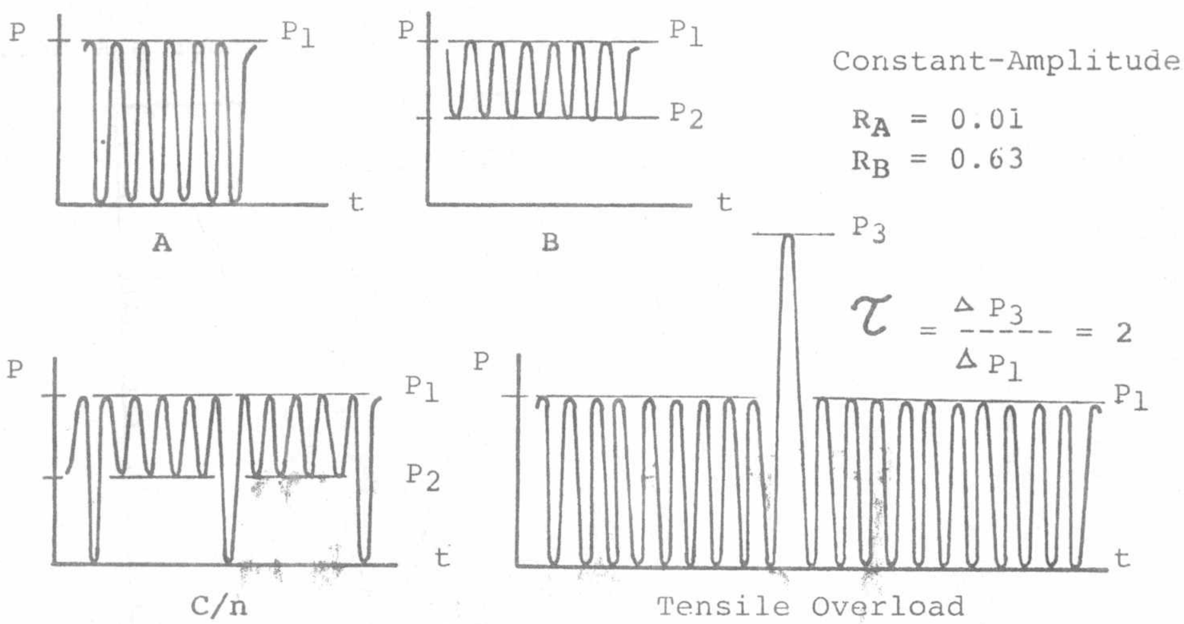

Fig. 1 Test Program

Testing Procedure

Flat,centrally cracked sheet specimens CCT (2 mm thick,200 mm wide) and compact tension specimens CT (12 mm thick,75 mm wide) were used in this study. Chemical composition,mechanical properties and heat treatment are listed in Ref.[18]. All tests were run at a frequency of 10 Hz and in air at room temperature. Crack opening level (P_{op}) was measured by a surface gauge located at the crack tip , tests and plots were made at 0.2 Hz frequency. Tested specimens were examined by scanning electron microscope.

Test Results and Analysis

Constant-Amplitude

Fatigue crack growth data in the form of da/dN (mm/cycle) vs stress intensity factor range ΔK (MPa$\sqrt{m}$), $\Delta K = C\Delta\sigma\sqrt{\pi a}$),a is crack length in mm,are represented in Fig. 2 . The two alloys showed a significant effect of R ratio on their fatigue crack growth rates. Higher R ratio would produce higher propagation rates. Recalling Elber's model:

$$da/dN = C\ (\ \Delta K_{eff})^m$$

$$\Delta K_{eff} = U \cdot \Delta K \quad ; \quad U = 0.5 + 0.4\ R$$

and based on the data for the R ratios 0.01 and 0.63 we adopted Elber's single curve independent of R ratio as shown in Fig. 3. The two lines of 2818AT851 are shifted and coincide with Elbers line. Fig.3b shows a typical plot of opening displacement δ (mm) against the load P(daN),from which crack opening level ratio: $\alpha = P_{op}/\ P_{max}$ for R ratio 0.1 is 0.5 confirming Elber's model.

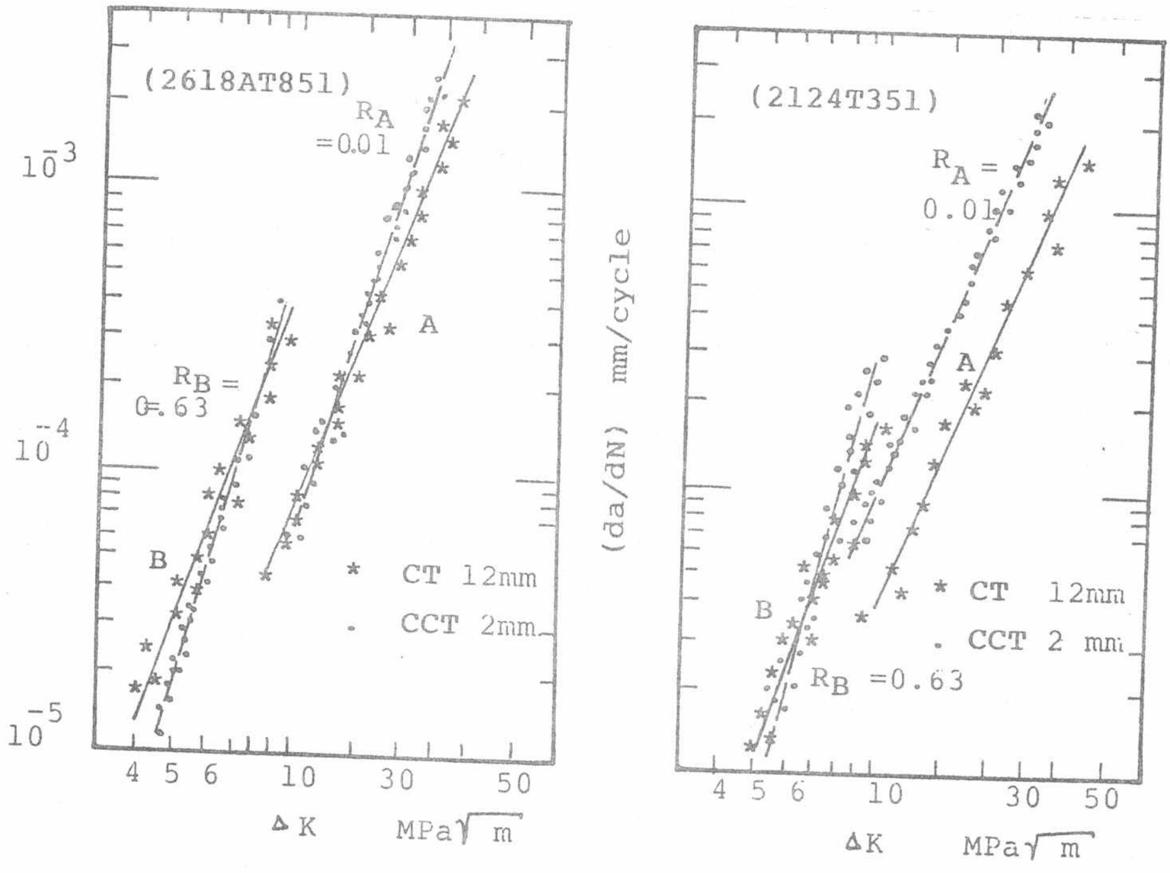

Fig. 2 Crack Growth Rates for R=0.1 and 0.63

Variable-Amplitude

Types C/n are characterized by a constant maximum load (P_1) and by one GAG cycle which occurs once per flight(block).

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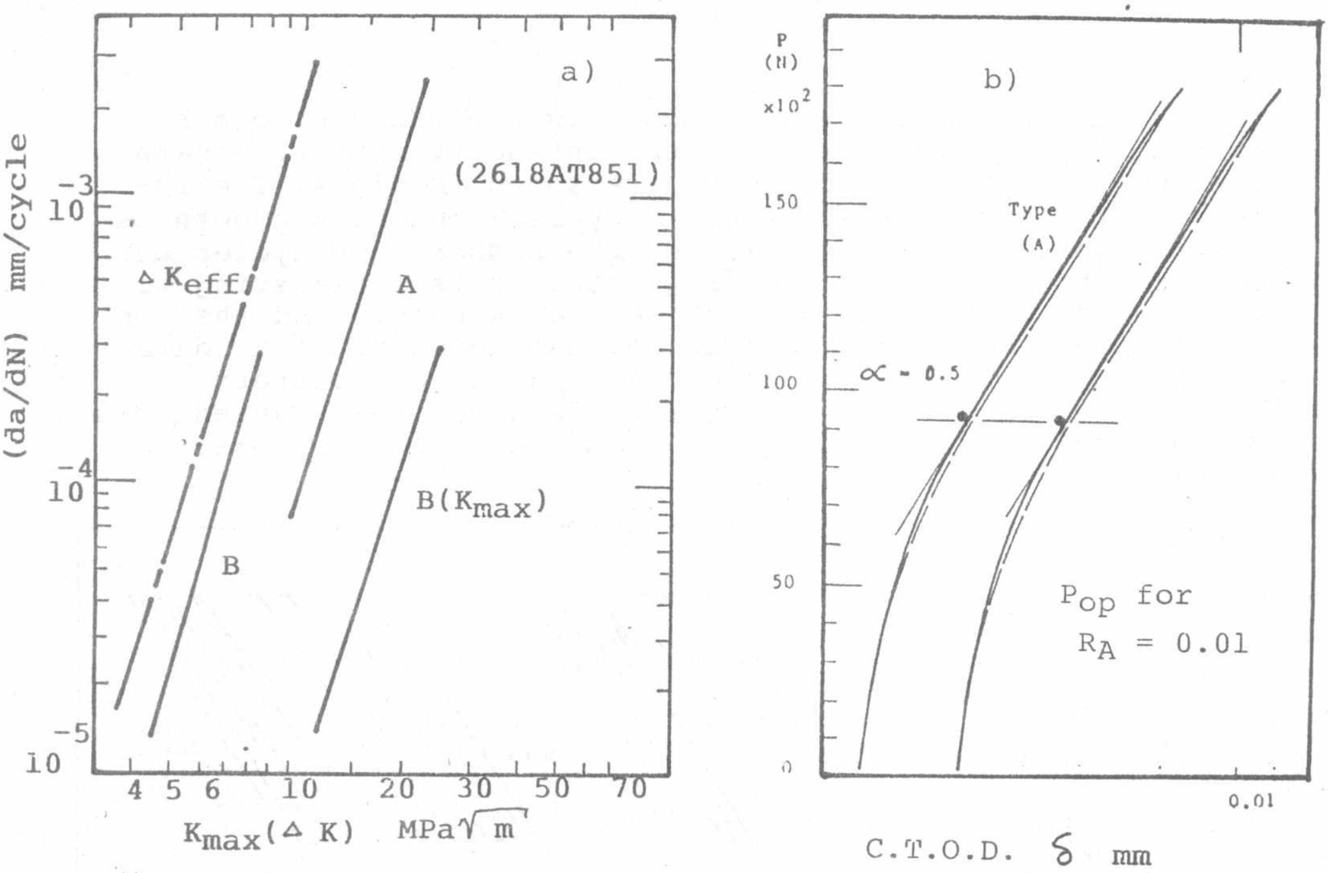


Fig.3 Adoptation of Elber's Line and P_{op} for R=0.1

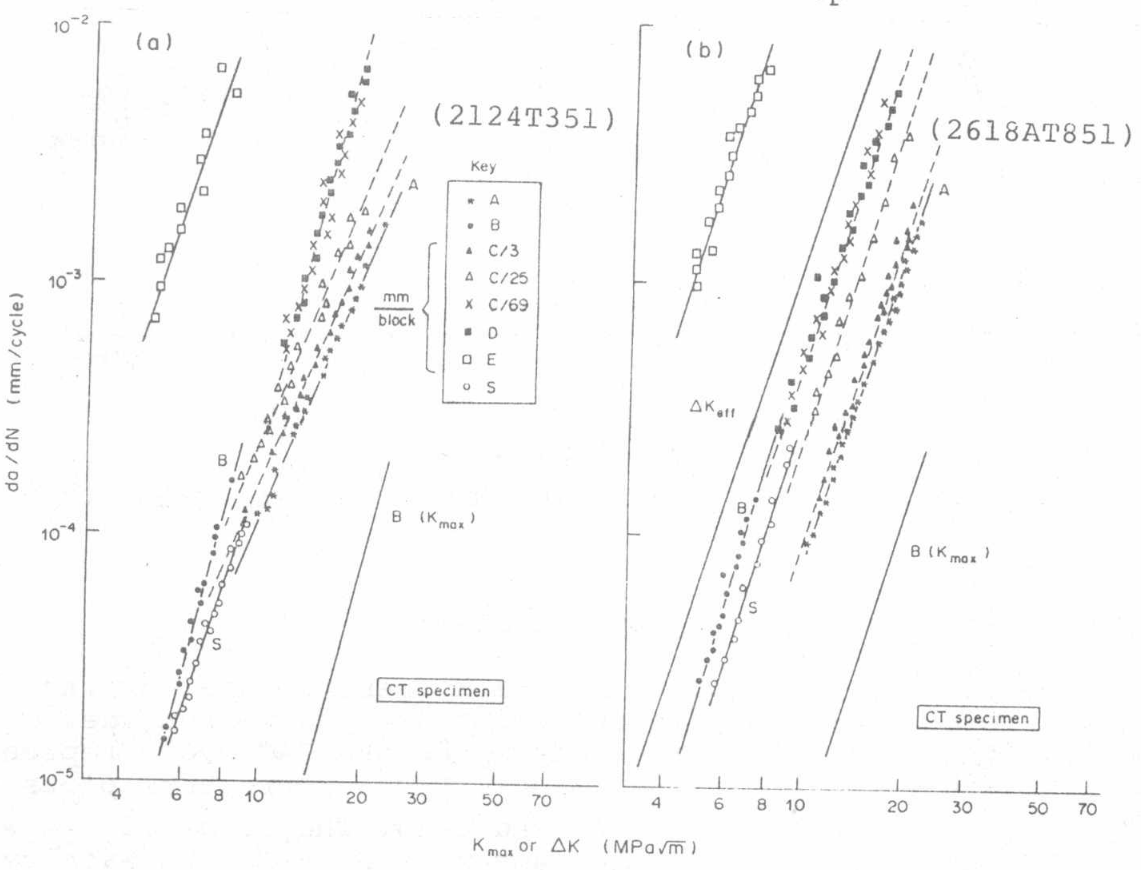
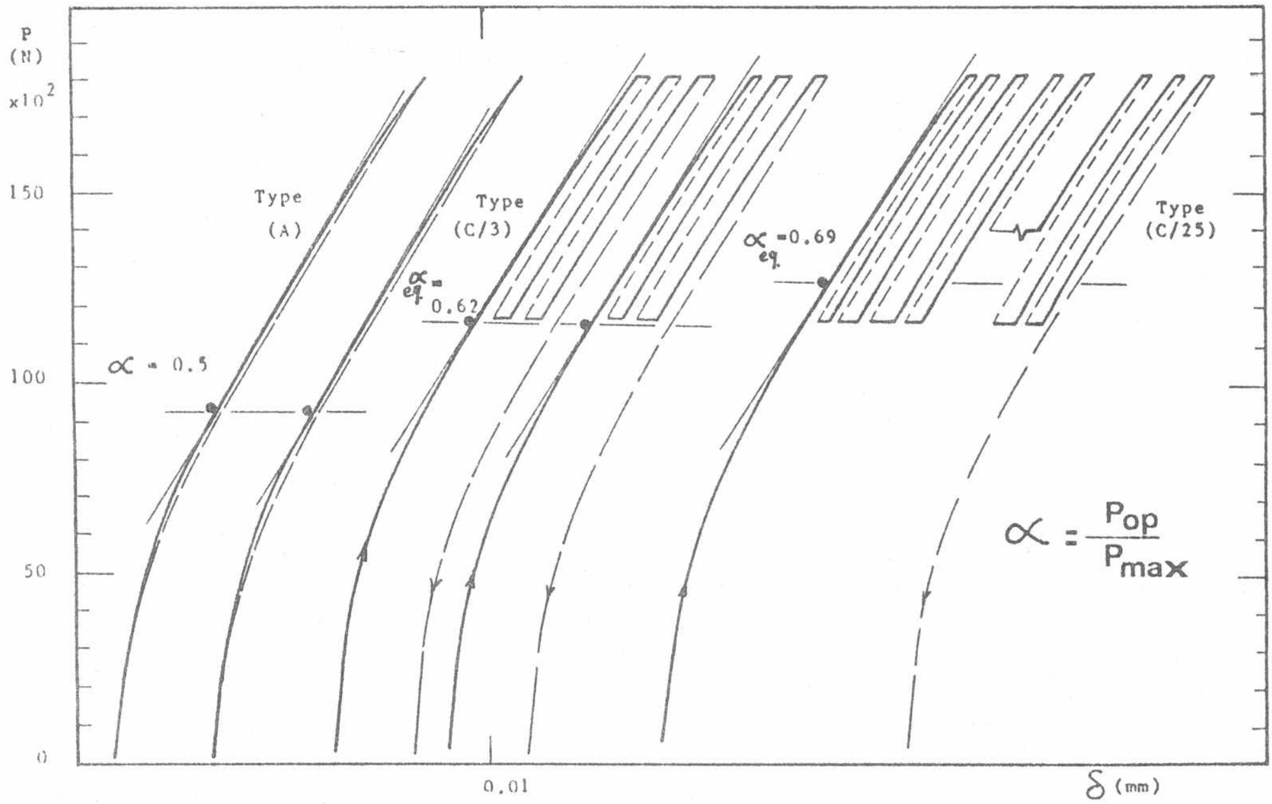


Fig.4 Crack Growth Rates Under Different Spectra

Thus, the fatigue crack growth per flight (mm/block) can be plotted vs $K_{max.}$ as maximum stress intensity factor. Growth data for 2618AT851 CT specimens are shown in Fig.4. The influence of flight disturbances (B-cycles) on crack growth is possibly investigated. Increasing the number of B-cycles per block, reflects a higher cracking rate. It is interesting to find a good coincidence between test data points and the non-interaction summation of growth corresponding to basic data of types A and B forming different types of C/n pattern. This implies that it is only R ratio effects that caused this growth acceleration without any significant load-interaction effects.



Aluminium Alloy 2124 T 351, CCT B=2 mm.
Fig.5.
Determination of P_{op} for Block Types C/3 and C/25

Analysis Based on Crack Closure Concept

It was difficult to measure the crack opening level during the low ΔK cycles (B-cycles) in the block C/n, so we considered the modification of the opening load P_{op} on the GAG cycle represent the equivalent $(P_{op})_{eq.}$ in the block. Fig.5 represents plots of $P = f(\delta)$ for loading types C/3 and C/25. The level of P_{op} was changed significantly with the number of B-cycles in each type. the avarage values of $\alpha = P_{op}/ P_{max}$ are given in table 1. It is logical to expect that for high enough number of B-cycles the crack opening level will be stabilized and corresponds to P_{op} of the constant-amplitude loading type B (R=0.63).

Type	A	C/3	C/25	B
Measured α	0.5	0.61-0.63	0.69	0.72

Table 1 Measured Values of Crack Opening Ratio α

Based on Elber's relation [1]:

$$U = \frac{P_{max} - P_{op}}{P_{max} - P_{min}} = \frac{P_{max} - P_{op}}{P_{max}\,(1-R)}$$

$$U = \frac{1-\alpha}{1-R} \quad ; \quad \alpha = 1 - U(1-R)$$

With U= 0.5 +0.4 R for Aluminium alloys

$$\alpha = 0.5 + 0.1\,R + 0.4\,R^2 \qquad (1)$$

So $\alpha_A = 0.5$ and $\alpha_B = 0.722$

This would suggest that for these types C/n , will have values such that $\alpha_A < \alpha < \alpha_B$. We can expect that the crack opening level under such sequences (P_{max} is kept constant) is stabilized after some crack growth and remain relatively constant.

Development of Corresponding Equivalent Constant-Amplitude Sequences

Barsom [18] showed that for some random load disturbances, the rate of crack growth was generally equivalent to the rate of crack growth under constant amplitude tests, with the same minimum load and an amplitude representing the root mean square (rms) of the random test. Elber [7] however, introduced this concept based on the crack closure phenomenon and on his test results.

Starting from Elber's definition for constant-amplitude loads and rearranging it as follows:

$$\frac{da}{dN} = C_{eff}\,(\Delta K_{eff})^m$$

$$= C_{eff}\,(K_{max} - K_{op})$$

$$= C_{eff}\,[\,K_{max}(1 - K_{op}/K_{max})\,]^m$$

$$= C_{eff}\,[\,K_{max}(1-\alpha)\,]^m$$

Assigning $\gamma = 1-\alpha$

$\gamma = \Delta K_{eff}/K_{max}$ as normalized effective stress intensity factor range.

Thus $da/dN = C_{eff} \, (\gamma K_{max})^m$ (2)

from equation (1) and for Aluminium alloys:

$$\gamma = 0.5 - 0.1\,R - 0.4\,R^2 \quad (3)$$

Now several observations can be made:

1. The crack growth rates in mm/block for different types C/n can be easily determined from the relation $da/dN = f(K_{max})$.
2. Measurements of $(P_{op})_{eq}$ showed that it acquires a certain constant (relatively) value between (P_{op}) of type A and (P_{op}) of type B depending on number of B-cycles per block.
3. The greater is n, the nearer is $(P_{op})_{eq.}$ to the crack opening level of type B $(P_{op})_B$

On the basis of the above considerations,it reasonable to expect that when dividing the growth rates in (mm/block) by the number of maxima n per block,we can find equal crack growth in (mm/cycle) based on equivalent damage accumulation due to equal effective stress intensities ΔK_{eff} in the block as shown in Fig. 6. Of course this holds good as long as $(P_{op})_{eq.}$ is higher than $(P_{min})_B$.

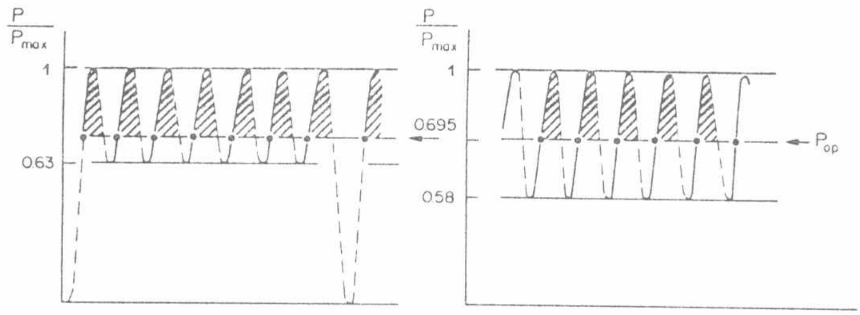


Fig. 6 Interpretation of eq.

We have applied this assessement to find the equivalent Paris relations for each type of C/n as indicated in Fig. 7 for the 2618 AT 851 Aluminium alloy.

The principle of equivalent-constant-amplitude loading is to get the same total crack length, an equivalent crack growth mode and an equivalent critical crack length for the two load sequences. All types C/n have the same value of P_{max} which is kept constant during the block loading. This value of P_{max} was taken to be P_{max} in the equivalent constant amplitude sequences. Thus,the same plastic zone envelopes are provided as the original block loading. By a simple translation of the equivalent Paris relations given in mm/cycle in Fig. 7 to the Elber's line , $\gamma_{eq.}$ corresponding to each type of C/n may be determined. Applying equation (3) corresponding equivalent constant amplitude cycle ratio R_{eq} could be determined.

Table 2 lists γ_{eq} and R_{eq} corresponding to each spectrum. These two parameters define the equivalent sequence that would replace the original block loading. A block of C/n can now be replaced by n

6 cycles of an equivalent constant amplitude sequence defined by R_{eq} , P_{max} and $P_{min_{eq}} = R_{eq} \times P_{max}$.

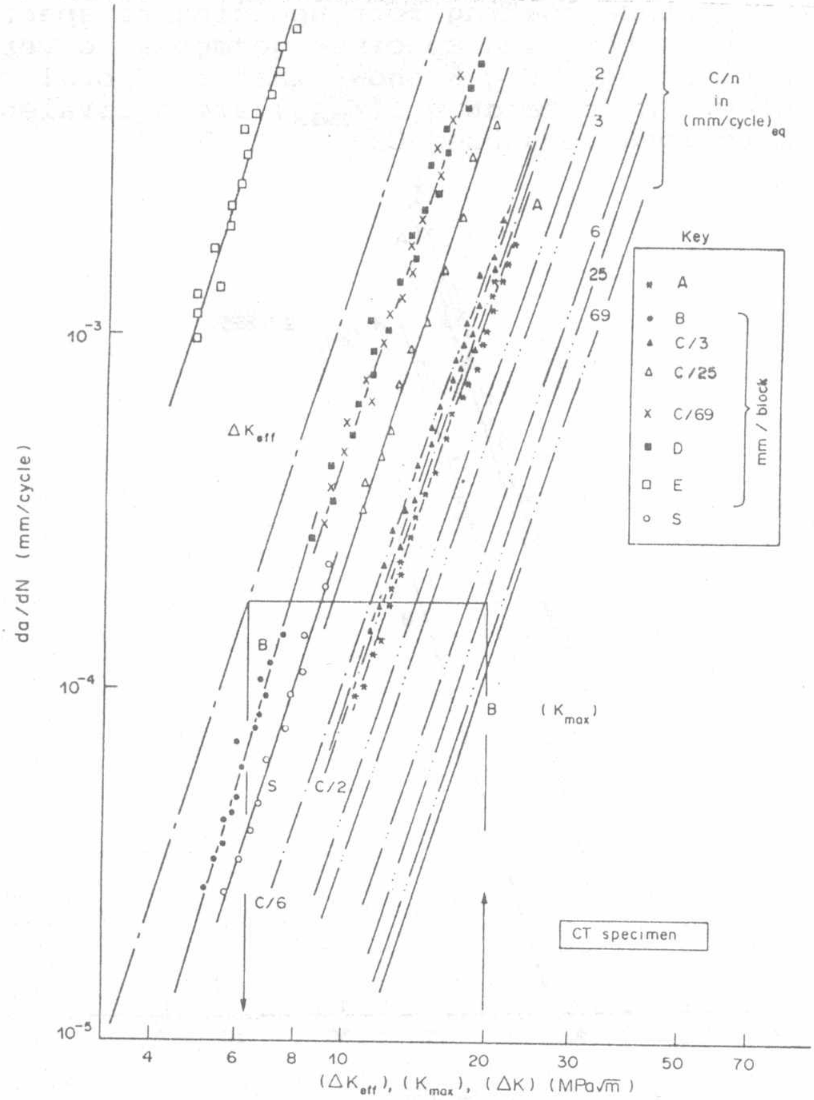


Fig. 7 Analysis Based on Crack Closure Concept

Type	γ_{eq}	R_{eq}	α_{eq}	$P_{op_{eq}}$
A*	0.5	0.01	0.5	$= (P_{op})_A$
C/2	0.445	o.25	0.555	$<\!\!< (P_{min})_B$
C/3	0.41	0.365	0.59	$\simeq (P_{min})_B$
C/6	0.355	0.489	0.645	$> (P_{min})_B$
C/25	0.305	0.58	0.695	$> (P_{min})_B$
C/69	0.29	0.61	0.71	$> (P_{min})_B$
B*	0.278	0.63	0.722	$= (P_{op})_B$

* Constant amplitudes(originally)

Table 2 Results of Equivalent Constant Amplitude Concept

Validity of The Equivalent Constant-Amplitude Concept

Tests of constant-amplitude loading corresponding to spectra C/3, C/6 and C/25 were run on the same specimen geometry to verify the validity of this equivalence. Fig.8 shows that the total crack growth and crack growth mode $da/dN = f(K_{max})$ are equivalent for the two corresponding load sequences C/3.

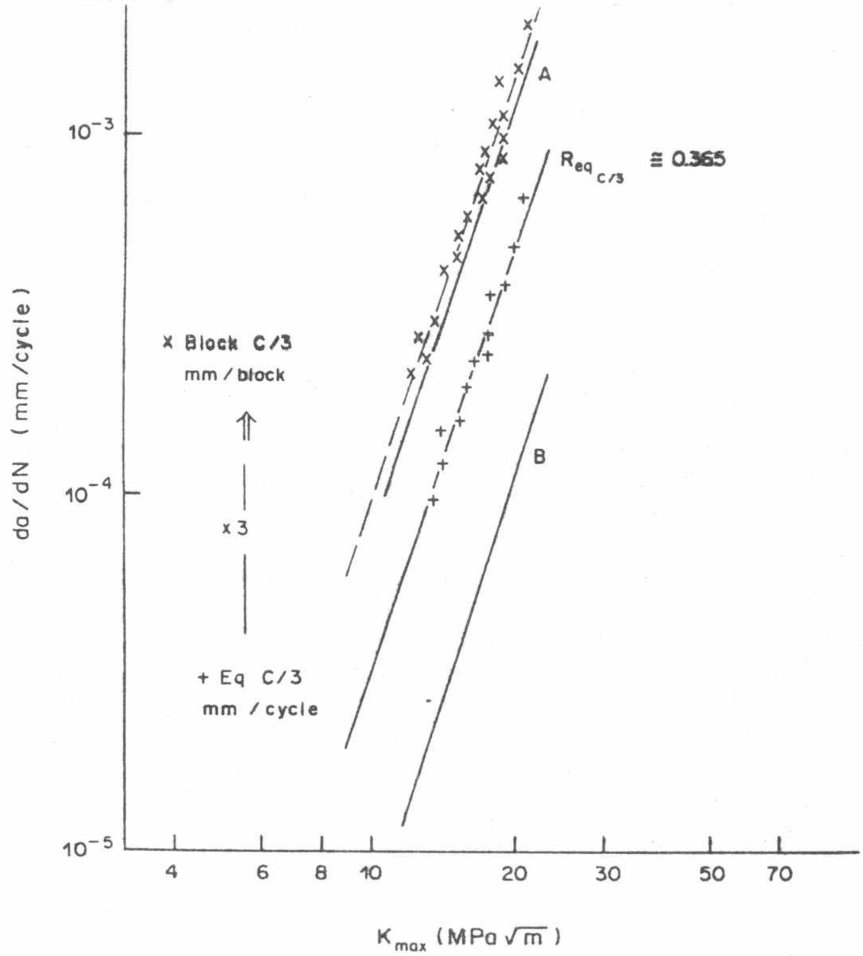


Fig.8 Validity of the Equivalent Constant-Amplitude Concept

Table 3 lists the ratio between actual number of blocks and the number of equivalent sequences ($N_{ex.}/N_{eq.}$). It ranges from 0.88 to 1.02, A range which can be met oftenly in fatigue data and would prove the applicability of this concept.

Type	$R_{eq.}$	a_0 mm	a_f mm	$N_{ex.}$ block	$N_{eq.}$ cycle	$N_{eq}(S)$ sequence	$[\frac{N_{ex.}}{N_{eqS}}]$
C/3	0.365	26	40	38100	112500	37500	1.02
C/6	0.489	26	40	28000	190000	31666	0.88
C/25	0.580	26	40	12700	355000	14200	0.89

Table 3 Validity of Equivalence

Retardation after A Single Tensile Overload

The crack growth data show a strong influence of the parameter R, the use of the ΔK_{eff} concept based on crack closure data proves to be successful and would suggest that crack closure might be responsible for the R-ratio influence. Attempts have been made to use crack closure in explaining crack growth retardation after overloading[1,15,20]. in our present study we measured the change of crack closure after a single tensile overload of $\tau = 2$,

$\tau = \Delta K_{ov.1} / \Delta K_0$, applied on a CCT 2124T351 specimen of 2 mm thickness. Fig.9 shows a typical plot of P_{op} level before,during and after the overload cycle. About 600 cycles after the overload peak were needed so that P_{op} would pass again by its original level,about 637.350 cycles were needed so that P_{op} level is the highest and about 690.050 cycles so that P_{op} regains its original level corresponding to the constant-amplitude sequence.
All documented reports and our experimental results indicate that the retardation after overload is not immidiate. After the overload, the crack can not be closed immidiately upon subsequent cycling,delaying the retardation and possibly causing initial acceleration.

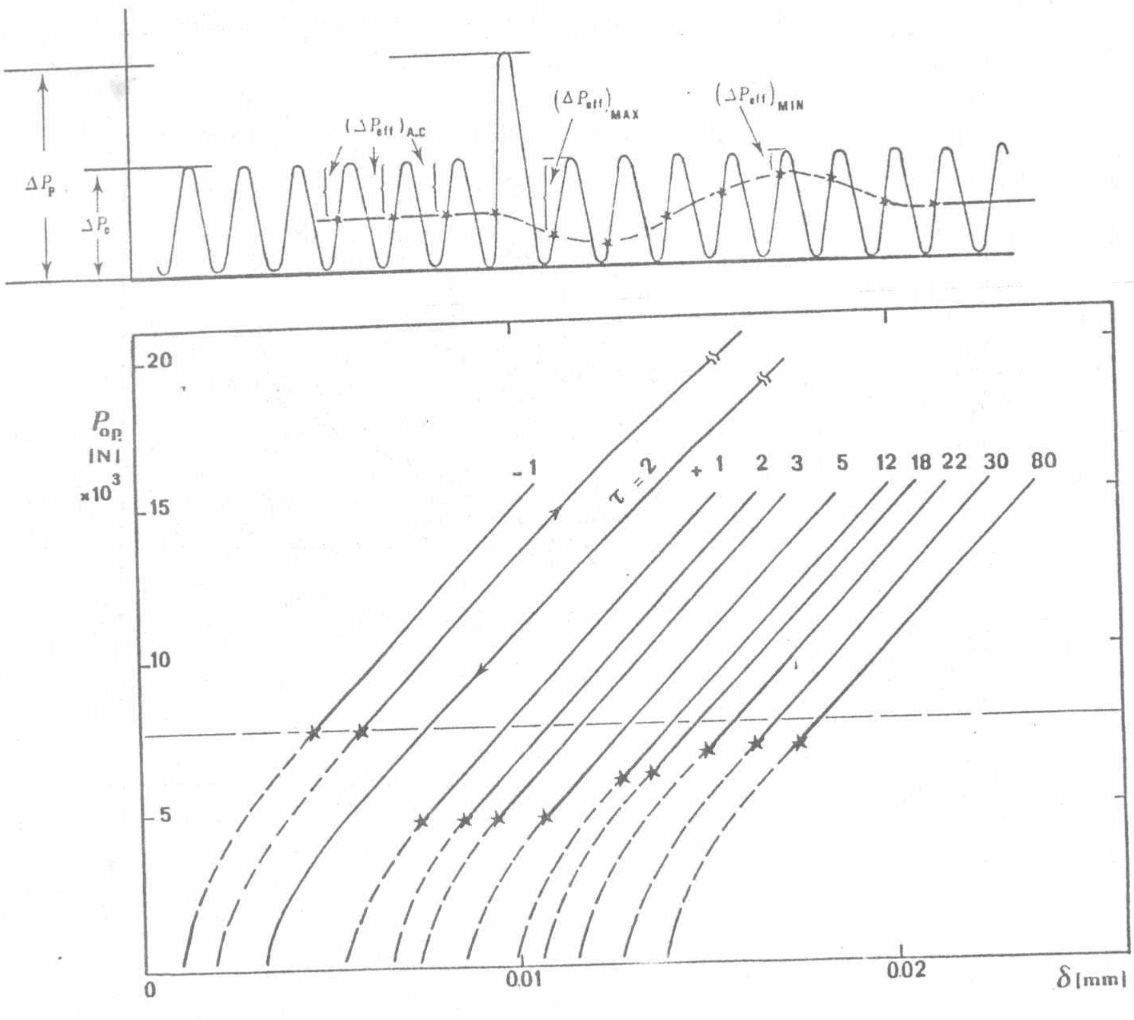


Fig.9 Varaition of P_{op} Level

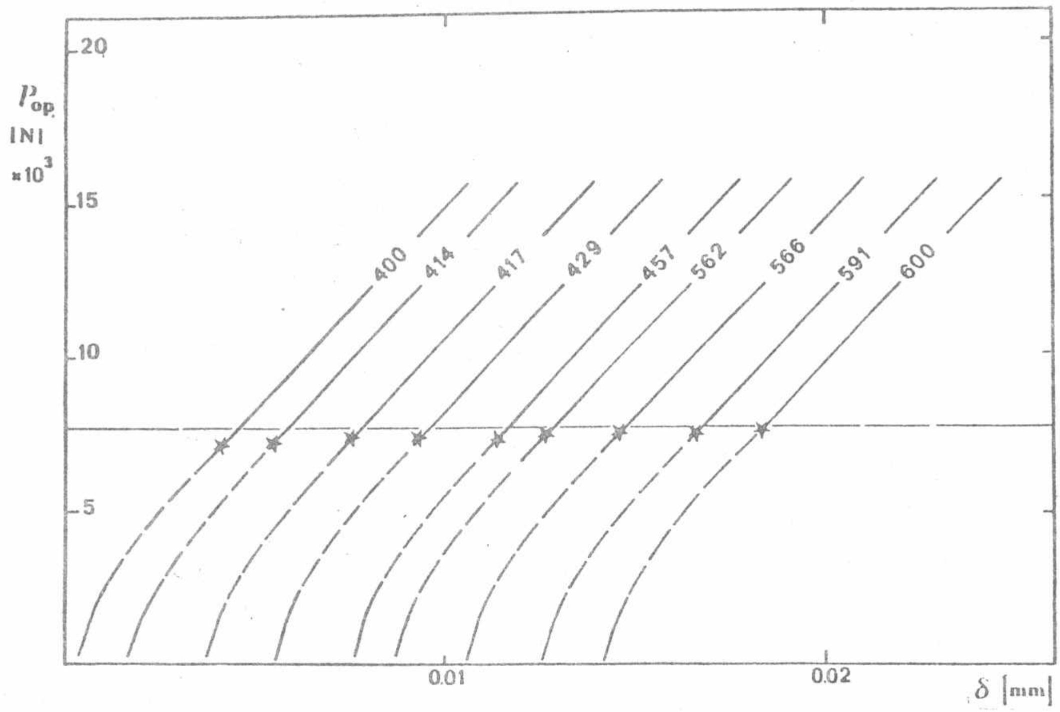


Fig.9 Continue.

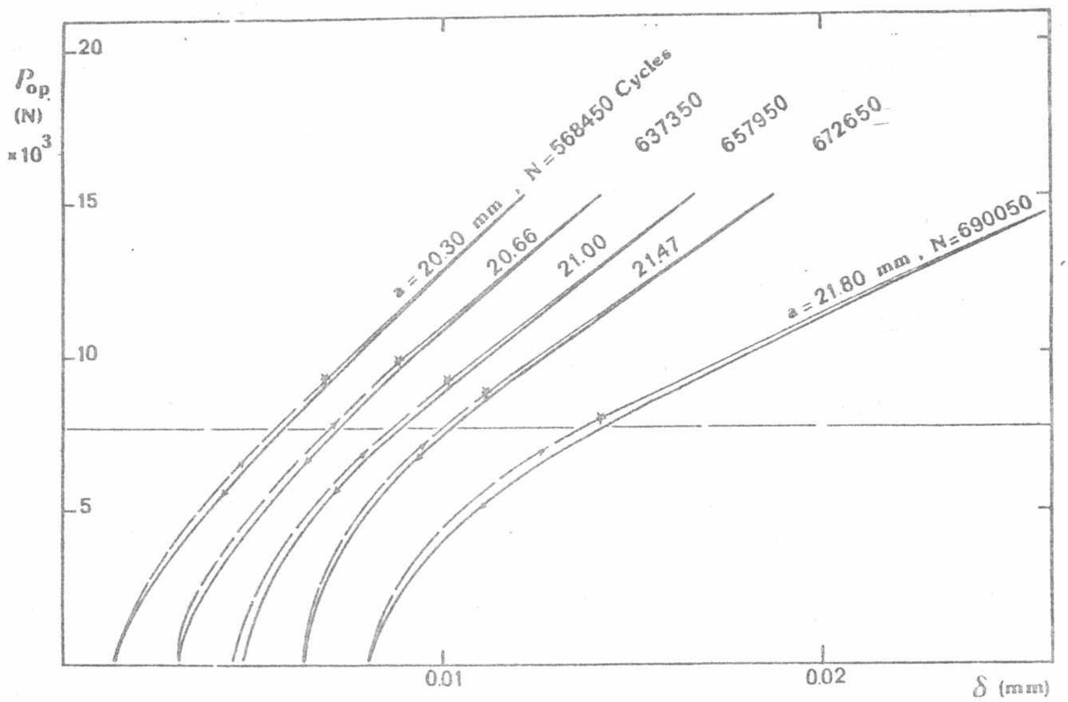


Fig. 9 Continue.

We think that the 600 cycles after overload peak were consummed in such a delayed retardation. Fig.10 shows that practically crack growth during these cycles was negligible. However, as the crack propagated into the plastic zone, the clamping action of residual stresses acts on the new fracture surfaces. This clamping action builds up reuiring a higher stress to open the crack. As a result the retardation occurs. the crack closure might further explain retardation as follows:
1. Deceleration phase corresponding to the cycles consummed to have maximum opening level(minimum ΔK_{eff}), 2. A relative acceleration phase corresponding to cycles consummed to regain the original crack opening level. the retardation process is usually described by means of two parameters: N_d, the number of cycles affected by retardation and a_d, the crack length along which the growth rate is disturbed as soon as the overload is applied. Determination of these two parameters based on crack closure concept is illustrated in Fig.10.

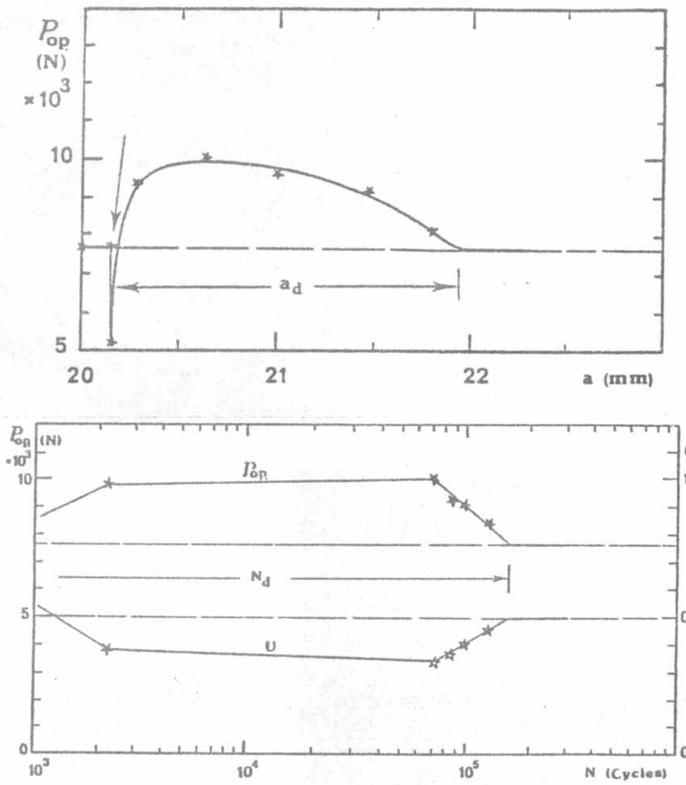
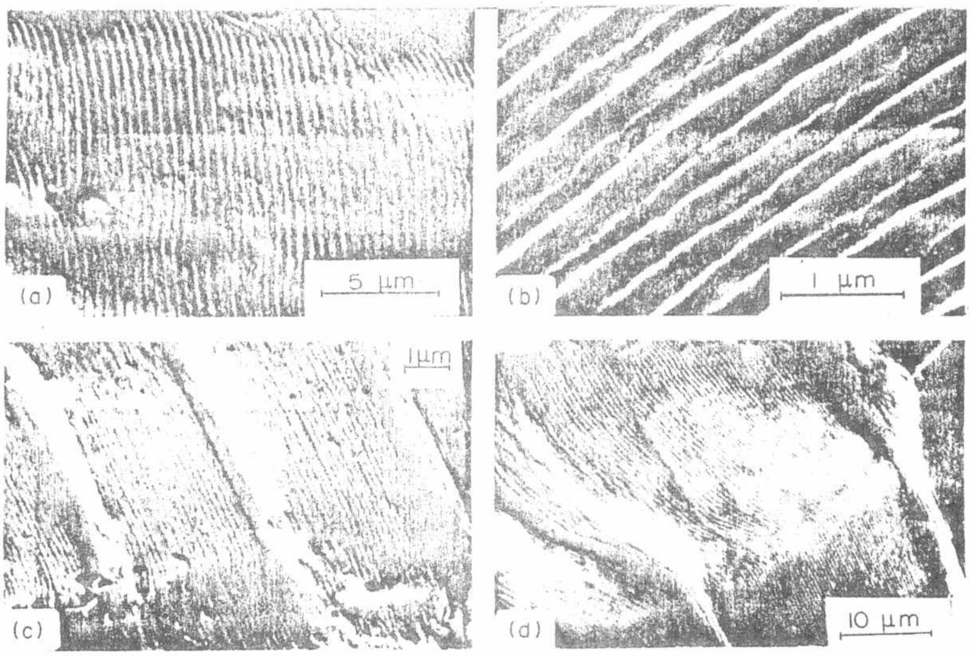


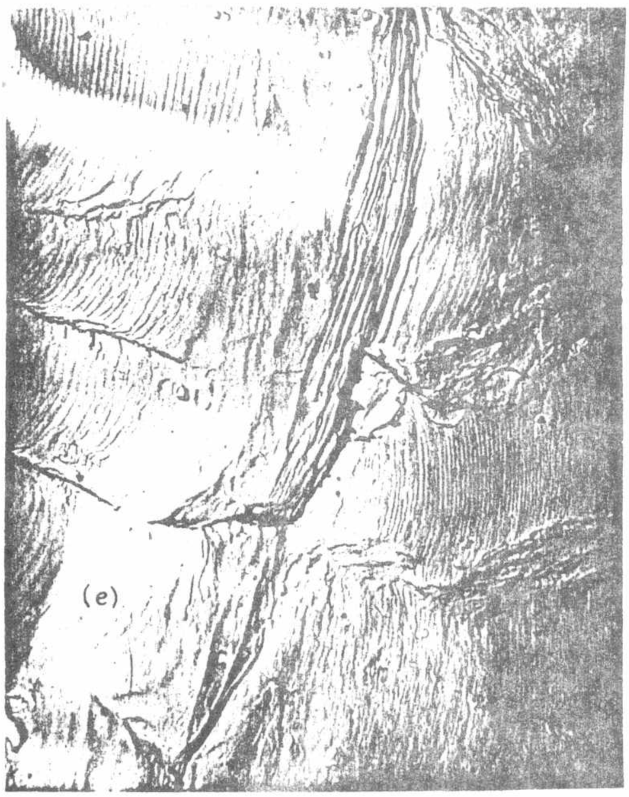
Fig.10 Determination of Retardation Parameters

Several models have been proposed to determine retardation parameters,among which are Wheeler[21] and Willenborg[22]. Unfortunately, the descripencies between experimental and predicted values are large enough. we think that this descripency is due to the fact that both models are based on immidiate retardation and the relative acceleration phase only,whereas, retardation is not immidiate as discussed before.

Microfractography

The fractured surface is a finger print or a record of the loads expeienced by the specimens. Cycle by cycle evidence, in the form of striation, of crack behaviour are provided through the use of electron microscope[23]. Tested specimens were examined through the scanning electron microscope. Different aspects of load-time history are easily recognized for different spectra.
Different flight types C/n and overload retardation are identified in Fig.11.





(a) Type C/2) 2618AT851
(b) Type C/3)
(c) Type C/25) 2124T351
(d) Type C/69)

(e) Single Overload

Fig.11 Fracture Surfaces

CONCLUSIONS

1. Aluminium alloys respond significantly to variation of the cycle ratio-R.
2. The crack closure gives a significant contribution to the investigation of fatigue crack propagation under variable-amplitude loadings.
3. Based on crack closure phenomenon, the developed equivalent constant-amplitude sequences to replace block loads is very promising in fatigue life prediction under variable-amplitude loadings.
4. Crack closure is necessary to define the cycle striation. The significant markings(deep valleys or high peaks) are associated with GAG cycle.
5. Aluminium alloys showed a significant variation in crack closure level after overloads. Crack growth retardation can be attributed to this variation.
6. retardation in Aluminium alloys after single overload is not immidiate, a delayed retardation is noticed. Crack closure concept can successfully account for this phenomenon.

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