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FATIGUE CRACK GROWTH IN ALUMINUM ALLOYS UNDER PROGRAMMED BLOCK LOADING

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ABSTRACT

Using fracture mechanics principles, crack growth rates can be predicted accurately for some simple crack configurations subjected to constant amplitude loading. However, for more complex loading sequences such as flight simulation loadings, the results are conservative by a factor 3 to 10 or more. The main objective of this study is to interpret the fatigue behaviour of two aluminum alloys under programmed block loadings. The effects of cycle ratio R (σ min/σ max) and material thickness on crack propagation rate are analysed. Fatigue crack growth under programmed block loading is presented. Linear damage accumulation is established for some simple flight simulation tests. Aspects covered include microscopic and fractographic observations. The incidence of crack closure is examined and the agreement between predictions and test results is very promising.

INTRODUCTION

In variable amplitude loading (V.A.L.) several effects are to be considered to predict correctly the fatigue crack growth /1/ Interaction effects are well manifested in the observed phenomena defined as retardation or acceleration of cracking. This implies that the crack extention in a loading cycle Δa will depend on what occured in the preceding cycles. Δa will depend on such factors as crack tip blunting, shear lip development, crack closure, cyclic hardening and residual stresses. All these phenomena occur around crack tip /2,3/. Schijve /2/ has classified the various types of loading in five main groups, namely: overloads, step loading, programmed blocks, random loading and flight simulation loadings. Moreover, he/4/ simplified these groups in two main categories : stationary V.A.L. where the sequence of load cycles is repeated excatly and regulary; non-stationary V.A.L. with no sequencial repeat-

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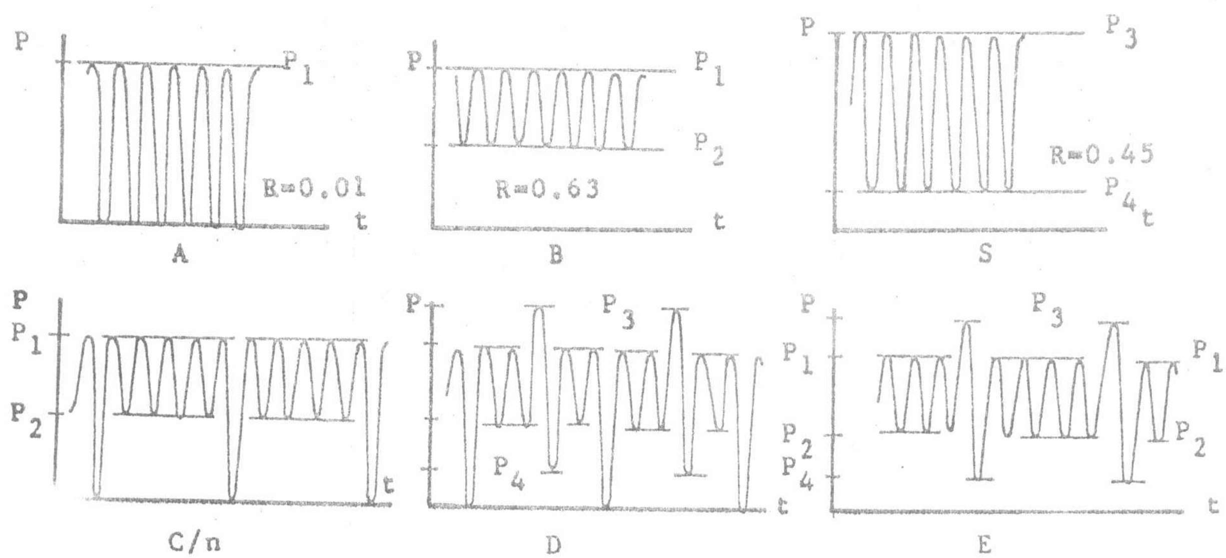
ion of a block of different load cycles. Elber /5/ defined a short spectrum to be one where crack growth during one repeated interval is less than the plastic zone created by the highest load in the spectrum. Our study is undertaken to investigate the crack growth rate behaviour in 2124 T 351 and 2618 AT 651 aluminum alloys widely used in aeronautical structures. Programmed block loading was chosen to simulate some simple flight types of the standardized load sequence for flight simulation tests on transport aircraft wing structure (TWIST). TWIST program /6/ comprises ten different types of flight adopted to the mean stress in flight (1-g condition). The fact that the chosen block loadings have not introduced any interaction effects and consequently a linear damage accumulation, implies that crack growth depends essentially on the stress intensity factor range ΔK and cycle ratio R. The good agreement between experimental results and prediction has directed our attention to determine the parameters of an equivalent constant amplitude sequence that replaces the original block loading in the crack grwoth calculations /7/. The developed concept is based on physical aspects of damage and crack closure phenomena, approved by microscopic observations.

TEST PROGRAM

The test program was designed so that the crack growth under different cycle ratio R would be investigated separately.The test matrix was defined in terms of three levels of loading: A, B and S with ratios (R=0.01, 0.63, 0.45) respectively. The patterns and loading values for the programmed blocks are shown in Fig.1. Type A is considered as a simple nondisturbed



	P1 (N)	P2(N)	P3 (N)	P4(N)
C.T.	6200	3940	6970	3170
C.C.T.	18350	11560	20486	9424

Figure 1 : Patterns and Loading Values

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flight and would represnt the Ground-Air-Ground cycle(G.A.G.). Types C/n (n takes values 2,3,6,25 and 69) however, represent the disturbed flight types in which B- cycles represent the flight disturbing loads (gust, manoeuvre, etc...). The same definition is valid for S and B- cycles in types D and E.

EXPERIMENTAL PROCEDURE

The materials used for this investigation are two aluminum alloys : 2124 T351 (AU 4G 1) and 2618 AT851 (AU 2 GN). The specimen geometries are: 1) compact tension specimens (C.T.) /12 mm thick, 75 mm wide/ ; 2) center crack tension specimen (C.C.T.) /2 mm thick, 200 mm wide/. The chemical composition, mechanical properties and heat treatment are listed in tables 1,2 and 3 respectively. The test specimens were polished to a mirror finish in the vicinity of the crack path to facilitate optical observation of the crack tip during crack growth measurements. Crack length was monitored continuously by a travelling microscope with a resolusion of 0.01 mm. Tests were performed on servo-valve, electro-hydraulic INSTRON and MAYES testing machines of ± 10 ton and ± 5 ton respectively.

ALLOY	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti
2124 T 351	0.09	0.21	1.40	0.63	1.50	0.01		0.04	0.03
2618 AT 851	0.22	1.12	2.61	0.06	1.63	0.01	1.14	0.02	0.12

TABLE 1 : Materials' chemical composition

ALLOY	Sense	$\sigma_{0.2}$ MPa	σ_m MPa	A%
2124 T 351	TL	328	472	15.16
2618 AT 851		410	450	6.03

TABLE 2 : Materials' tensile properties

ALLOY	Heat treatment
2124 T 351	Solution heat treated,cold work-naturally aged
2618 AT 851	Solution heat treated,cold work-artificially aged at 190° C

TABLE 3 : Materials' heat treatment

All tests were run at a frequency of 10 HZ and in air at room temperature.In order to measure the crack opening level (P_{op}) a surface gauge located at the crack tip was used to plot the opening displacement (δ) against the load (P), tests and plots were made at a frequency of 0.2 HZ. The programmed block loading were generated by a mini-computer PDP 11 which pilots the testing machines continuously during the test.

TEST RESULTS AND ANALYSIS

Constant Amplitude Loading

Fatique crack growth data in the form of da/dN (mm/cycle) versus stress intensity factor range ΔK (MP$\sqrt{m}$), for different cycle ratios R and for the two thicknesses are represented in Fig.2 The two aluminum allyos showed a significant effect of R ratio on their fatigue cracking. The effect of R ratio is either through the modification of the coefficient C or the exponent m in the Paris relation :

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

Consequently, a higher propagation rates for higher R ratios as pointed out in /8,9,10/. For the same loading conditions, thick specimens (C.T.) showed higher propagation rates than thin ones (C.C.T.). This is due to the different states of stress which depend mainly on the through thickness constraints.

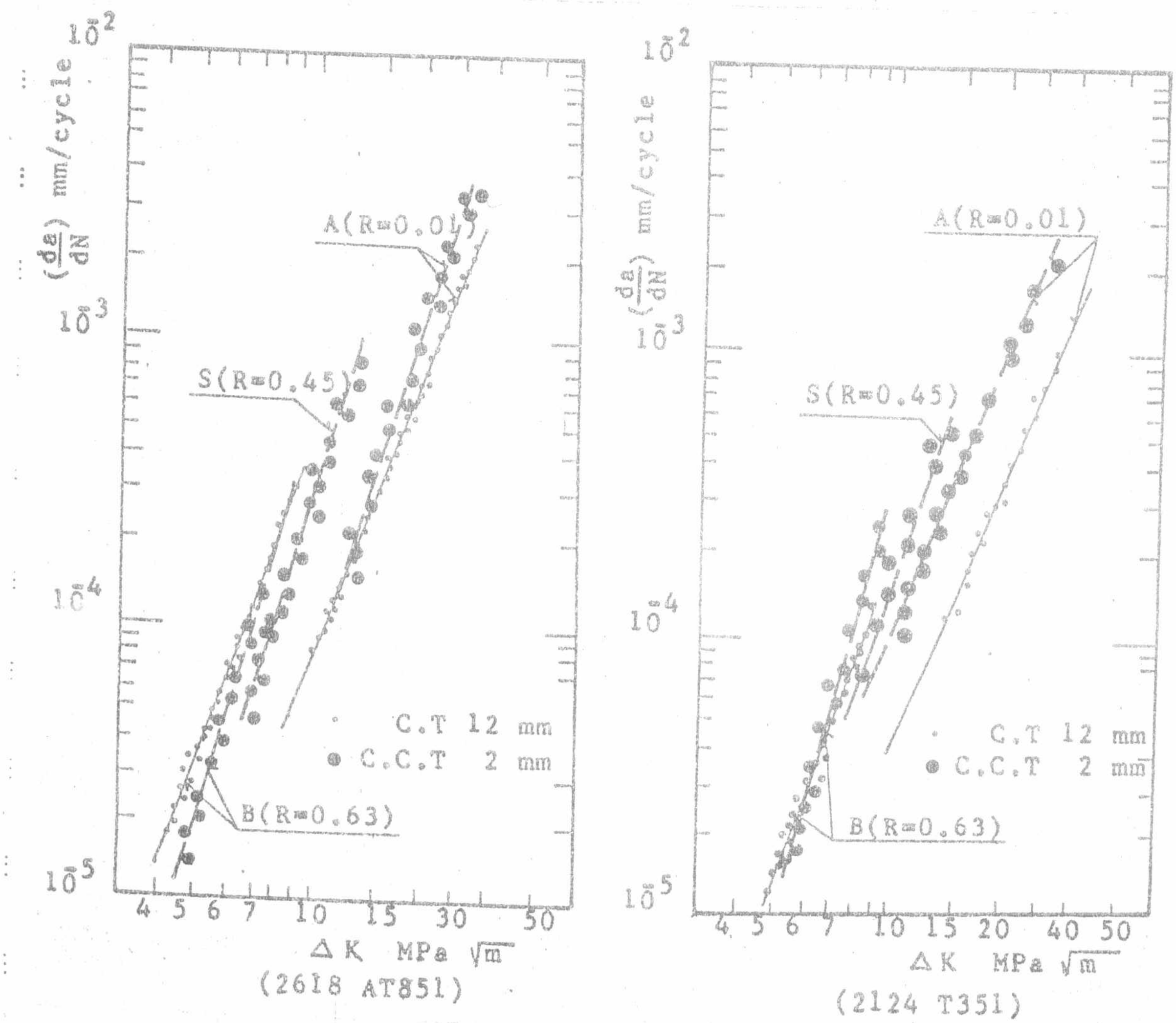


Figure 2 : R-ratio and thickness effects on fatigue crack propagation.

Spectrum Loadings

Fatigue crack growth data obtained for C.T. specimens are shown in Fig.3 in the form of a plots a=f(N) where N represents the number of flights (cycles for type A or blocks for types C/n). Types C/n are characterized by a constant maximum load level (P_1) and by one G.A.G. cycle which occurs once per flight.

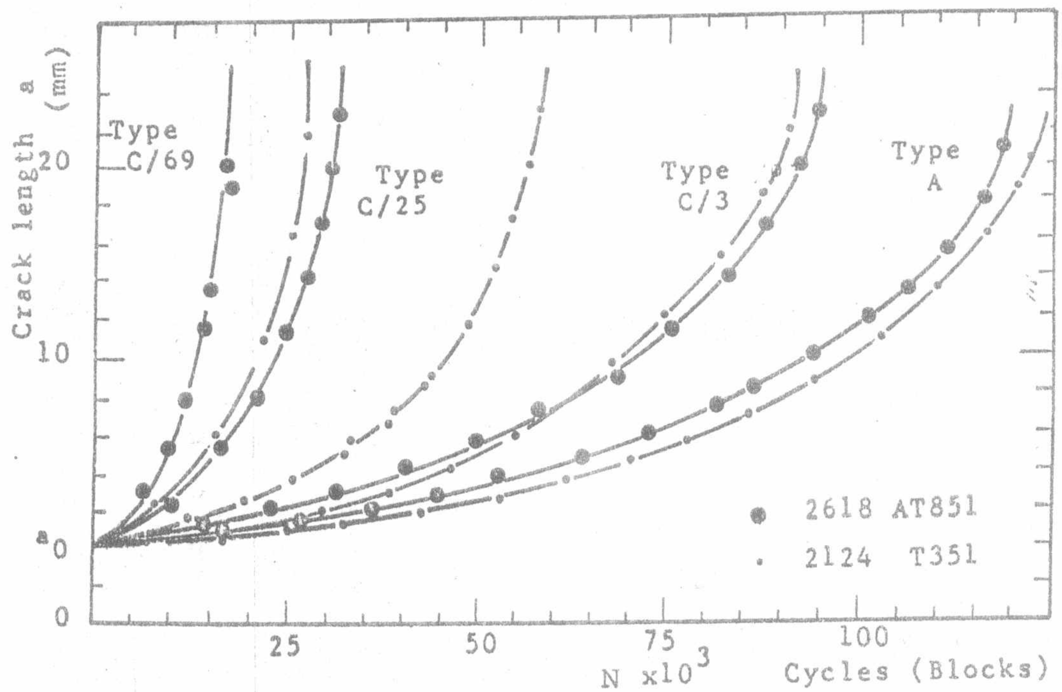


Figure 3 : Fatigue crack growth under different loading types.

Thus, distubed flights (types C/n) can be compared with simple non-disturbed flight (type A). Comparison being based on number of flights to failure and crack growth rate per flight expressed as a function of K_{max} for different C/n types as shown in Fig. 4. Consequently, the influence of flight disturbances (B-cycles) on crack propagation is possibly investigated. The dashed lines in Fig. 4 represent the non -interaction summation of crack growth corresponding to basic data of types A and B. It is interesting to find a good coincidence between these theoritically calculated growth rates and test data points for different types of C/n. This implies that it is only R ratio effects which caused these accelerations without any significant interaction effects.

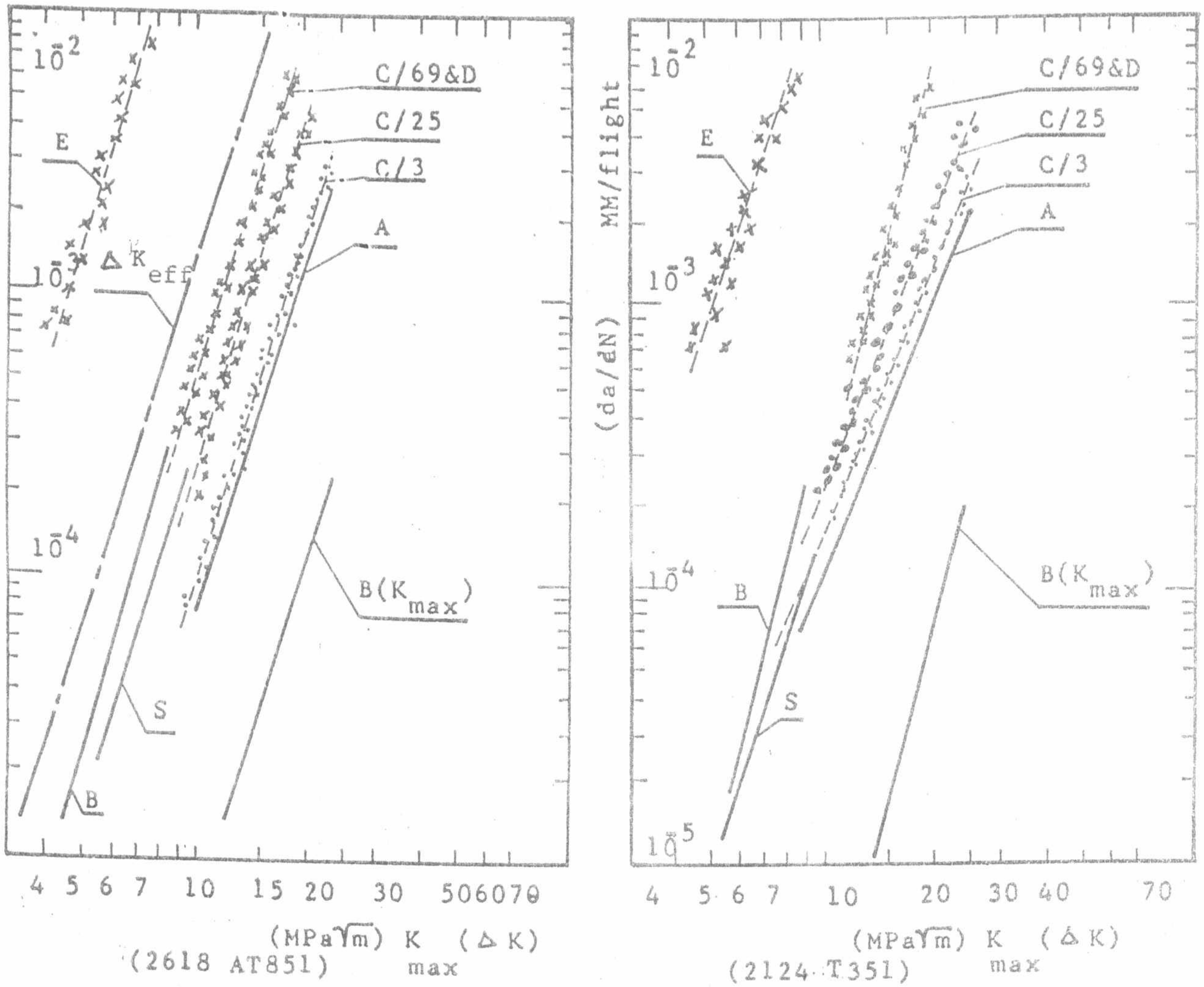


Figure 4 : Fatigue crack growth rate under different block loadings.

Analysis Based on Crack Closure Concept

In an attempt to better understand the mechanism of crack propagation under spectrum loading, it was decided to measure the crack opening stress level on a 2 mm thick C.C.T. specimen of 2124 T 351 under loading types (A,C/3 and C/25). The same technique of Elber /11/ was used. Fig. 5 gives typical plots of $P=f(\delta)$ corresponding to each type of loading. It was difficult to measure P_{op} during the low ΔK cycles (B-cycles) in the block, so we considered the modification of opening level P_{op} on the G.A.G. cycle as representing the crack opening load $(P_{op})_{equiv.}$ during the whole block. It is interesting to note that the level of P_{op} changes significantly with the number of B-cycles in each block. The average values of $\alpha = P_{op} / P_{max}$ are given in table 4

TYPE	A	C/3	C/25	B
MEASURED α	0,5	0,61-0,63	0,69	0,72

TABLE 4: Measured values of α (P_{op} / P_{max})

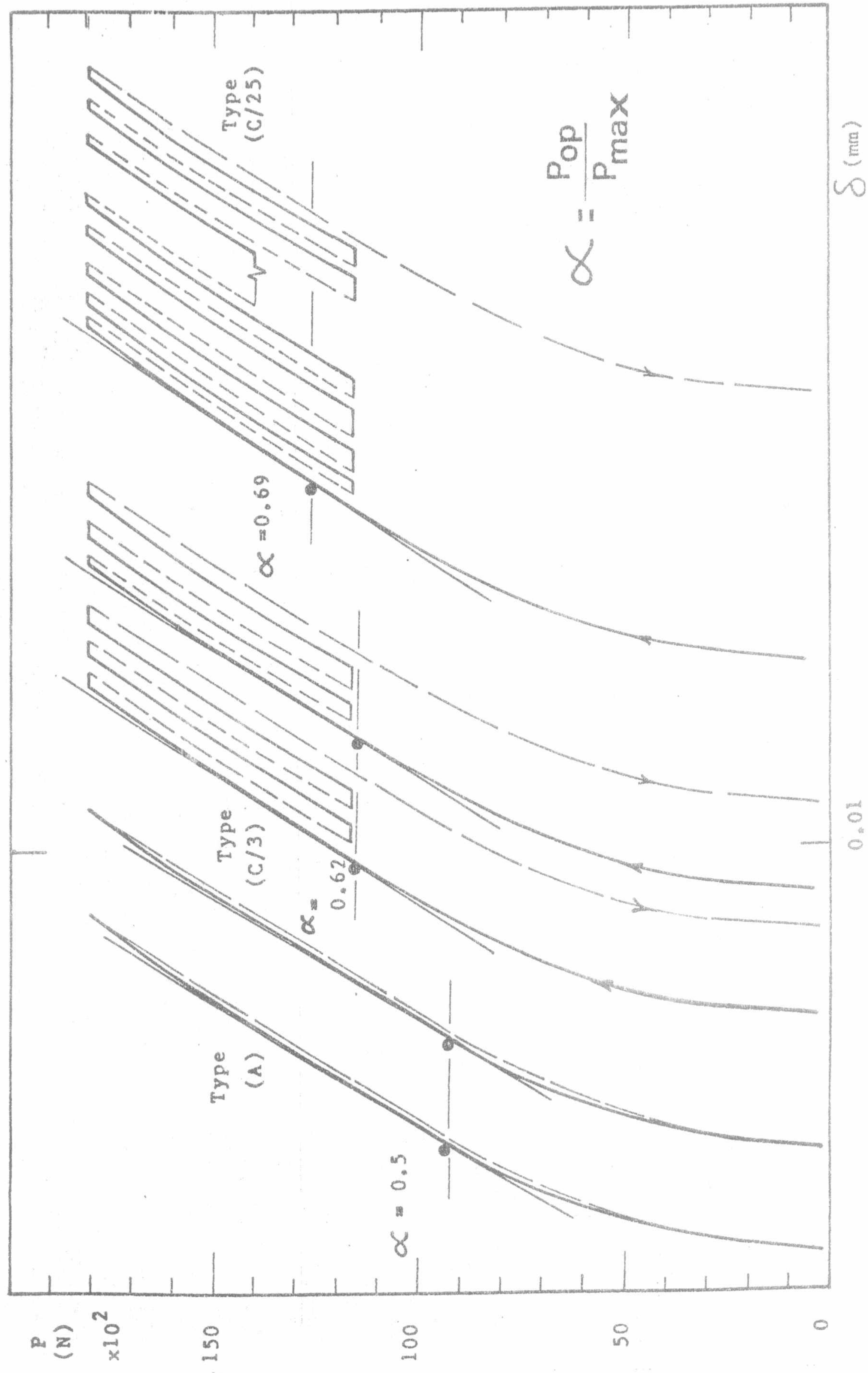


Figure 5 : Modification of Crack Opening Level

Based on Elber relation /11/

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

α is defined as P_{op} / P_{max}

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

For aluminum alloys $U = 0.5 + 0.4\ R$ (2)

This would yield that :

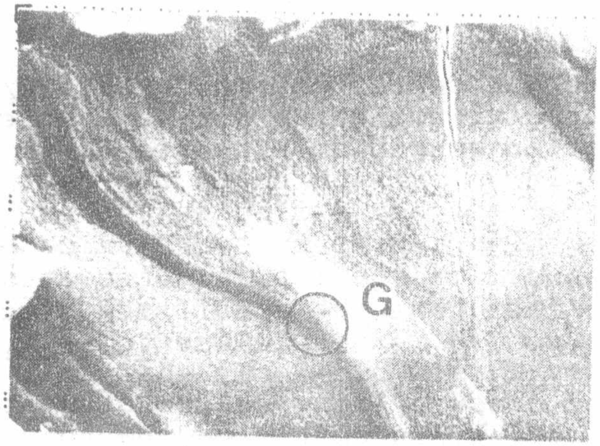
$$\alpha = 0.5 + 0.1\ R + 0.4\ R^2 \qquad (3)$$

As a first suggestion the ratio α for types C/n will have values such that $\alpha_A < \alpha < \alpha_B$ depending on the number of B-cycles per block. Consequently, we can expect that the crack opening level under such sequence (P_{max} is kept constant) will be stabilized after some crack growth and remain relatively constant through the crack propagation under these regular, short and stationary spectrum loadings.

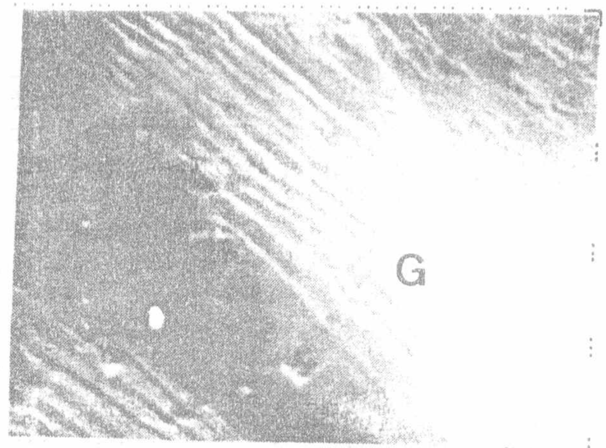
INTERPRETATION OF CRACKING MECHANISM

Microfactography

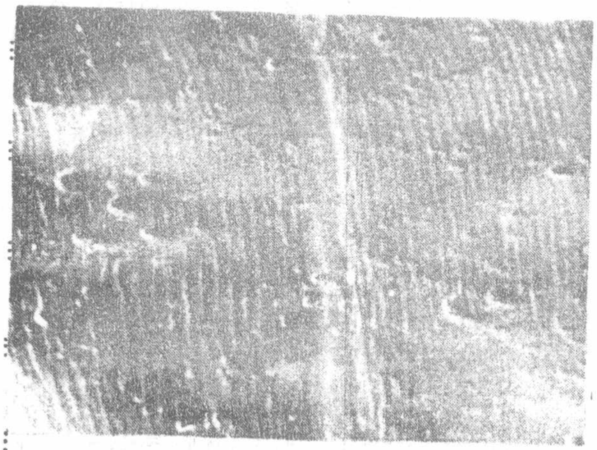
The fracture surface is a finger print or a record of the loading experienced by the specimen. Study of the fracture surface through the use of the electron microscope provides cycle by cycle evidence, in the form of striation, of crack behaviour that normally can not be established from macroscopic observations /12/. Tested specimens corresponding to each type were examined through the scaning electron microscope type CAMBRIDGE - STEREOSCAN 100.
Different aspects of load - time history are easily recognized for different specra where striation groups representing individual flight were identified as shown in Fig. 6. Only the block types C/2 and C/3 showed some ambiguity in distinguishing the flight disturbing loads (B-cycles) from the G.A.G. cycles. The fracture surfaces corresponding to load types C/6 C/25 and C/69 showed a clear correspondance between the spectrum and the striations. We think that in these blocks the unloading part of the(Air-ground) cycle (A) presents a heavy cyclic deformation that changes microscopically the cracking plane and cycles B reorient it. The first few cycles of B-cycles are enough to regain the cracking plane and their striations are well marked on this disorientation. This is clearly present in Fig. 6. Thus, a well defined closure of the crack does exist in each and every cycle forming these types of spectrum. This would emphasize that crack closure is an essential factor in defining the striation during fatigue



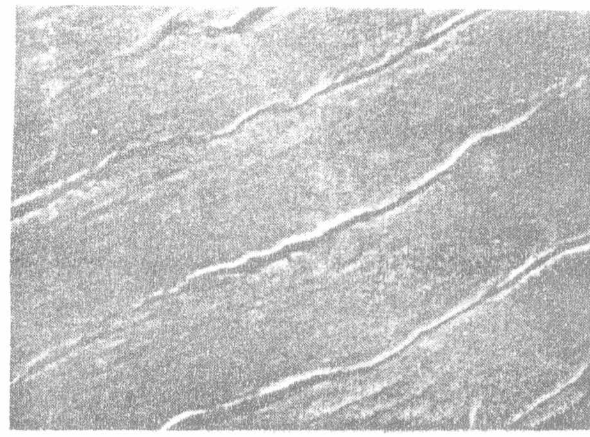
Type C/69 x1500



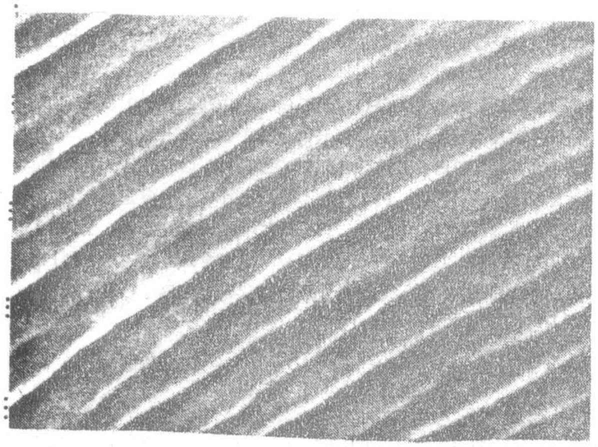
Type C/69 x 10.000



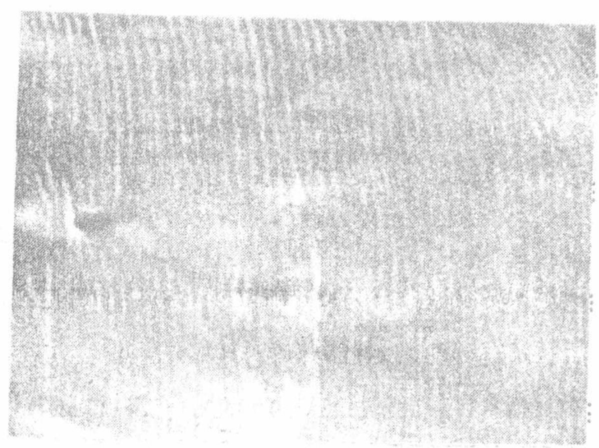
Type C/25 x 5000



Type C/6 x20.000



Type C/3 x 20.000



Type C/2 x 4000

Material : Aluminum alloy 2124T 351

Figure 6 : Microfractography and interpretation of Fatigue Cracking Mechanism.

crack propagation. Fracture surface corresponding to type C/3 showed equal striations without distinguishing between cycles B and A. Considering the striation mechanism proposed hereabove, the provoked ambiguity can be attributed to the fact that in type C/3, two cycles of B are not sufficient to reorient the cracking plane being disoriented by every unloading A. This leads to a continuous microscopically curregated fracture surface. Besides, the fact that the stabilized crack opening level $(P_{op})_{equiv}$ for type C/3 is very close to (P_{min}) of loading level B in the block. This would imply that an instantaneous crack closure and crack opening is produced at $(P_{min})_B$. Consequently, equal striations corresponding to levels A and B are to be expected as found in Fig.6. Whereas, in type C/2 the crack opening level $(P_{op})_{equiv}$ is far low from $(P_{min})_B$ in the block. This would suggest either a very poor or even no crack closure during the one B-cycle in the block type C/2. Consequently, the microfractography of this type would only show striations corresponding to the G.A.G. cycle in each block during which the crack closure does exist.

CONCLUSIONS

1) Aluminum alloys respond significantly to variation of the cycle ratio R (P_{min}/P_{max}). For a given value of ΔK the crack growth rate increases pronoucely with R. The ratio R has a simultaneous effect on the translation of Paris relation.
2) Linear damage accumulation is established during crack propagation under the studied spectra where R ratio effects play the essential role.
3) The crack closure gives a significant contribution to the investigation of fatigue crack propagation under variable amplitude loadings.
4) Microfractography and its interpretation are essential tools in understanding fatigue crack propagation.
5) Crack closure is necessary to define the striations. The significant markings (deep valleys or high peaks) are associated with the G.A.G. cycle and the peak flight load cycle. They appear to be caused by the heavy deformations due to the large unloadings preceding the B-cycles.

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