

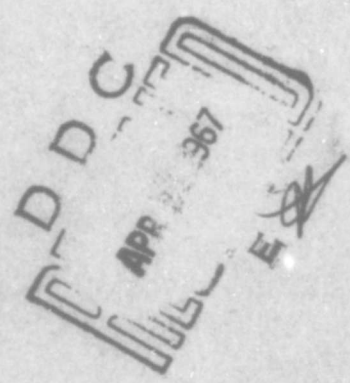
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Fatigue Crack Propagation under Programmed and Random Loads

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UNDER
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by

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and
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July 1966

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ABSTRACT

The influence of maximum stress, stress range, and sequence of load application on the rate and mechanism of fatigue crack propagation in 2024-T3 aluminum alloy was studied by means of electron fractography. Variable amplitude loading programs were designed to provide tests under the following conditions:

1. Constant maximum stress with three different levels of stress range,
2. Constant stress range with three and four levels of maximum stress,
3. Pseudorandom load application achieved by random distribution of the load spectra defined in items (1) and (2),
4. Uniform maximum stress with peak overloads and underloads.

The macroscopic growth rates were determined on center-notched crack growth panels and the fracture surfaces were examined by electron fractography. The analyses of the influence of program loads on the rate and mechanism of fatigue crack growth were accomplished by:

1. Comparing plots of crack length *versus* measured rates of crack propagation for the different programs. The measured rates were also compared with rates calculated by a computer program.

7. Relating the count and spacing of the fatigue striations observed on the fracture surfaces to the applied load program, by means of electron fractography.

An empirical equation relating relative microscopic growth rates at a given crack length to maximum loads and load amplitudes was obtained. It was also found that the advance of a fatigue crack front takes place only during the loading part of a cycle and that in the pseudorandom load case the sequence of load application can markedly influence crack growth rate on any one cycle.

I. INTRODUCTION

The "fail-safe" concepts used in design of aircraft structure require a basic knowledge and understanding of the fatigue crack propagation behavior of airframe materials. Although considerable progress has been made in the last twenty years^{1,2,3,4,5} toward understanding fatigue crack propagation, the methods used to predict the fatigue properties of structure under program or random loads still have a low degree of reliability and confidence. In particular, the relationship between the fatigue damage created by random service loads and by programmed test loads has not yet been established. One of the main technical difficulties has been an inability to separate the fatigue damage induced by each load application in a complex load history. For instance, in a typical fatigue test the smallest crack length change measured with a 50X traveling microscope is of the order of .001", which may correspond to 100 or 1,000 load programs, or to an even larger number of mean crossings in a random load test. Even if we were to use a higher magnification microscope the surface measurements of crack length would not give us a load-crack length relationship with significantly greater resolution because of the uncertainty of the definition of the actual, subsurface crack tip position.

Fortunately, in most of the aluminum alloys used as airframe materials, the fatigue fracture surface itself shows the successive positions of the fatigue crack front with an amazing resolution. Suc-

cessive crack front positions spaced less than 1×10^{-6} inches apart have been observed. The successive crack front positions are represented by a series of groove ridge lines on the fracture surface, and are called crack front arrest lines or simply fatigue striations. These striations were first observed with the optical microscope⁶ but can best be studied with the electron microscope at magnifications ranging from 1,000 to 20,000. In the case of the 2000 and 7000 series of aluminum alloys the striations are remarkably well defined, at least for crack growth rates ranging from 1 to 1,000 $\mu\text{inch}/\text{cycle}$. At the lowest growth rates, where the need for growth rate information is greatest, nearly all of the fracture surface shows striations. At higher growth rates the percentage of fracture surface occupied by striations decreases. That is, fracture by cyclic ductile tear predominates as the crack approaches critical crack length.

The fact that the striations represent successive positions of the crack front enables us to study the mechanisms and rates of fatigue crack propagation as a function of crack length, load history, stress intensity factor, and environment. So far, most studies of fatigue fracture surfaces by electron microscopy have been limited to qualitative observations of the striation shapes and profiles, and to striation interactions with grain boundaries or second phase particles.⁷ A limited amount of quantitative work has shown that for uniform cyclic loads and for crack growth rates greater than 1 to 10 $\mu\text{inch}/\text{cycle}$, there is a one-to-one correlation between striations

and load cycles.⁸ Also, it has been shown that the measurements of striation spacing, which represent the microscopic rate of crack propagation, correlate very well with the macroscopic measurements of crack propagation rates.^{9,10}

In recent studies at Boeing we used optical and electron fractography to study the fatigue fracture surfaces of many structural test components tested under programmed loads designed to simulate service conditions. In each case the load program could be readily related to the general topography of the fracture surface. However, the complexities of the test components and of the load spectra were such that it was not possible to make a direct correlation between each applied load and the observed striation spacings. As a consequence, we ran a number of fatigue crack propagation tests with different simplified spectra of loads. These loads were programmed in such a way as to lead to an unambiguous interpretation of the microfractographic observations.

The purpose of this research program was to achieve a better understanding of the following problems:

1. The influence of maximum load, load amplitude, and load sequence on crack propagation rates. Two basic types of load programs were studied: (a) constant maximum load with variable load amplitudes, and (b) constant load amplitude with variable maximum loads.

2. The comparison of pseudorandom loading with program loading. The two basic types of load programs defined above were

randomized and the crack growth rates were compared.

3. The occurrence of crack arrest and crack acceleration.

Striations were counted and striation spacings were measured following changes of maximum loads or load amplitudes.

4. The mechanisms of fatigue cracking and striation formation. Some of the load sequences were planned to distinguish clearly between loading and unloading behavior at the crack tip.

5. The prediction of programmed or pseudorandom load crack propagation rates. Using crack growth data from constant maximum load and constant load amplitude tests, a computer program calculated the expected crack growth rates for all the programmed and random load tests. The validity of Miner's rule for crack propagation was evaluated by comparing calculated with observed growth rates.

II. EXPERIMENTAL PROCEDURE

Materials

The material chosen for this program was 2024-T3 aluminum alloy in the form of bare 0.160-inch gage sheet. The 2024-T3 alloy was selected because its fatigue crack growth rates are less susceptible to environmental effects such as humidity, than are alloys of the 7000 series.¹¹ Also, the fatigue striations of the 2024 alloy are always clearly defined and are of the ductile type.¹² Thus, they lend themselves to a detailed striation profile and spacing analysis. A number of similar tests were also conducted on aluminum alloy 7075-T6

to confirm the generality of relationships established for the 2024 alloy. The chemical composition and mechanical properties of the transverse grain direction of the 2024-T3 material used in this program are shown in Tables I and II, respectively.

Test Procedure

The test specimen used in the fatigue testing portion of the program was a 24" x 9" center-notched fracture panel, with the transverse grain direction parallel to the tensile axis. Fatigue testing was accomplished in a vertical 125 kip electrohydraulic fracture jig of Boeing design at a cyclic rate of 90 cpm.

Program and random loads were introduced by punched tape digital programming through a Boeing-designed forced closed loop, servo system, random load controller. Previous work has shown this testing system to be capable of applying loads with an absolute error of ± 1 percent of the maximum programmed load for the random load case at cyclic rates up to 90 cpm. A typical load recording is shown in Figure 1.

The initial center crack (2a) was 0.5-inch with a crack root radius of .003-inch. Crack growth was monitored with a 50X traveling microscope. Specimens were normally cycled to failure. All testing was conducted in a laboratory environment. Temperature and relative humidity, recorded periodically throughout the tests, ranged from 65°F to 79°F and 17 percent to 52 percent relative humidity. The averages were approximately 70°F and 40 percent relative humidity.

TABLE I

CHEMICAL COMPOSITION

<u>Programs</u>	<u>Cu</u>	<u>Mg</u>	<u>Mn</u>	<u>Zn</u>	<u>Si</u>	<u>Cr</u>	<u>Fe</u>	<u>Ti</u>	<u>Al</u>
P1 to P7, P11, P12	4.10	1.65	0.56	<0.03	0.07	<0.03	0.21	<0.03	BAL.
P8, P9, P10	4.44	1.56	0.66	<0.05	0.08	<0.01	0.17	<0.03	BAL.

TABLE II

MECHANICAL PROPERTIES

<u>Programs</u>	<u>F_{TU} (psi)</u>	<u>F_{TY} (psi)</u>	<u>% Elong.</u>	<u>% RA</u>
P1 to P7, P11, P12	68,400	46,900	17.0	23.0
	68,400	47,700	18.0	24.0
	69,000	48,000	19.5	26.0
P8, P9, P10	70,200	46,700	20	27
	69,700	45,200	20	28
	70,500	45,100	19	26

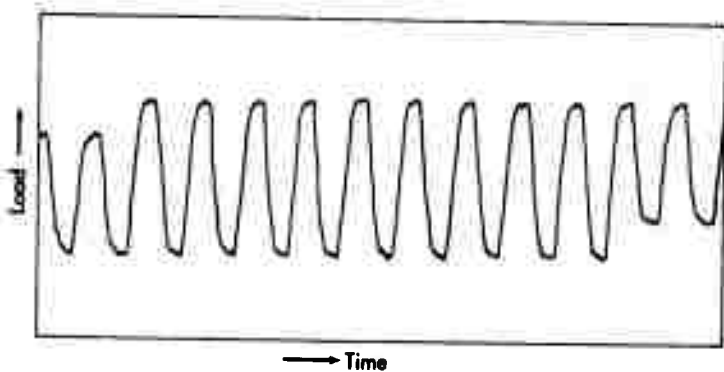


Figure 1 Typical recording of load for part of Program P13.

All the test data, crack length *versus* number of periods, are reported in Appendix I. The crack rates $\frac{dl}{dn}$ have been calculated as the linear average over the interval between two successive crack length readings. The crack rate obtained is assumed to be the crack rate at the middle of the crack length interval.

Standard two-stage replicating techniques were used to prepare replicas for examination with the electron microscope. The shadowing material was germanium, and in every case but one, the shadowing direction was parallel to the overall crack propagation direction. Replicas of the fracture surface were examined at average crack lengths of $2a = 0.6, 0.9, 1.3, \text{ and } 1.7$ inches. The crack length corresponding to each electron micrograph was recorded with an accuracy of $\Delta a = \pm 0.02$ inch. The critical fatigue crack lengths for all specimens ranged from $2a = 6$ to 7 inches.

Test Programs

Thirteen load programs, P1 to P13, were run. Each program was broken down into spectra identified as A, B, C, and D. In each spectrum the maxima and minima of loads were numbered in sequence so that any cycle or part of a cycle could be identified and referred to without confusion. For instance, P1-A9-B1 refers to the compression part A9 to B1 of the first cycle of Spectrum B of Program P1. The cycle digits should always be read in the forward direction.

Tables IIIA and IIIB list the programs, the spectra sequence,

TABLE IIIA

PROGRAMS WITH CONSTANT MAXIMUM STRESS

(Maximum Stress $S_g = 12000$ psi)

Programs	P1	P2	P3	P4	P5
Sequence	ABC	CBA	CBA	ABCD	Random
Spectrum					
A					
n cycles	9	9	6	12	
β	1.2	1.2	2	2	
B					
n cycles	8	8	8	8	
β	3	3	3	3	
C					
n cycles	7	7	10	20	
β	20	20	20	20	
D					
n cycles				8	
β				3	

TABLE IIIB

PROGRAMS WITH CONSTANT STRESS AMPLITUDE

(Stress Amplitude $\Delta S = 7000$ psi)

Programs	P6	P7	P8	P9	P10	P11	P12
Sequence	ABCD	DCBA	ABC	CBA	Random	AB	AB
Spectrum							
A							
n cycles	4	4	20	20		4	3
S max ksi	14	14	14	14		14	12
β	2.0	2.0	2.0	2.0		2.0	2.4
B							
n cycles	5	5	16	16		20	21
S max ksi	12	12	12	12		12	14
β	2.4	2.4	2.4	2.4		2.4	2.0
C							
n cycles	6	6	12	12			
S max ksi	10	10	10	10			
β	3.33	3.33	3.33	3.33			
D							
n cycles	7	7					
S max ksi	8	8					
β	11.4	11.4					

the number of cycles in each spectrum, the maximum gross area stress and stress amplitude, and β factors $\left(\beta = \frac{S_{\max}}{S_{\min}}\right)$.

The programs are shown in Figures 2, 3, and 4. Load was approximately a sine function with time represented as triangular waves on the sketches for simplicity. Programs P1, P2, P3, P4, and P5 represent a constant maximum load with variable load amplitudes. P2 is the reverse of P1, and P3 was obtained by modifying P2 in order to obtain crack propagation with the smallest load amplitude level. P4 was made up by juxtaposing P3 and a reversed P3 to measure the influence of the sequence of load spectra. Program P5 was obtained by "randomizing" P3. The first three cycles were purposely planned with a constant $\Delta S = 11,400$ psi in order to have a reference marker on the microfractographs.

Programs P6, P7, P8, P9, P11, and P12 represent a constant load amplitude with variable maximum loads. P7 and P9 are the reverse, respectively, of P6 and P8. P8 and P9 were designed after it was found that P6 and P7 gave a striation profile difficult to analyze. P11 and P12 were used to identify unambiguously the cracking sequence in each cycle and also to measure the influence of overloads or underloads. P10 was obtained by "randomizing" the same number and levels of S_{\max} and S_{\min} values present in P9. Four pseudorandom programs were produced by alternately drawing a maximum and minimum stress value from separate boxes. Program P10 was then arbitrarily picked from among the four pseudorandom programs. In this paper,

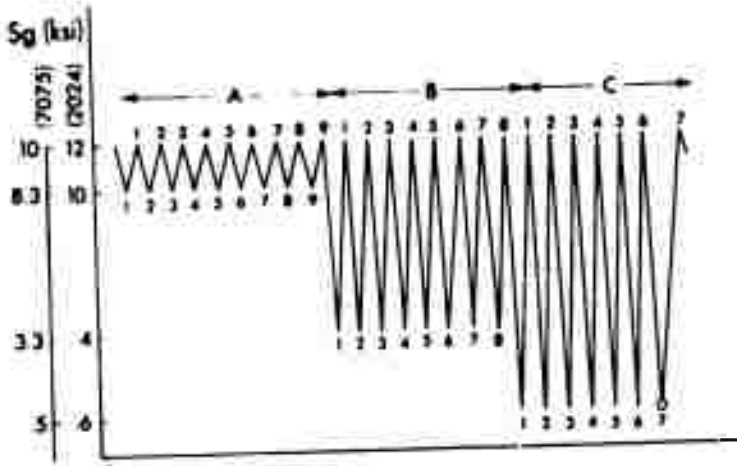


Figure 2a Program P1.

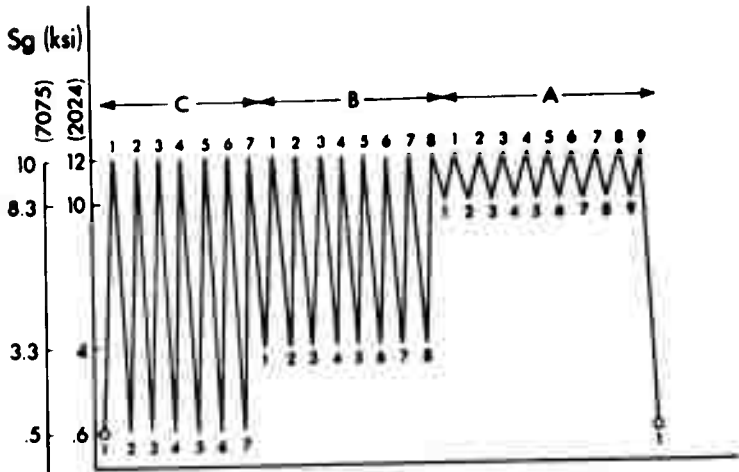


Figure 2b Program P2.

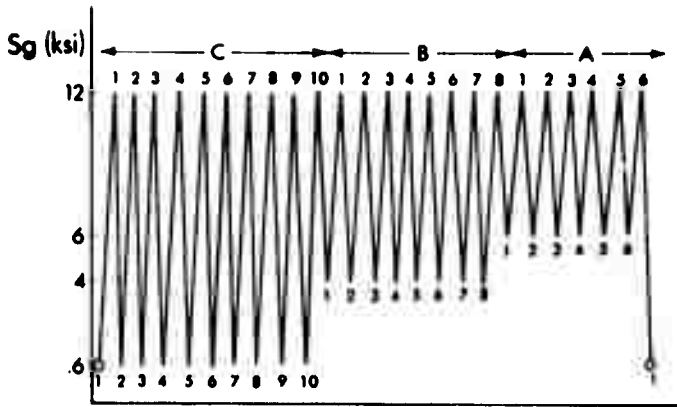


Figure 2c Program P3.

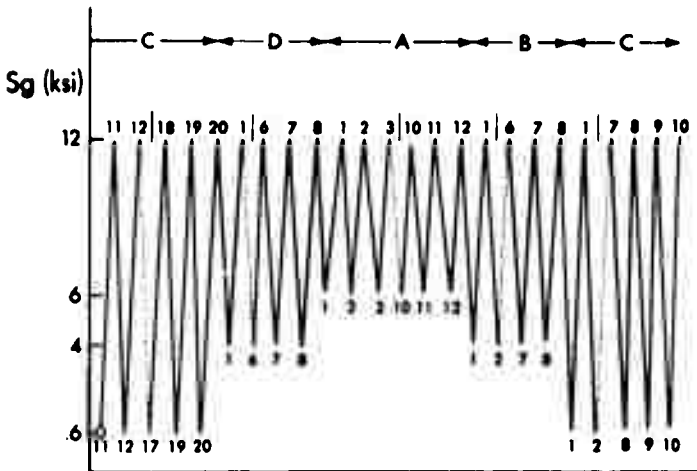


Figure 2d Program P4.

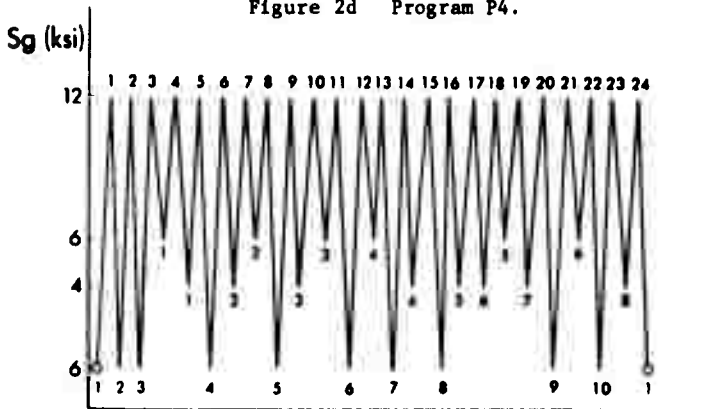


Figure 2e Program P5.

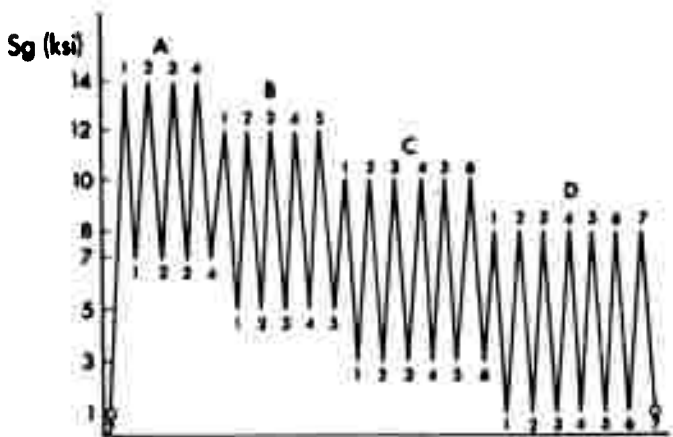


Figure 3a Program P6.

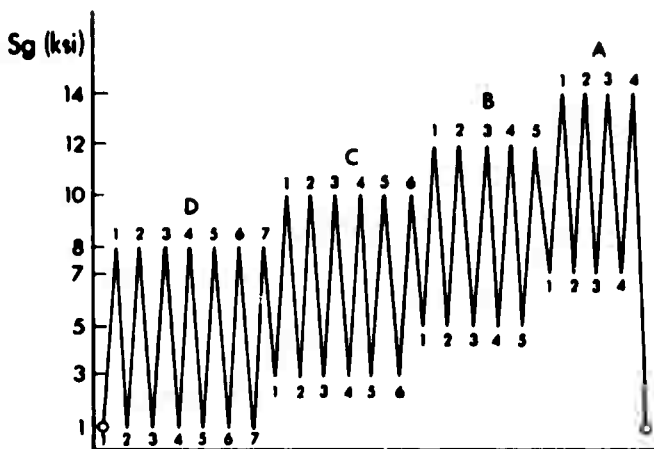


Figure 3b Program P7.

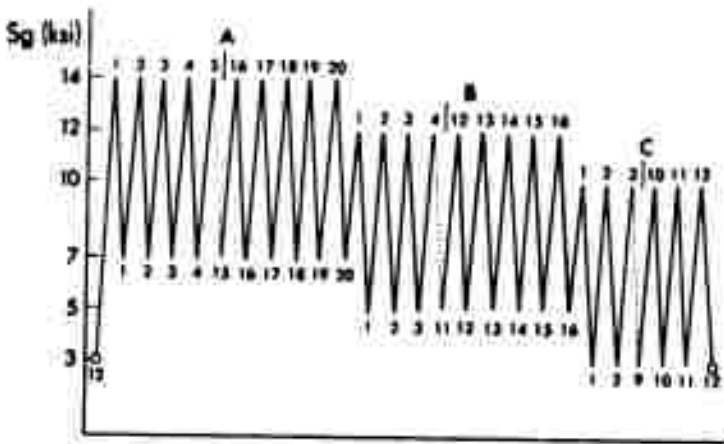


Figure 3c Program P8.

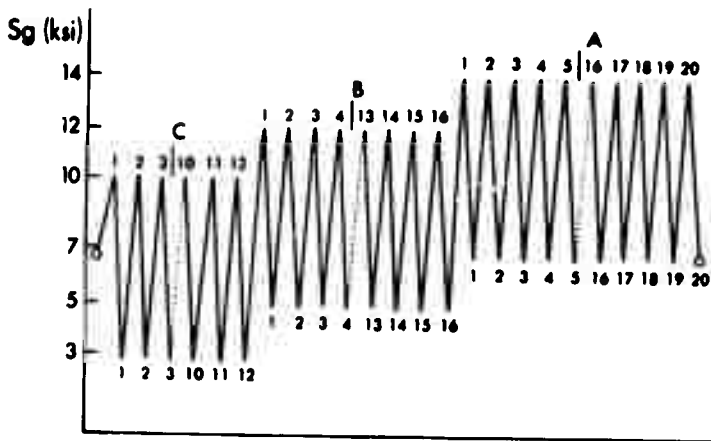


Figure 3d Program P9.

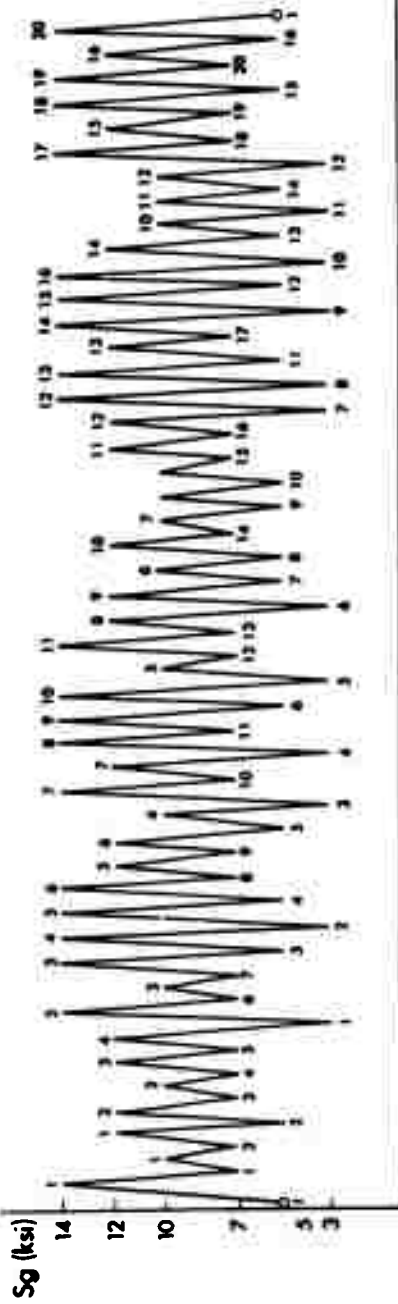


Figure 3e Program P10.

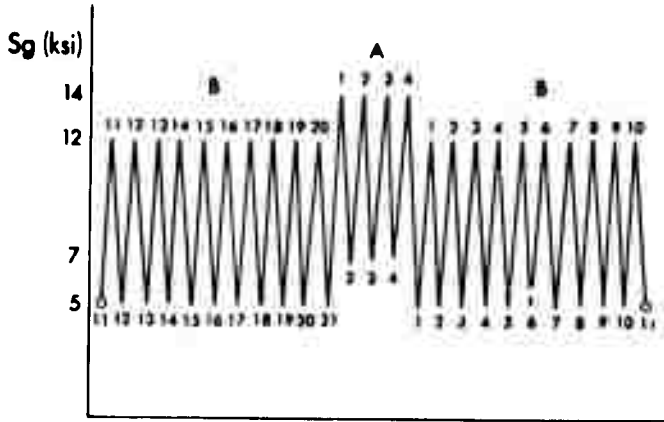


Figure 4a Program P11.

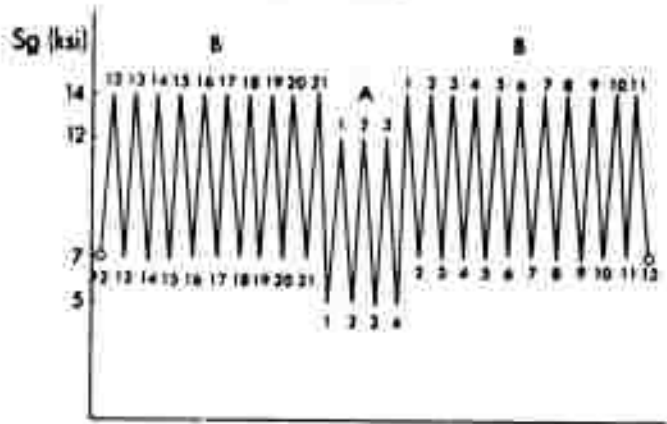


Figure 4b Program P12.

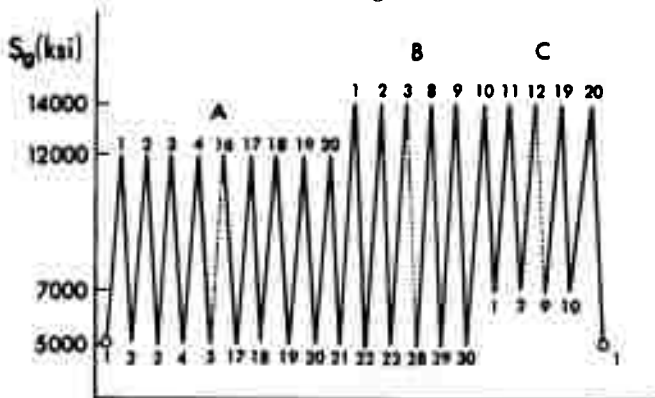


Figure 4c Program P13.

Programs P5 and P10 will be called random programs, although we know they are not truly random. Program P13 was designed to separate the influence of a change of maximum load and of a change of load amplitude on the rate of crack propagation.

III. RESULTS

Fatigue Cracking and Striation Formation

In order to understand clearly the relationship between striation spacing and load cycles, the mechanism of striation formation should be explained.

All the fatigue striations observed in this work were of the ductile type.¹² The fatigue striations, which are well resolved at high magnification, show a ridge or "sawtooth" profile with light and dark sides on each side of the ridge. The replicas were the two-stage plastic-carbon type shadowed in the direction of crack propagation. By comparing the contrast resulting from shadowing, we can determine unambiguously the slope orientation on each side of a striation. In one case, shadowing was done in a direction opposite to the direction of crack propagation to reverse the contrast and verify our conclusions. Matching areas on opposite faces of the fracture surfaces were also studied and some stereo micrographs from one side of the fracture surface were examined. All these different techniques led to the following conclusions, which are summarized in the sketches of Figures 5 and 6:

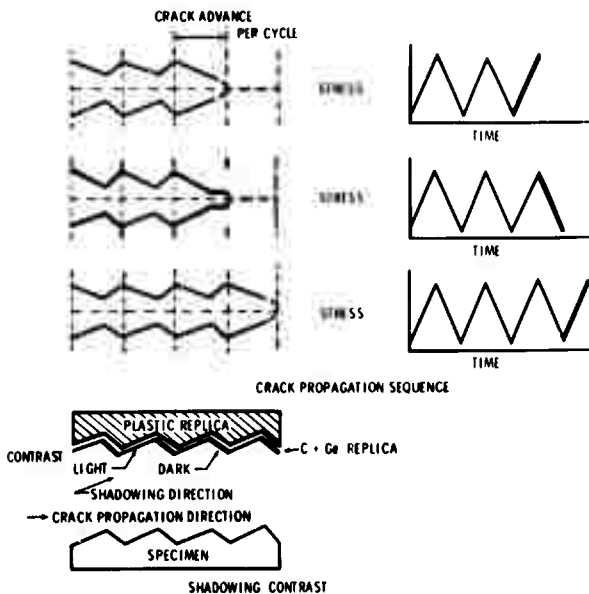


Figure 5 Sketches showing the formation of a striation. Crack advance occurs only during the load rise part of the load cycle.

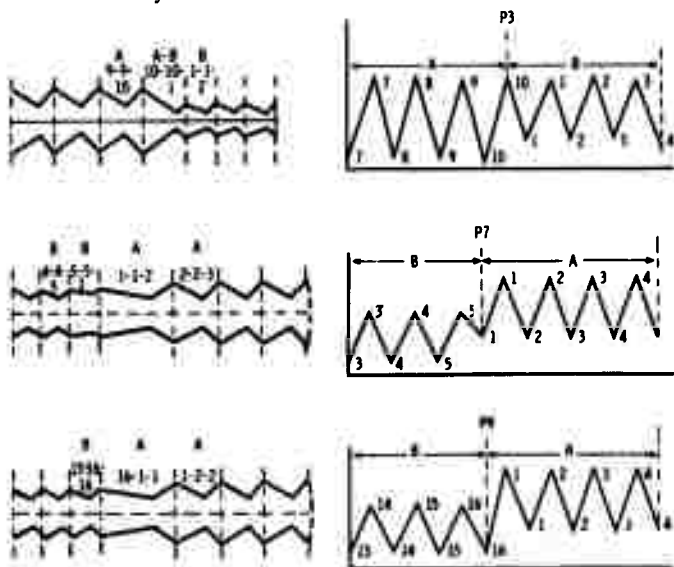


Figure 6 Sketches a, b, c show the striation profile and spacing for parts of Programs P3, P7, and P9.

1. The dark side of the striation (on either of the fracture halves) always faces the crack front when shadowing is in the direction of crack propagation. By opposition, the brighter part of the fatigue striation faces away from the crack front. The dark side of the striation always has a rumpled appearance with fine, wavy, "slip" lines which are usually parallel to the crack front, indicating heavy deformation. The bright side of a striation is flat and generally featureless. The relative width of the dark to bright sides of a striation is quite uniform for a constant cyclic load. Changes of maximum load or load amplitude result in marked changes in striation spacing, striation contrast, and relative widths of the bright to dark sides of a striation.

2. Fatigue cracking occurs only during a load rise, or opening of the crack, and it accounts for the entire crack extension. Figures 7 and 8, showing striations developed during Programs P11 and P12, demonstrate this finding clearly. In Figure 7 the large bright striation is due to the load rise B21-A1 at the beginning of Spectrum A, and in Figure 8 it is due to the load rise A4-B1 at the end of Spectrum A.

3. During unloading, or closing of the crack, the two fracture surfaces created during the preceding stress rise are heavily deformed near the crack tip. This leads to the formation of the dark, rumpled side of the striation and erases, in part, the bright appearance of the fracture face created during the loading part of the cycle. The ratio of dark to bright sides of the striation depends



Figure 7 Typical fracture surface resulting from Program P11. Note the large striation spacing due to the load amplitude B21-A1 (9000 psi) followed by three large striations corresponding to the load cycles of Spectrum A ($2a = 1.7$ inches).

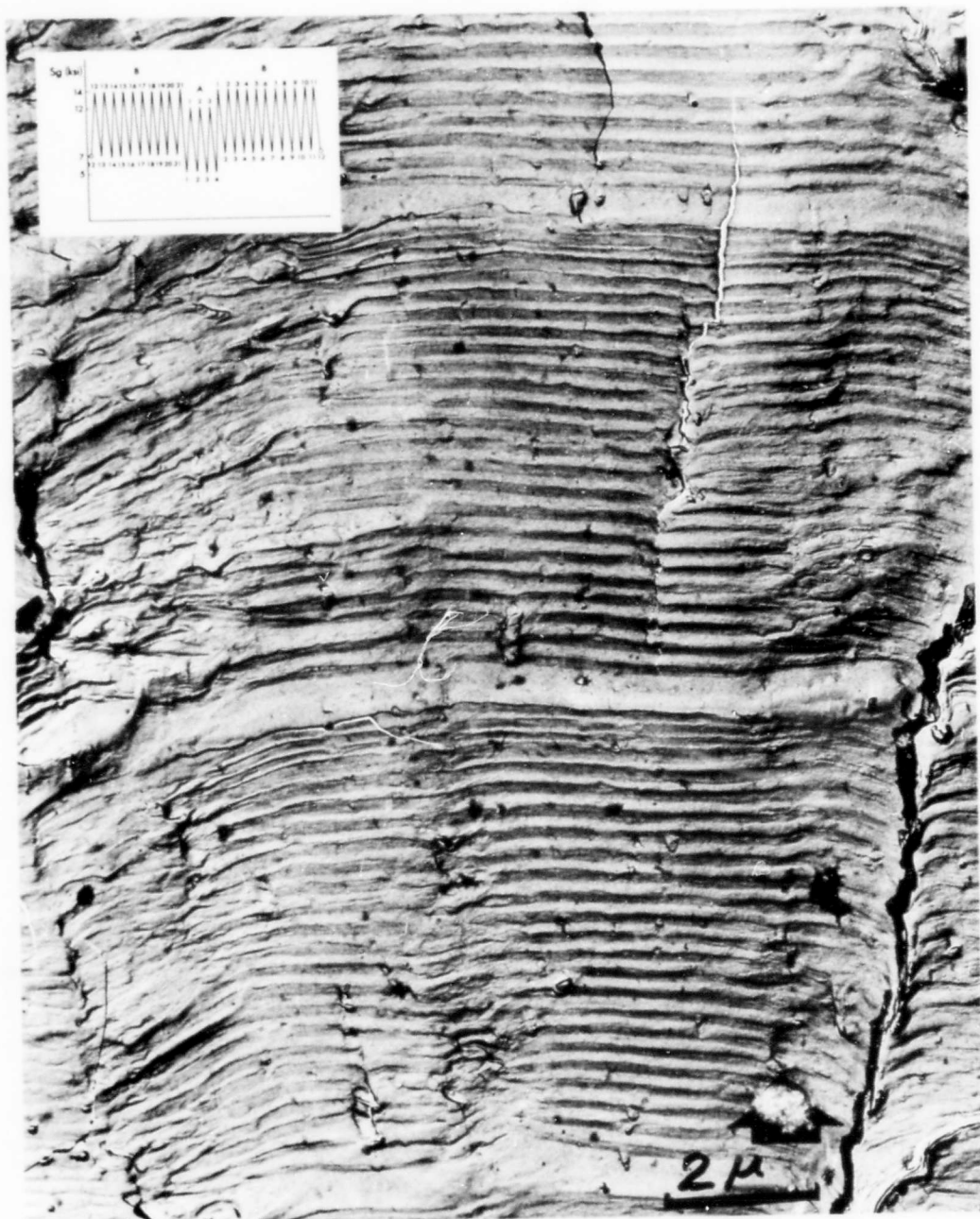


Figure 8 Typical fracture surface resulting from Program P12. Note the large striation spacing due to the load amplitude A4-B1 (9000 psi) preceded by three smaller striations corresponding to the load cycles of Spectrum A ($2a = 1.7$ inches).

on loading *versus* unloading load amplitudes. But, even when the unloading load amplitude is much larger than the preceding load rise, the deformed width of the striation (dark side) is never greater than the crack advance due to the preceding load rise.

Figures 6a, 6b, and 6c illustrate different fatigue striation profiles and the corresponding load sequences. Since the exact shape and size of the crack tip is unknown, it is represented as a dotted line in each sketch. The height of the striations is magnified for better illustration.

Laird¹³ has recently presented a review of fatigue cracking and striation formation. There is little doubt that, as was shown by Laird and Smith,¹⁴ and by McEvily,¹⁵ there is a sharpening of the crack tip during unloading. Resharpener of the crack tip takes place by heavy deformation on the shear planes at 45° to the plane of the crack at the crack tip. This deformation, which can be called a macrocooperative slip or shear, can take place in noncrystalline as well as in crystalline materials. In the case of crystalline materials the orientation of a grain and the slip systems available may facilitate the resharpener process by a dislocation mechanism similar to the one suggested by Schijve.¹⁶ Most of Laird's¹⁴ observations were made on fracture surfaces resulting from low cycle fatigue. That is, there was always enough deformation or shear at the crack tip to create a well-defined groove, regardless of the crystallography of the materials. On the other hand, in the case of high

cycle fatigue -- that is, growth rates smaller than one micron/cycle -- the fine fatigue striations are not observed in all the alloy systems. Striations are well defined for the 2024 alloys, they are sharp and angular in the 7000 series aluminum alloys, very irregular in titanium alloys, and rarely defined at all in high strength steels. In conclusion it can be stated that:

1. Striation formation is a two-step process, with crack extension on the loading portion of the stress cycle followed by striation definition through plastic flow and resharpening of the crack on the unloading portion of the stress cycle, and,
2. The crystallography of the material can accentuate the localization of this flow leading to sharp, well-defined ridges and grooves.

At this point, before presenting the results, it is worthwhile to stress the fact that crack propagation by striation formation is the principal mechanism of fatigue crack propagation for short crack lengths and slow growth rates; that is, for our tests, for $0.500" < 2a < 1.5$ to 2 inches. Figure 9 shows typically the uniformity of crack propagation by striation formation. Striations are formed right at the root of the notch as soon as the crack starts propagating, as shown in Figure 10. Stage I¹² crack growth was not observed.

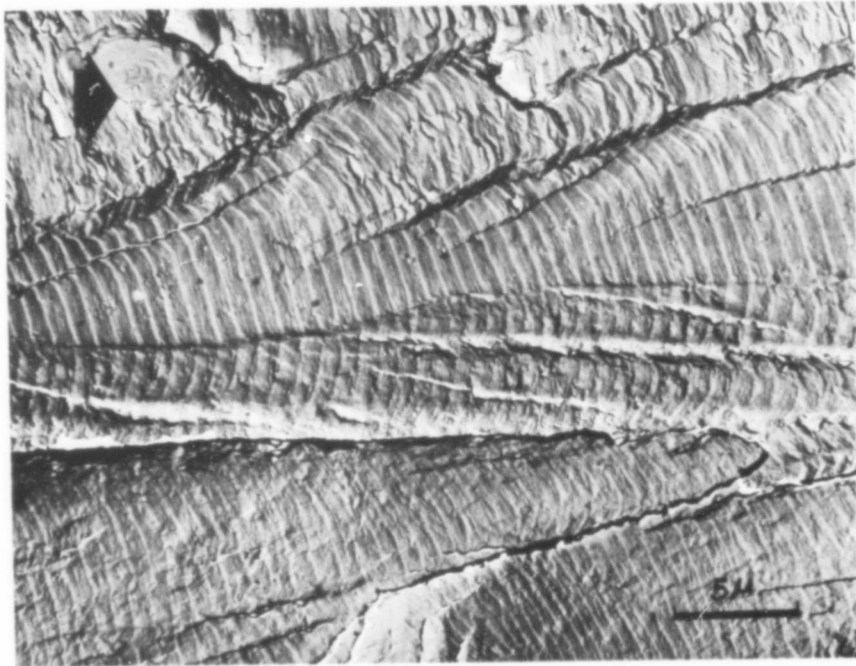


Figure 9 Note the uniformity of the striation spacing and the extent of fracture surface covered by striations. Program P11 ($2a = .6$ inch).

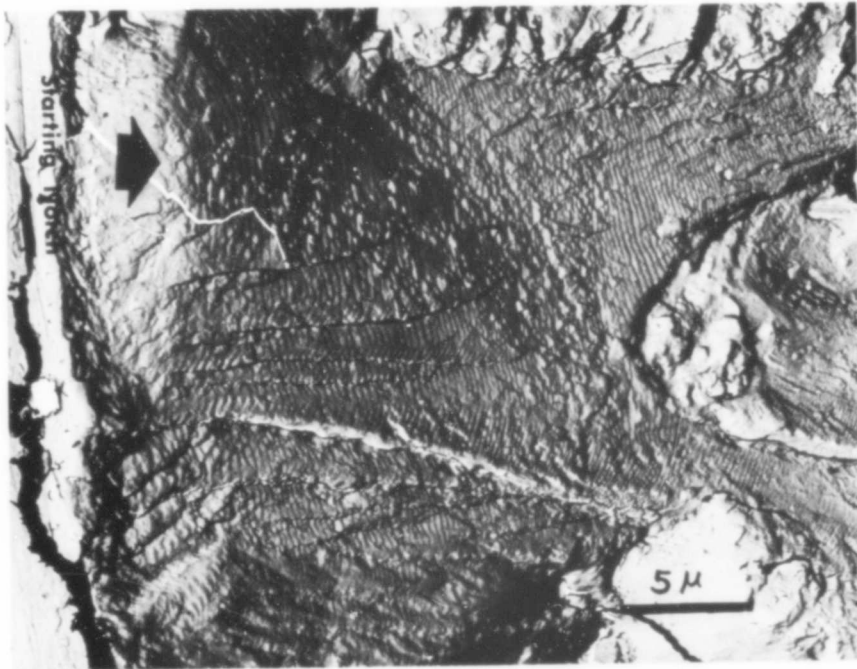


Figure 10 Crack propagation by striation formation (Stage II) starts right at the root of the sawtooth notch. Program P11 ($2a = .5$ inch).

Constant Maximum Load and Variable Load Amplitude Programs

Five programs, P1 to P5, with constant S_{max} and variable ΔS were planned and tested. The test data are reported in Figures 11 and 12, which represent plots of crack length versus crack growth rates.

Programs P1 and P2 were designed and run first. There was no significant difference in crack growth rates between the two programs. The fracture surfaces did not show any striations or crack growth for Spectrum A ($\Delta S = 2000$ psi) of either program. Consequently the programs could not be differentiated by examination of the micrographs alone, since the absence of striations due to Spectra A resulted in the same spectra sequence for the two programs; that is, BCBCBC for P1 and CBCBCB for P2. Figures 13, 14, and 15 show typical fractographs for Programs P1 and P2, respectively. The only significant feature besides the change in striation spacing between Spectrum B and Spectrum C was a brighter striation corresponding to C77-A-A9B1 in P1 and to C77-B71 in P2. In P2 this striation had the same spacing as the other striations in Spectrum C, but appeared brighter because of the smaller width of the dark part of the striation, which corresponded to the smaller unloading amplitude C7-B1. In P1 the bright striation had the same appearance as in P2 but appeared to be larger than the other C striations, which would mean that Spectrum A resulted in some limited crack extension but with no resolvable striation formation. Spectrum A does not

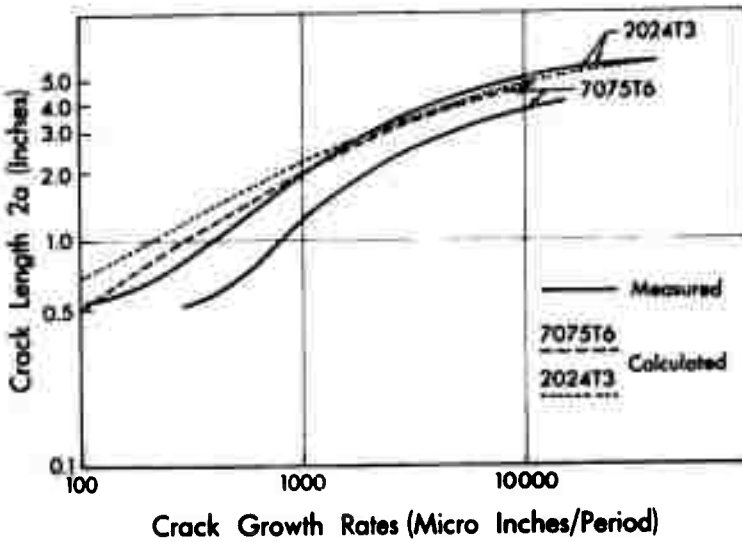


Figure 11 Crack length *versus* crack growth rates for Programs P1 and P2, and alloys 2024-T3 and 7075-T6.

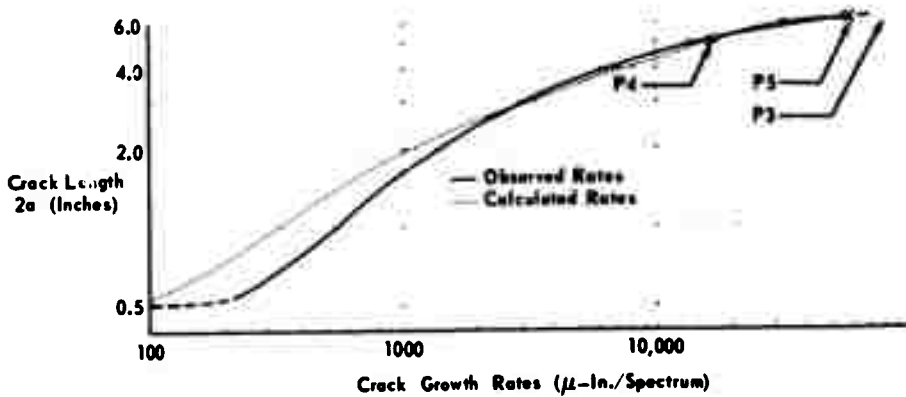


Figure 12 Crack length *versus* crack growth rates for Programs P3, P4, and P5.

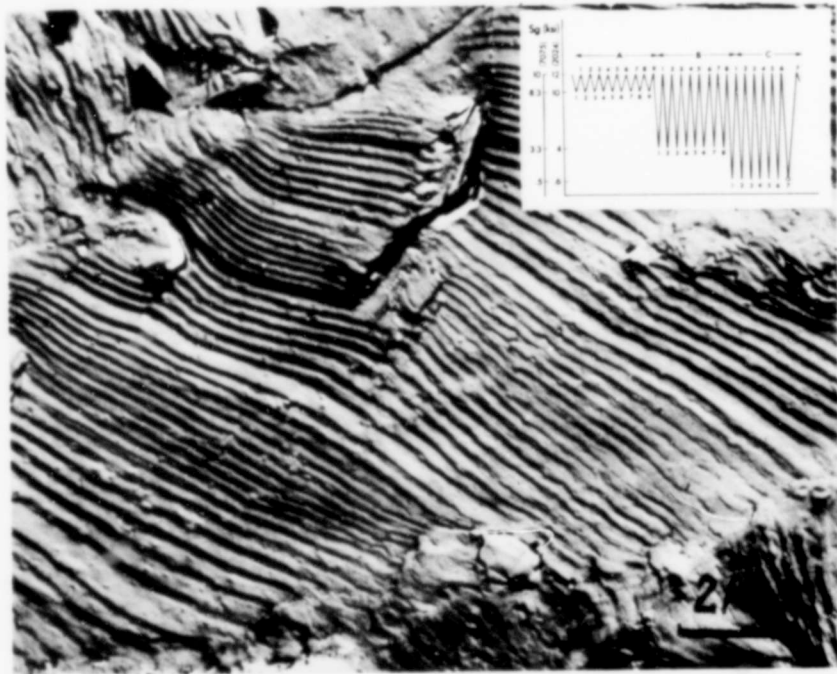


Figure 13 Typical fracture surface due to Program P1. ($2a = .7$ inch)

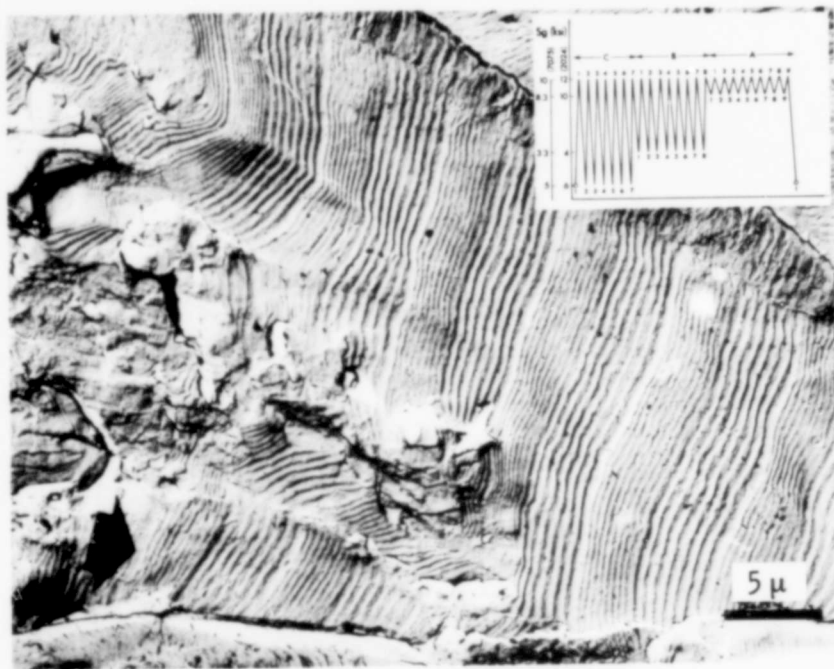


Figure 14 Typical fracture surface due to Program P2. Compare with Figure 13. ($2a = 1.3$ inches)

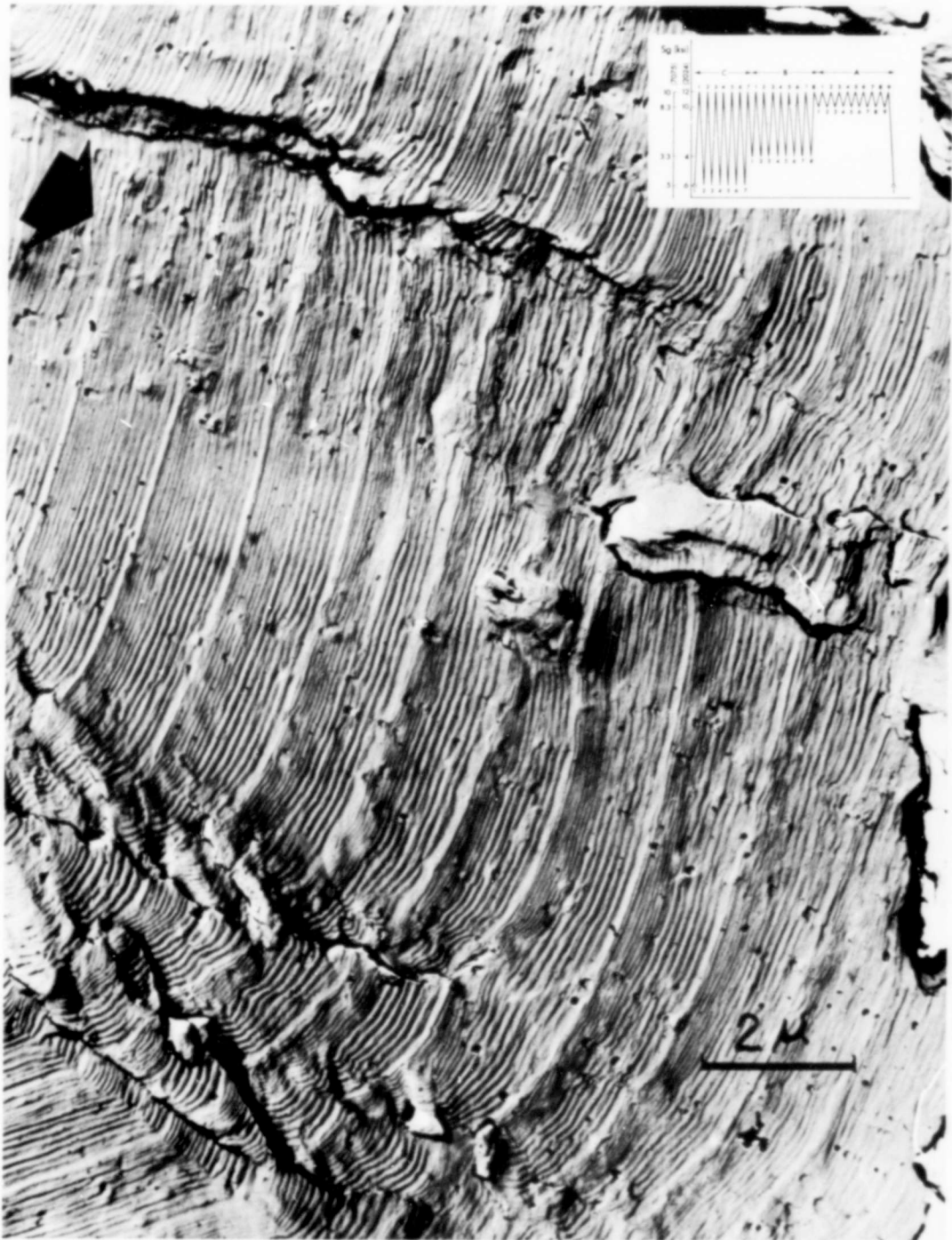


Figure 15 Typical fracture surface due to Program P2, showing the uniformity of striation spacing ($2a = .6$ inch).

show up even at the longest crack lengths whereas striations are still observed for Spectra B and C amidst large regions of ductile tear.

Program P3 was designed as a modified P2, with $\Delta S = 6000$ psi for Spectrum A and a different number of cycles in each spectrum. This time Spectrum A resulted in well-defined A striations between striations C and B, as shown in Figures 16 and 17. Programs P4 and P5 were then designed and run. Characteristic fractographs are shown in Figures 18 and 19.

Figure 12 gives a log-log plot of observed and calculated crack length *versus* growth rate per program for P3, P4, and P5 (for P4 the rates plotted correspond to a half program). The crack growth rates for the random case, P5, were the same as for the programmed spectra, P3 and P4. This shows that in the tests at constant maximum load the sequence of load application did not measurably influence the overall crack growth rates. This was confirmed by the fracture analysis with the electron microscope:

1. There was no marked crack front advance at the change of load amplitude between different spectra.

2. After a change of load amplitude, the spacing of the striations for the next load amplitude sequence reached a stable and uniform value on the first cycle of the new load amplitude sequence.

The average rates of crack propagation per load cycle for each load amplitude sequence in Programs P3 and P4 were measured for

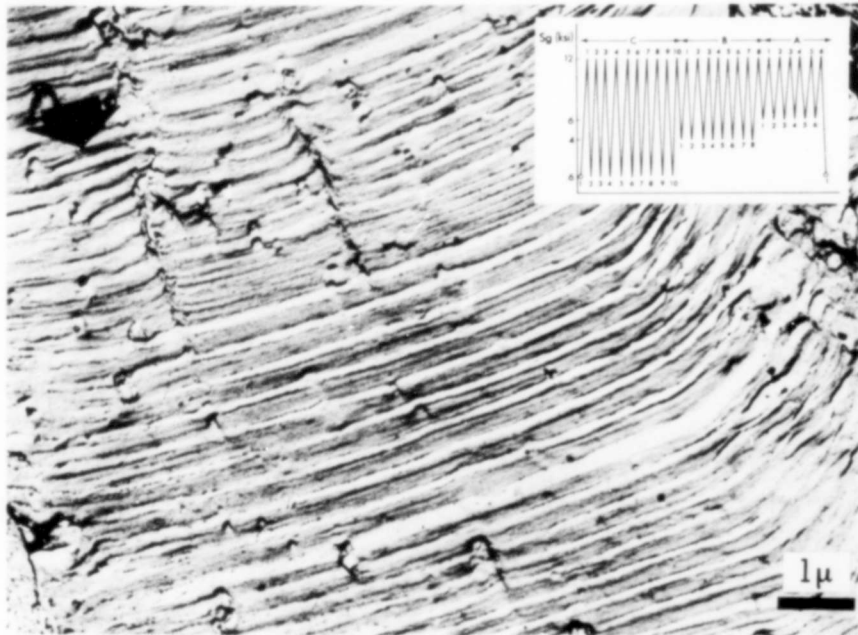


Figure 16 Typical striation profile corresponding to Program P3
($2a = 0.9$ inch).

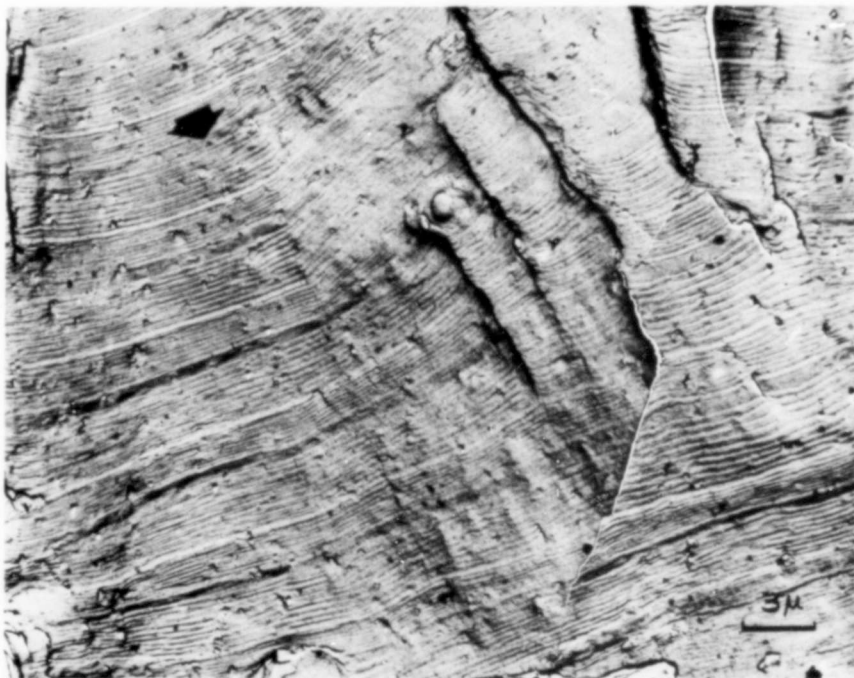


Figure 17 Typical fracture surface, showing the uniformity of the
striation spacing for the three spectra of Program P3
($2a = .7$ inch).

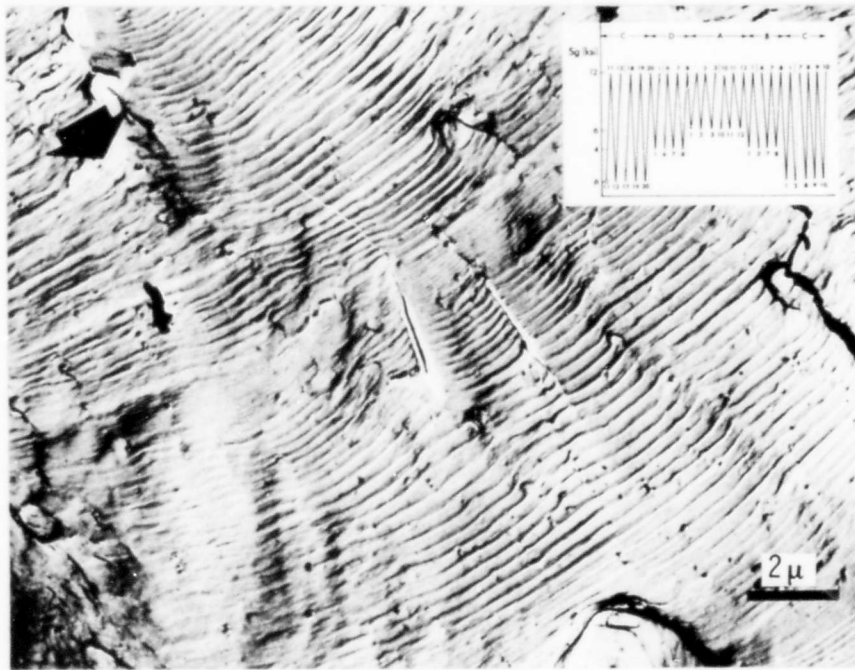


Figure 18 Typical fracture surface due to Program P4. The sequence of application of the load amplitudes does not seem to change the striation spacing markedly ($2a = .9$ inch).

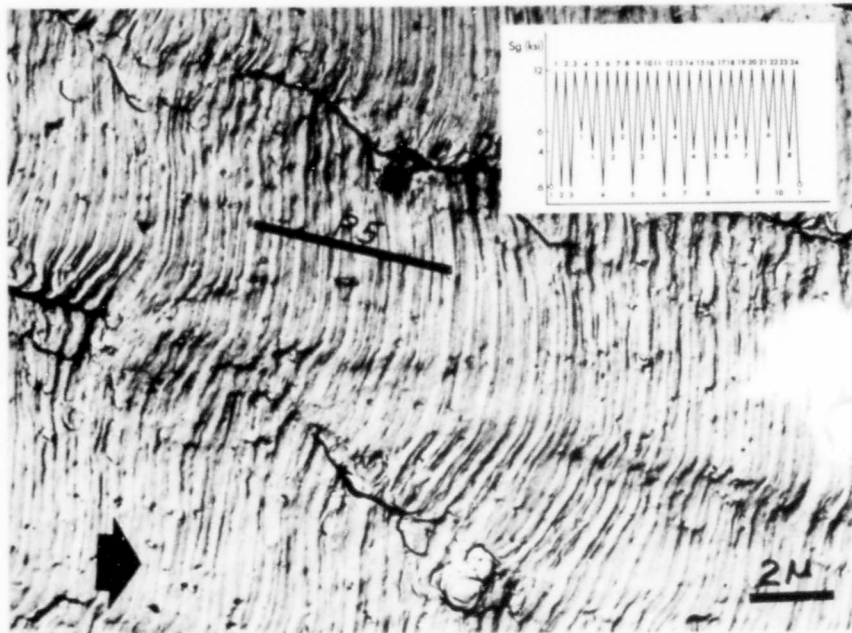


Figure 19 Striation profile corresponding to pseudorandom Program P5 ($2a = .9$ inch).

various crack lengths between $2a = 0.5$ inch and $2a = 0.9$ inch. The growth rates per cycle in each field of view were compared with the larger growth rate (taken as unity) corresponding to $\Delta S = 11,400$ psi. This procedure partially eliminated the scatter in absolute growth rates, which is always observed at high magnification even at a constant crack length.

Figure 20 is a plot of $\log \Delta S$ versus \log relative crack growth rate per cycle. There was a certain scatter in the data, but it showed that, for constant S_{max} , the following relative crack rate equation could be written:

$$\text{rate} = C(\Delta S)^n \quad (1)$$

with $n = 1$ for ΔS between 8000 and 12,000 psi, and increasing from two to four for ΔS lower than 8000. It is unfortunate that we were not able to extrapolate this plot for $\Delta S = 2000$ psi. The possibility that measurable growth could be achieved by large increases in the numbers of stress cycles at $\Delta S = 2000$ psi was considered, but no testing to investigate this point was conducted.

Constant Load Amplitude and Variable Maximum Load Programs

Seven programs, P6 to P12, with constant ΔS and variable S_{max} were planned and tested. The test data are reported in Figures 21, 22, and 23, which represent plots of crack length versus crack growth rates.

There was no significant difference in macroscopic crack

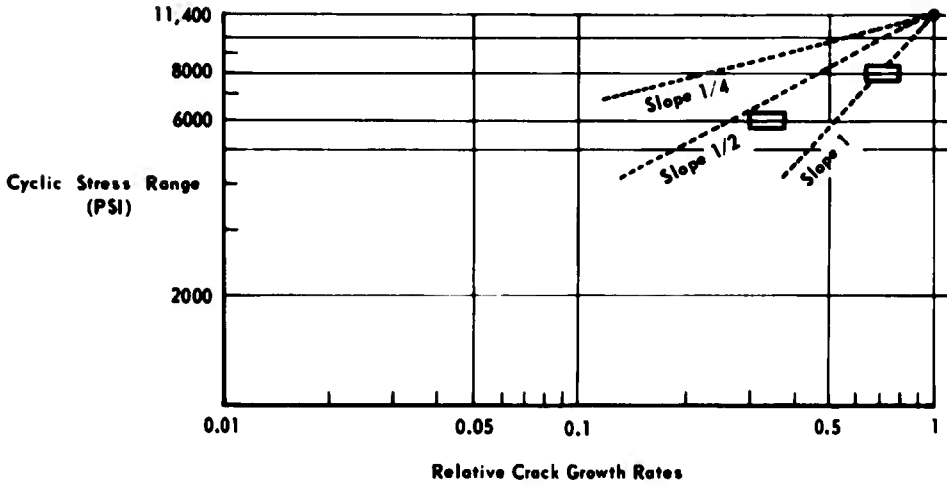


Figure 20 Relative crack growth rates at constant S_{max} for Programs P1, P2, P3, and P4.

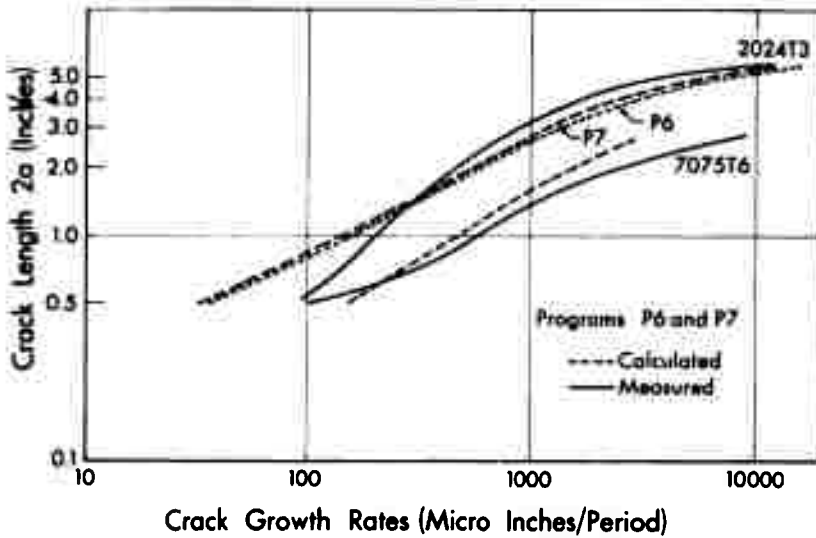


Figure 21 Crack growth rates *versus* crack length for Programs P6 and P7.

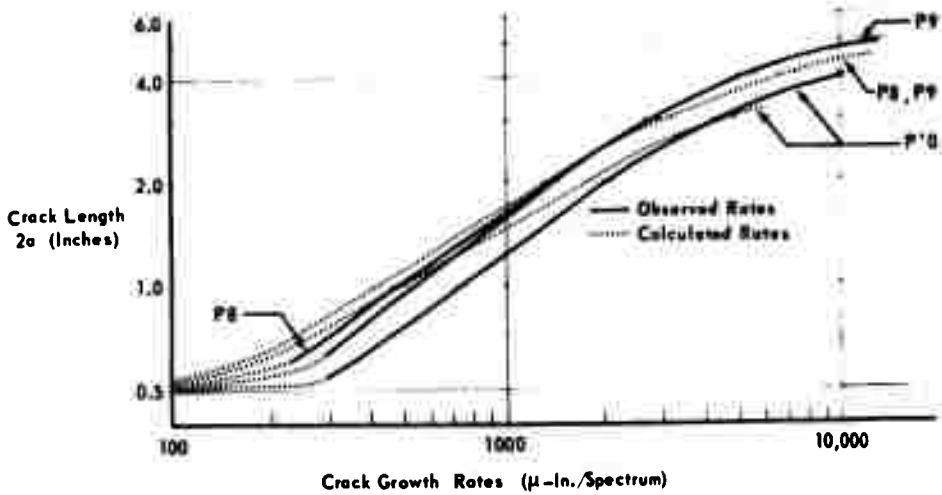


Figure 22 Crack growth rates *versus* crack length for Programs P8, P9, and P10.

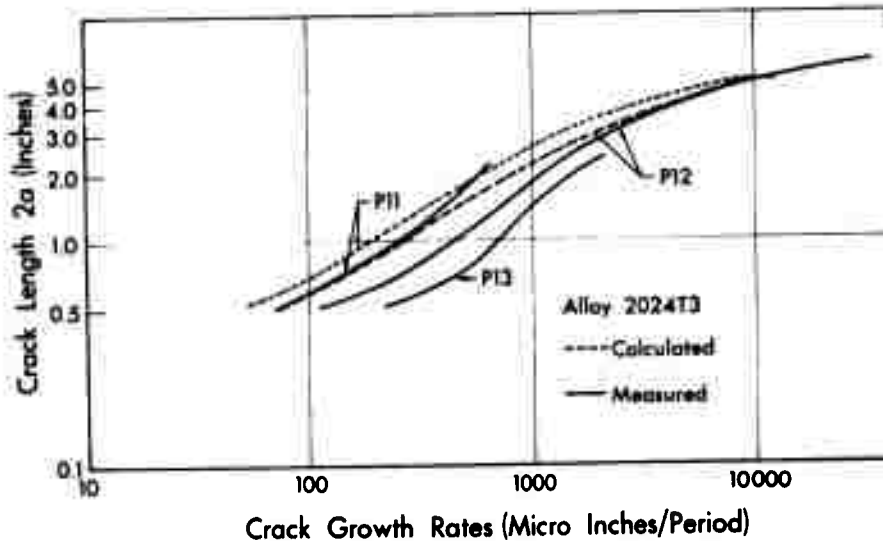


Figure 23 Crack growth rates *versus* crack length for Programs P11, P12, and P13.

growth rates between Programs P6 and P7. The striations observed on the fracture surface were never as well defined as for Programs P1 to P5. However, Spectra A, B, and C of P6 could be easily identified, as shown in Figure 24. Spectrum D did not show any crack advance or striations but accounted for a very narrow and sharp compression groove before the large crack jump at D7-A1, which corresponds to the largest change in load amplitude for P6. The crack jump due to this load change was equivalent to the total crack advance due to the three following cycles, A12, A23, and A34.

Program P7 was similar to P6. That is, Spectra C, B, and A were easily identified on the fractographs, and Spectrum D did not result in any visible cracking. Each change of maximum load at C66-61-A11 and B55-51-A11 created a larger striation spacing, as shown in Figure 25. The crack jumps and the corresponding striation profiles between Spectra B and A are sketched in Figure 6. The sketch shows clearly the marked difference in striation spacing between cycle A11-12 and the following cycles A22-23, A33-34, and A44-A4D1, although all these cycles had the same load amplitude and the same maximum load.

Programs P6 and P7 proved difficult to analyze, with too many load levels and too few cycles at each load level. For this reason, Programs P8, P9, and P10 were designed and tested. Figure 22 presents a plot of log crack length *versus* log macroscopic crack growth rates for P8, P9, and P10. At lower growth rates P9 was faster than

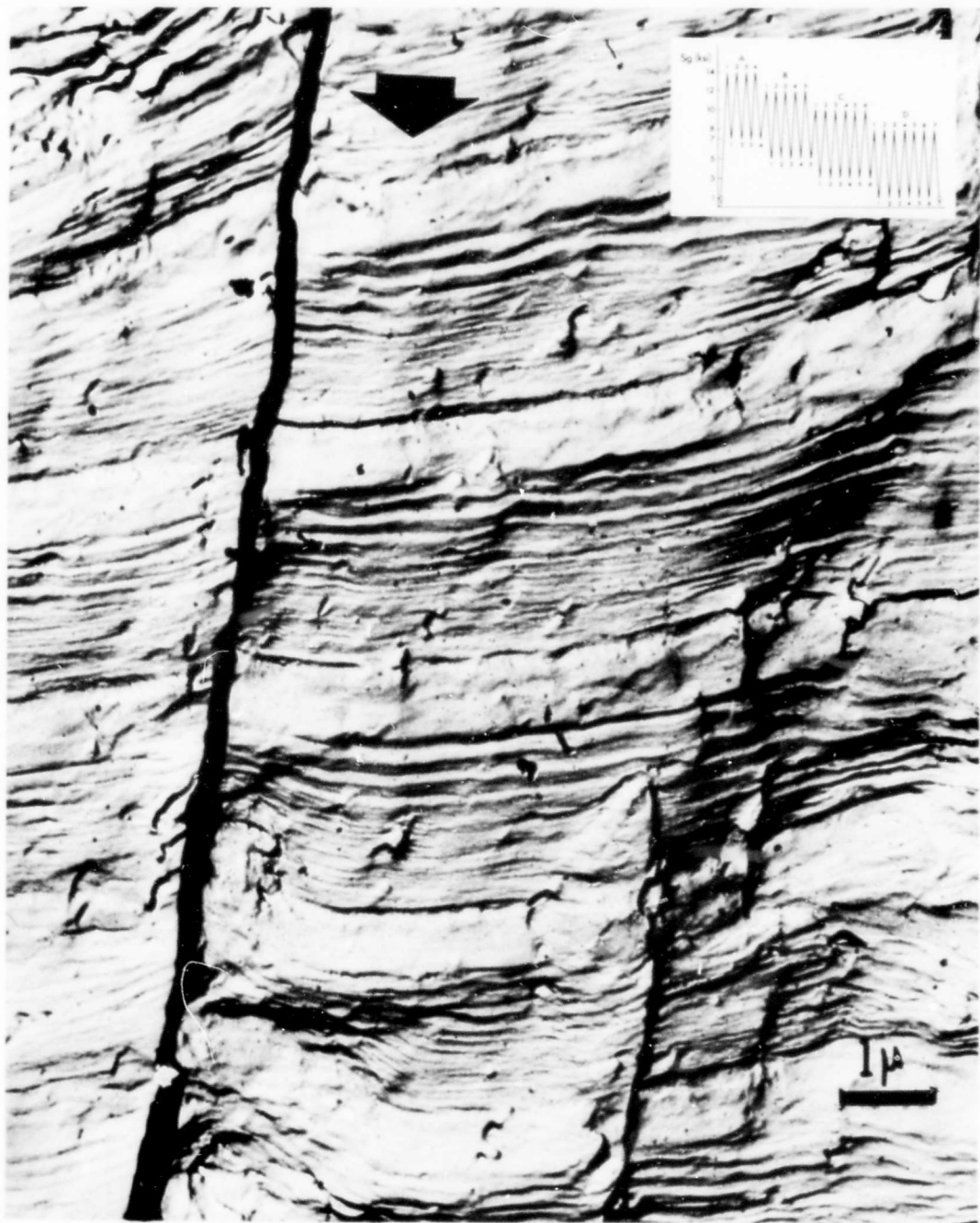


Figure 24 Typical fracture surface due to Program P6. Note the large crack jump corresponding to D7-A1 ($2a = .9$ inch).

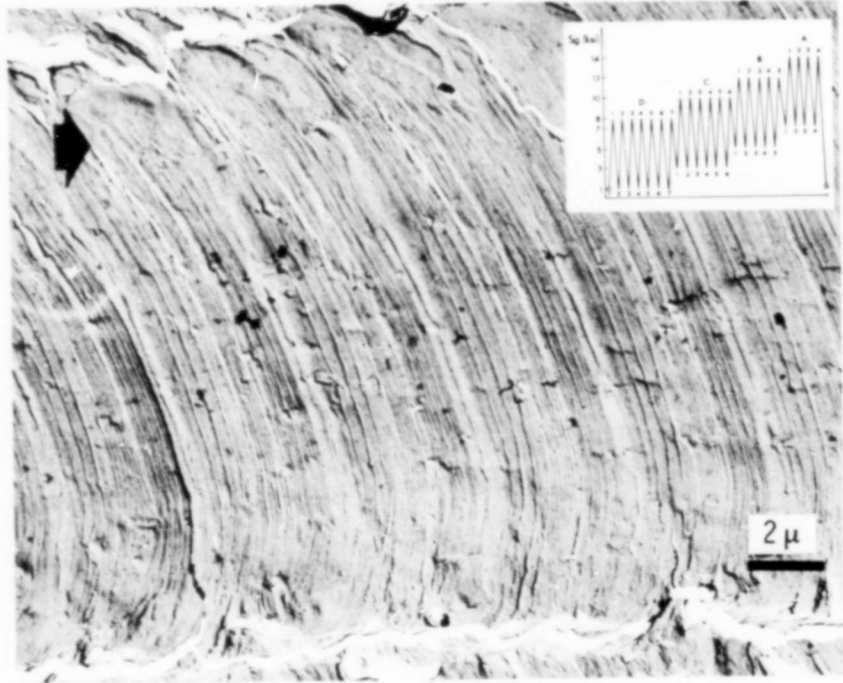


Figure 25 Typical fracture surface due to Program P7 ($2a = 1.7$ inches).

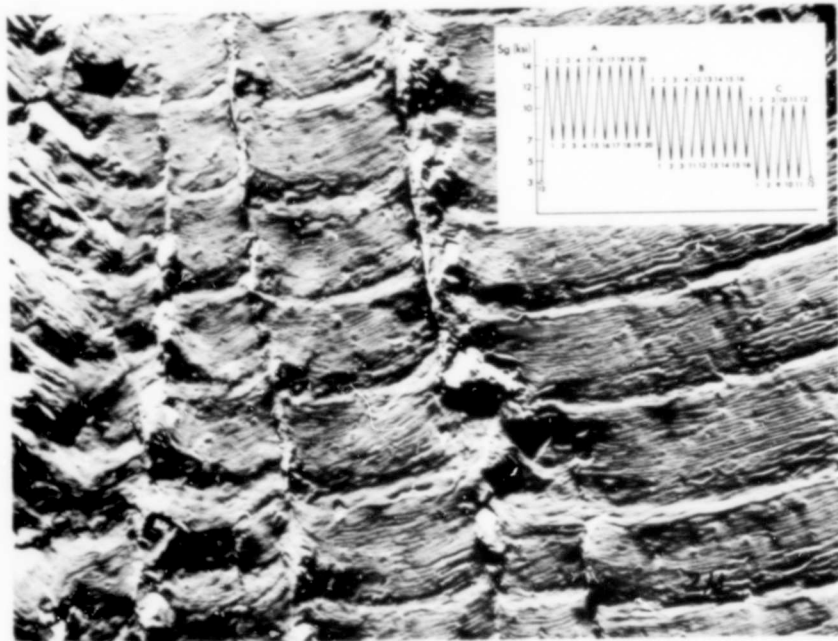


Figure 26 Fracture surface topography due to Program P8.

P8, while the random program P10 was always faster than P8 or P9. Figures 26, 27, 28, and 29 show typical fractographs of P8, P9, and P10. Spectra A and B are well resolved, with all the striations accounted for. The cracking due to Spectrum C cannot be resolved on the micrographs. The crack jumps due to change in maximum load levels P9-A20-C1 and P9-C12-B1, and P9-B16-A1 are clearly identified.

The average microscopic rates of crack growth per load cycle for Spectra A and B of Programs P6, P7, P8, and P9 were measured within each program and compared with the larger growth rate (taken as unity) corresponding to $S_{max} = 14,000$ psi. The effect of the maximum load amplitude on the relative crack growth rate per cycle is shown in Figure 30. The scatter was quite large, but a relationship of the type:

$$\text{rate} = \text{constant}(S_{max})^m \quad (2)$$

could be written to represent relative crack growth rate. At a given crack length and for a constant maximum load, m varied from two to three at large S_{max} to three to five at smaller S_{max} . In the same figure the relative microscopic rates confirm the fact that P9 had a larger growth rate than P8. This can be explained by assuming a crack growth retardation in Spectrum B of P8 because Spectrum B followed the higher load level of Spectrum A. The crack growth retardation could be due to a work softening of the plastic zone by Spectrum B and a consequent lower crack growth rate.

Program P10, as expected, was much faster than P8 and P9.¹¹

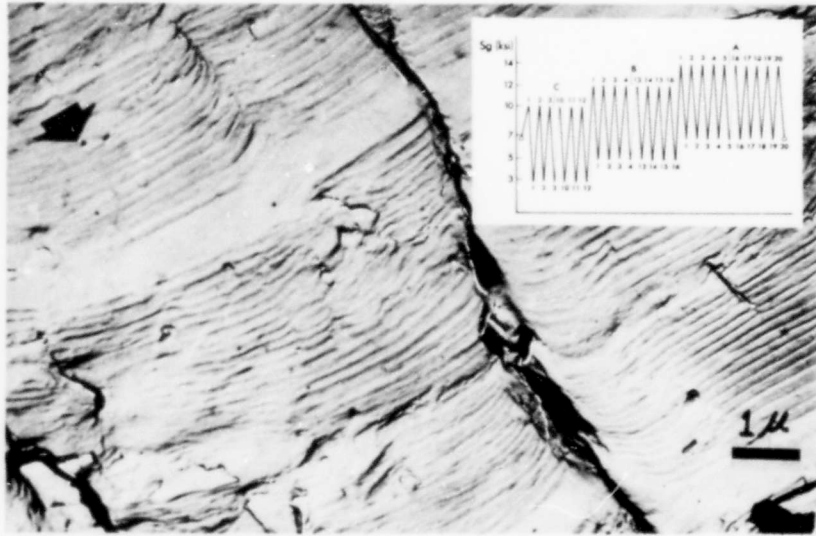


Figure 27 Fracture surface topography due to Program P9
($2a = .9$ inch).

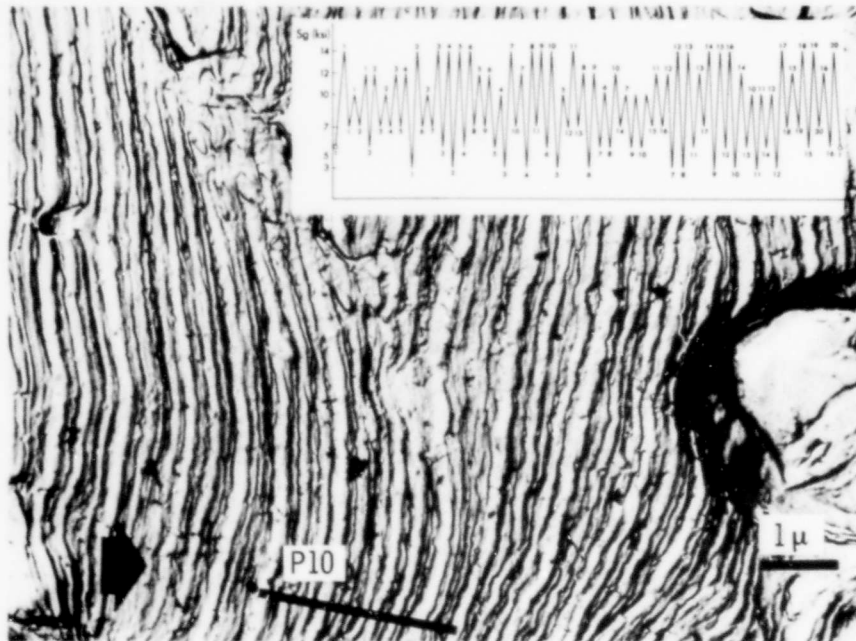


Figure 28 Fracture surface topography due to Program P10
($2a = .6$ inch).



Figure 29 Fracture surface topography due to Program P10. Note the sharpness of the striation ridges, indicating a sharp crack tip ($2a = .6$ inch).

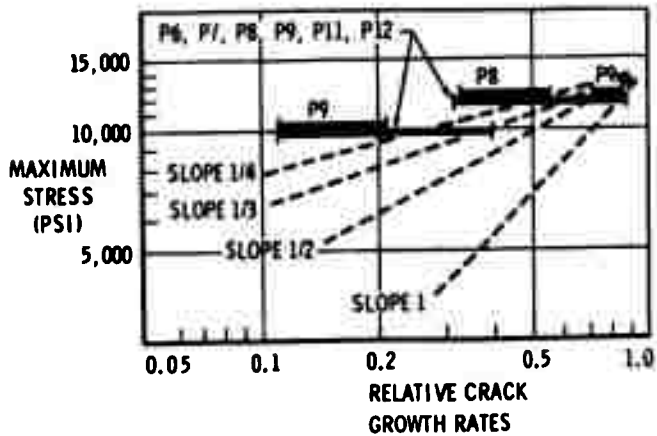


Figure 30 Relative crack growth rates at constant load amplitude, variable maximum loads, for Programs P6, P7, P8, and P9.

The large number of high load rise amplitudes coupled with many changes of load level accounts for this large difference in growth rates. In Figures 28 and 29 the striation spacings and profiles can be related to the applied random loads if S_{max} , ΔS , and prior S_{max} are considered. With few exceptions, only striations due to $S_{max} = 14,000$ psi are clearly resolved. This implies that S_{max} effects are more important than ΔS or prior S_{max} effects.

Programs P11 and P12 were designed to show that cracking takes place only during the opening of the crack. The test data are reported in Figure 23, which shows plots of crack length versus crack growth rates. Spectrum A in P11 did not result in any crack arrest since all the cycles of Spectrum B could be counted; on the contrary, the first striations of Spectrum B were often observed to have a slightly larger spacing than the last one. This crack acceleration at a lower level following a high load level was not clearly observed in P9.

Program P13 complements P11 and P12. In P11 and P12 a change of maximum load level is always accompanied by a change of load amplitude and it is impossible to separate the effect of load level and load amplitude. This can be done in P13 by comparing the striation spacing due to cycles A21-B1 with the following cycles, B22-2, B33-3, etc. It can be seen in Figures 31 and 32 that the first cycle at the higher load level creates a larger crack advance than the following cycles. As will be discussed later, this can be explained by con-

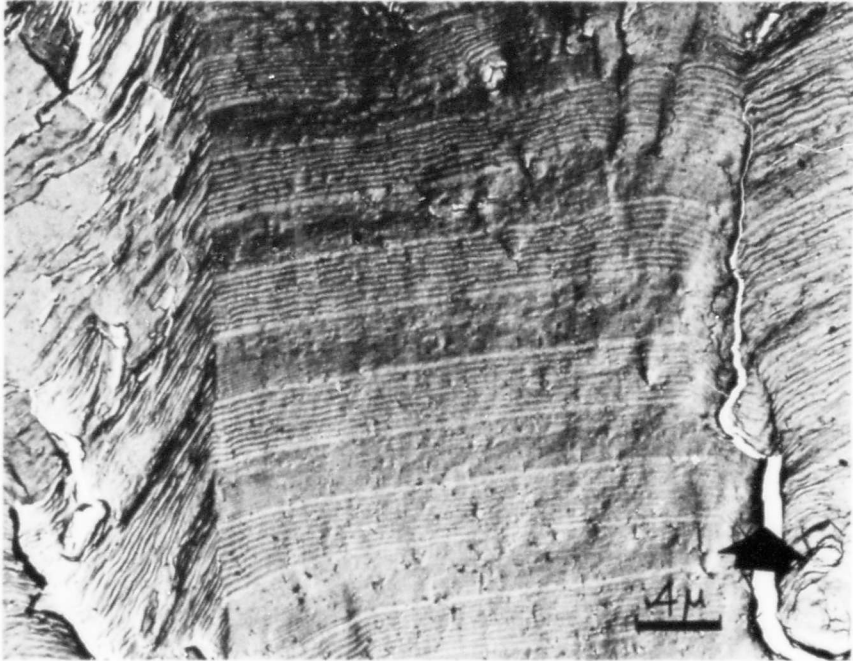


Figure 31 Fracture surface topography due to Program P13 ($2a = .9$ inch).

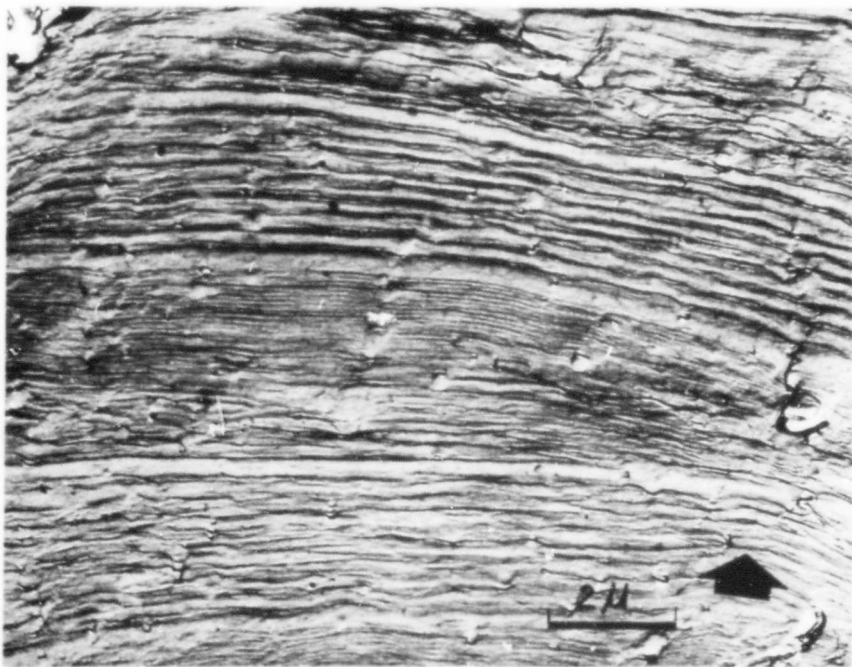


Figure 32 Fracture surface topography due to Program P13. Note the large striation spacing corresponding to A21-B1 ($2a = .9$ inch).

sidering the difference in notch effect due to different crack tip shapes and radii prior to a change in load level.

Computed Crack Growth Rates

An available computer program was used to calculate the crack growth rates of all the programs tested. The crack growth data used in the computer program were taken from previous tests at constant S_{max} and constant ΔS values. These "in house" data correspond to different heats of material, and the difference between computed and measured growth rates can be attributed to chemistry, environment, and testing variables. However, since one practical aim of fatigue cracking tests is to predict random and programmed crack growth from load-crack growth data, an attempt was made to use these data for our programs. The computer calculated the crack advance for each load cycle and consequently took into account the large changes in load amplitude at each change of maximum load level. The computed data showing crack length *versus* number of periods are given in Appendix II. Figures 11, 12, 21, 22, and 23, giving crack length *versus* crack growth rates also show the computed curves of crack length *versus* growth rates.

All the computed growth rates were slower than the observed macroscopic rates for the same crack length between $2a = 0.5$ inch and $2a = 2$ inches. At larger crack lengths the computed rates were equal to the observed rates, and, in many cases, at very large crack lengths the computed rates were faster than the observed rates. We

see that the computed growth rates differ from the measured rates by a factor less than two, but the calculated rates are not conservative in the long life region. This conclusion is better illustrated in Table IV, which compares the measured and calculated number of periods to achieve the same crack growth (from .5 inch to near critical crack length). The column giving $\sum \frac{n}{N}$ shows the deviation from Miner's rule.

IV. DISCUSSION

The different program load sequences have clearly demonstrated that crack extension in 2024-T3 aluminum alloy occurs only during the stress rise part of a load cycle, but the striation profile and appearance depend on both the loading and unloading amplitudes of the load cycle. The smallest striation spacing observed was of the order of one micron or 250 Å. The resolving power of the replicating technique is approximately 100 Å. In all the programmed load tests, whenever the striations were defined well enough to be easily counted, we found a perfect one-to-one correlation between the number of striations and the number of load cycles in a spectrum. In the random programs, P5 and P10, correlating striation spacing to load cycles in the program was more difficult, but with some time and effort it was done for all the micrographs taken. With training one can, by looking at a random load spectra, select the load levels and load amplitudes which will account for the largest striation spacings observed on the fracture surface. In

TABLE IV

CALCULATION OF $\sum \frac{n}{N}$ FOR CRACK PROPAGATION
($2a = .5$ inch)

<u>Programs</u>	<u>2a*</u>	<u>N Calculated</u>	<u>n Measured</u>	<u>$\sum \frac{n}{N}$</u>
Alloy 2024-T3				
P1	6.00	7956	4950	.625
P2	6.00	7956	5340	.675
P3	6.50	5526	3639	.658
P4	5.40	5526	3639	.658
P5	6.50	5526	3610	.650
P6	5.80	12151	10755	.885
P7	4.59	13320	11900	.900
P8	5.80	4440	3855	.870
P9	5.30	4450	3675	.830
P10	2.80	3500	2275	.650
P11	2.90	8970	7900	.885
P12	5.80	6942	5060	.730
P13	----- Not Calculated -----			
Alloy 7075-T6				
P1	4.08	5500	2700	.490
P2	3.69	5410	3981	.730
P6	2.70	3468	3275	.945
P7	2.26	3460	2450	.710

* 2a represents the maximum crack length calculated by the computer program.

summary, this work was very valuable in gaining an understanding of the mechanisms of formation and the appearance of fatigue striations. This understanding is being directly applied to the evaluation of crack propagation in test components and service parts subjected to simulated or real load programs.

The microscopic crack growth rate measurements for Programs P1 to P5 and P6 to P12 yield the following empirical equation of crack growth rate by combining Equations (1) and (2):

$$\text{growth rate} = \text{constant } (\Delta S)^n (S \text{ max})^m \quad (3)$$

Like the measurements from which it is derived, this empirical equation gives a relative change of growth rate at a given crack length for relative changes of ΔS and $S \text{ max}$. Equation (3) applies to a stabilized growth rate with uniform striation spacings at a given ΔS and $S \text{ max}$ load level. It does not apply exactly to the growth rate corresponding to the one large striation created by the first load cycle of a higher load level. The exponent n varies from one to three and up to four for decreasing values of ΔS . For ΔS ranging from 8000 psi to 11,400 psi it is surprising to find $n = 1$, since Paris¹⁸ has shown that $n = 4$ is a general trend in fatigue crack growth. The only explanation for this difference can be given in terms of $S \text{ max}$. Most of the tests with variable ΔS were conducted (see Schijve) at constant $S \text{ mean}$, which means that $S \text{ max}$ varies at the same time as ΔS ; consequently the changes of growth rates are the result of combined changes of ΔS and $S \text{ max}$. As it will be shown

later, changes of S_{max} can markedly influence the growth rates. It would be interesting to do more testing to measure accurately the dependence of growth rates on ΔS at constant S_{max} . For ΔS varying from 8000 psi to 6000 psi and 2000 psi n increases to two or three. This increase corresponds to smaller growth rates than expected at low ΔS as a result of crack retardation, or even arrest, following the application of loads with a large ΔS . The most striking result at constant S_{max} is the independence of the crack growth rate with respect to the sequence of load amplitude application.

In Equation (3) the exponent m , which relates S_{max} to the growth rate, varies from three to four and up to five when S_{max} varies from 14,000 psi to 10,000 psi. Schijve had found $m \approx 3$. This large dependence of the crack growth rate on the maximum stress level accounts for the marked change in striation spacing whenever the maximum load level is changed. It also explains the fact that in a random load test the peak loads result in large crack jump with large, well-defined striations.

Table IV shows that the prediction of crack growth rates, using Miner's rule, was unconservative for all the test programs run. It is interesting to note that the prediction was better for the Programs P6 to P12 with variable maximum loads, than for Programs P1 to P5 with constant maximum loads. This can be easily explained if, for Programs P6 to P12 the higher load levels have a marked de-

celerating effect on crack propagation at the lower load levels.

In Table IV it is also interesting to note that $\sum \frac{n}{N}$ for the pseudorandom Program P10 is much smaller than for the other Programs P8 and P9, which shows that estimation of random load crack growth rates is less accurate than estimation of programmed load growth rates.

It is clear by now that the application of Miner's rule to predict crack growth rates does not give a satisfactory answer. For the tests reported here we found $\sum \frac{n}{N}$ varying from .65 to .85 (unconservative prediction), while Schijve¹¹ found values of $\sum \frac{n}{N} = 3$ for programmed load tests with peak overloads. In order to be able to predict crack growth rates for random and program loads we have to be able to account quantitatively for the three following observations:

1. Crack acceleration or crack deceleration,
2. Crack arrest,
3. Crack jump at a change of load level.

Crack Acceleration or Crack Deceleration

It is well known¹¹ that high stress amplitudes have a decelerating effect on the subsequent crack propagation rates at a lower stress amplitude and *vice versa* for the reverse sequence of low-high loads. Hardrath²¹ shows (using his symbolic writing) that values of $\sum \frac{n}{N}$ for the following sequence $\triangleright \triangleright$ are equal to two or three times the value of $\sum \frac{n}{N}$ for the sequence $\triangleleft \triangleleft$. The overall

growth rates for Programs P6 and P7, P8 and P9 were not markedly different, although these programs are of the same type as the programs run by Hardrath. The difference between Hardrath's tests and ours is probably due to the limited number of cycles at each load level in our programs. The difference in growth rate at the lower load levels is not as striking as would be expected for a large number of cycles.

The accelerating and decelerating effect is difficult to measure by electron fractography. It requires a comparison of absolute measurements of growth rates (striation spacing) at the same crack length or the same stress intensity factor between two difference fracture surfaces. The scatter in the measurements of striation spacing does not allow an accurate comparison. On the other hand, local changes of growth rates are easier to measure, and we have observed in the case of P11 that the first B cycles (17,000 psi) immediately following four A cycles (14,000 psi) result in a larger striation spacing than the last B cycles. Hertzberg²⁰ has made a similar observation for similar load programs. Therefore, in this case it seems that an abrupt decrease in load level is accompanied by a slow decrease in growth rates at the lower load level. The larger growth rates at the lower load level are certainly due to the fact that the material near the crack tip had been subjected to a deformation strain very close to the fracture strain, making cracking easy even at a lower load level.

Crack Arrest

After a high positive load, crack propagation at a lower

load level stops or is delayed for a certain number of cycles. (Schijve,¹¹ Plunkett¹⁷) In our programs crack arrest was observed for P1, P2, P6, P7, P8, and P9, and in each case only for the lowest load amplitude, or the lowest load level spectrum. It should be pointed out that crack arrest in some cases has been observed at the surface of a test specimen, but fractography shows that crack propagation is proceeding at the lower load level in the plane strain region, resulting in a "tunneling" of the crack front in the center of the test specimen. In general, however, crack arrest seems to take place over the whole crack front. Schijve¹¹ explains crack arrest on the basis of the building up and the elimination of residual stresses. This general explanation would need some experimental evidence to support it. For instance, the work of Hardrath²² who measures the cyclic plastic stresses at a notch root, should be extended to see the rate of change of the residual stresses as a function of a change of load amplitude. It can also be said that we have paid little attention so far to the cyclic stress-strain hardening curve and how we can change the work-hardened state of a material from a monotonic workhardening to a cyclic workhardening. Following the application of a peak overload there is formation of a plastic zone at the tip of the crack which has been monotonically work-hardened. It is going to take a certain number of load cycles to reach the cyclic workhardening state typical of the plastic zone which controls fatigue cracking. When the plastic strain distribution within the plastic zone is found it will be possible to simulate the workhardening behavior of the plastic

zone with test bars subjected to controlled strain amplitudes increasing in the same way as the plastic strains at the tip of a fatigue crack.

Crack Jump at a Change of Load Level

A typical example is shown in Figure 33 where the first of six cycles at 28,450 psi corresponds to a large crack jump. Similar observations were made with Programs P6 to P13. It is felt that the crack tip radius and the related stress concentration factor will markedly influence the crack advance on the application of the first higher load cycle.

Although we partly understand the sequence of striation formation right at the crack tip, we still do not know the exact shape and size of the crack tip. It is difficult to see how we can get a better crack tip image with the existing tools and techniques. At this stage it is convenient to assume a uniform crack tip shape, with the crack tip radius r becoming an important variable determining the intensity of the stress concentration at the tip of the crack. In a first approximation it seems that r is closely related to the width of the part of the striation created during the closing mode of the crack, which is a measure of the resharping of the crack tip during unloading. In the case of random load programs, resharping of the crack tip to a very small r value will be due to all the small load amplitude, low level load cycles. The peak overload will be more damaging in a random load sequence than in a program sequence because of the larger stress concentration at the

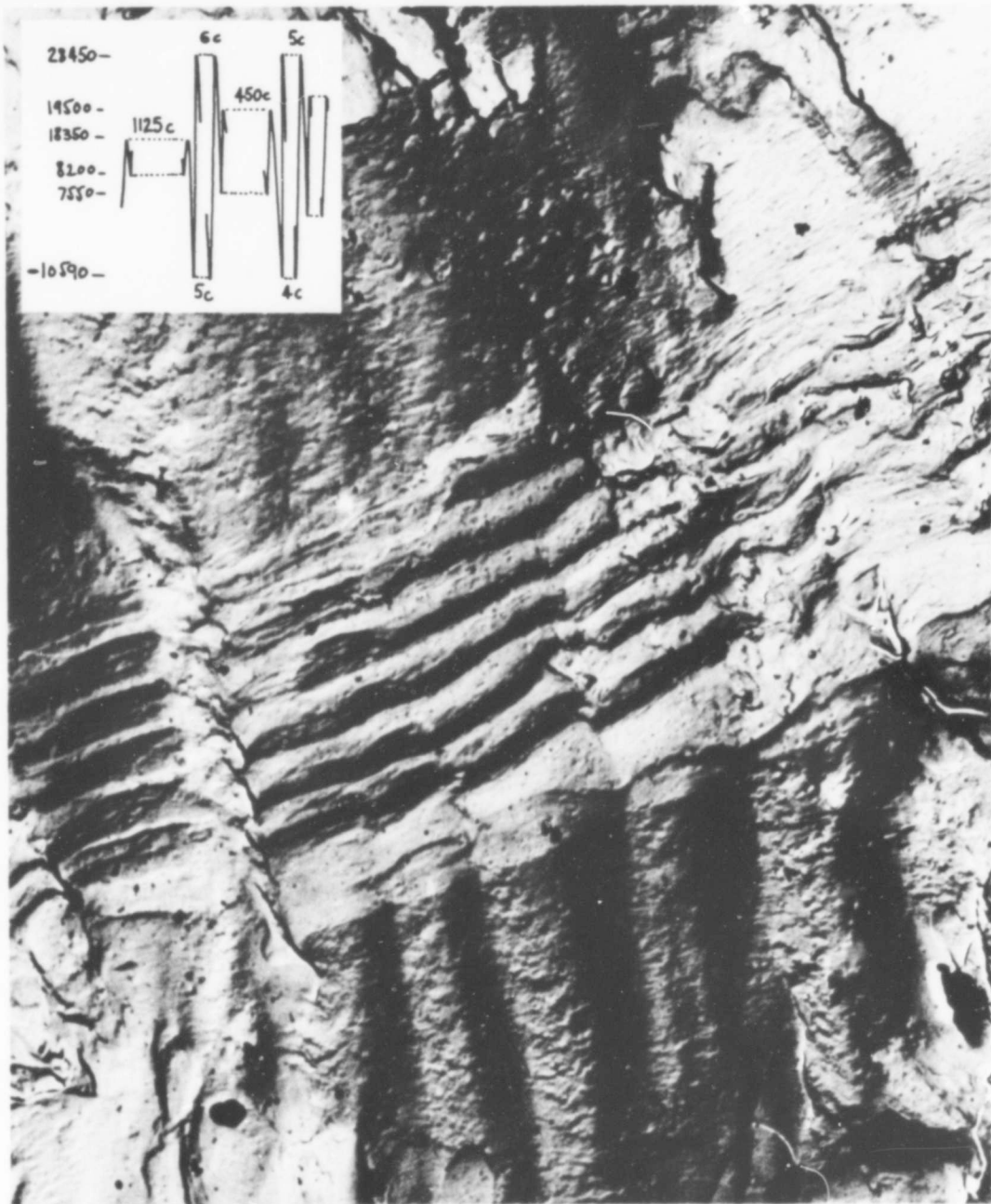


Figure 33a (courtesy of Rutkiewicz and Mavec, Wichita Division)
 Note the large crack jump occurring on the application of the first large load. The spacing of the first striation is larger than for the following five striations, although the load amplitude and level are the same. Use with Figure 33b to form a stereo image, and note the difference in crack tip profile after 1125 cycles at 18,350 psi and at each of the large load cycles (28,450 psi).

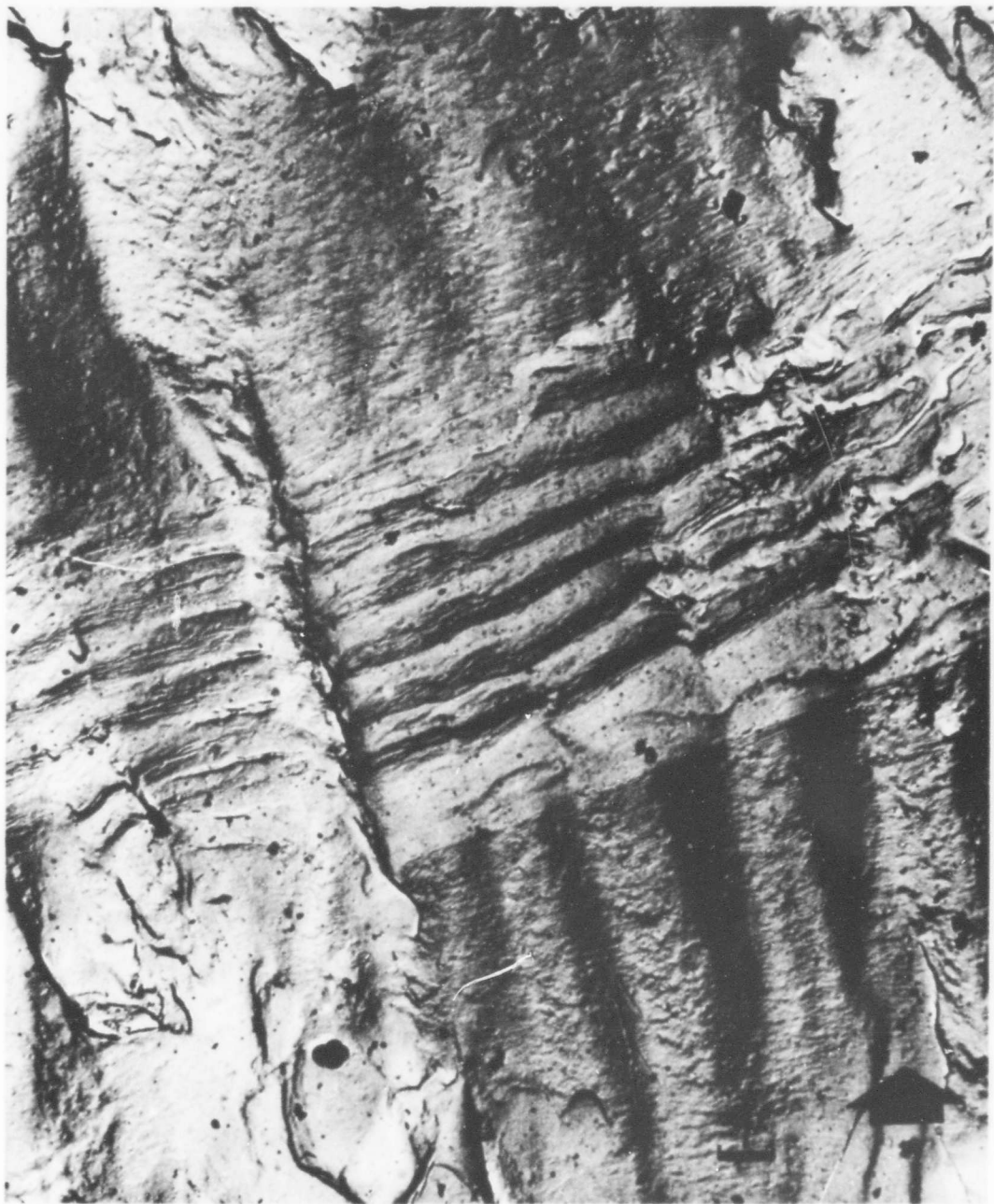


Figure 33b (courtesy of Rutkiewicz and Mavec, Wichita Division)
Note the large crack jump occurring on the application of the first large load. The spacing of the first striation is larger than for the following five striations, although the load amplitude and level are the same. Use with Figure 33a to form a stereo image, and note the difference in crack tip profile after 1125 cycles at 18,350 psi and at each of the large load cycles (28,450 psi).

crack tip due to a smaller crack tip radius. The sharpness of the crack tip can be qualitatively observed in Figures 28 and 29, where the ridges of the striations are very sharp. The difference between random and program loading will be more marked at the slower growth rate where the crack tip is much sharper. This was observed by Paris¹⁶ and Smith,¹⁹ who found that random loading is faster than sinusoidal loading for growth rates below 10^{-5} or 10^{-4} inches/cycle. It should also be mentioned that crack tip blunting under a peak overload may account for part of the crack arrest phenomena. On the other hand, continuous crack tip resharping in a corrosive medium explains the acceleration of crack growth rates in corrosion fatigue.

In summary, it can be said that the importance of the crack tip radius and the associated stress and strain concentration factors has been underestimated in all the analysis of the mechanisms of fatigue crack propagation. Also, before we can understand the complex fatigue crack propagation behavior of a material under program or random loads it will be necessary to have a better knowledge of the cyclic workhardening which takes place in the plastic zone. Our present work has not given an answer to these two challenging problems. However, we have been able to appraise the important contribution that the techniques of fractography can provide in this field of research. Further tests with higher peak overloads to create larger crack jumps and crack arrest are underway. The number of cycles at a given stress level has been increased markedly in order

to measure changes in rates due to arrest or deceleration. In the long range this type of work is aimed at determining the different parameters which control growth rates in order to establish a set of relationships which can be used first for the analysis, and then for the prediction of cumulative damage.

V. SUMMARY

In this paper it has been shown that fatigue crack propagation tests under program and random loads, combined with a study of striation counts and spacing measurements by electron microscopy, have given us a better understanding of the mechanisms of fatigue cracking. The main findings with respect to aluminum alloy 2024-T3 are as follows:

1. The advance of the fatigue crack front takes place only during the stress rise portion of a cycle.
2. The profile or sides of a striation are related to the loading and unloading sequence of a load cycle.
3. Microscopic crack growth rates were measured as a function of load amplitudes ΔS and maximum loads S_{max} and an empirical crack growth rate equation was obtained:

$$\text{crack growth rate} = \text{constant } (\Delta S)^n (S_{max})^m$$

This equation relates the relative growth rates at a given crack length under program loading.

4. In random load programs with constant S_{max} , the growth rate is the same as the programmed spectra rates. No sequencing effect is apparent in changes in ΔS alone.
5. In random load programs with variable S_{max} , the crack growth rates were higher than for the equivalent programmed load programs. The importance of the crack tip radius in controlling crack rates for random loads was pointed out.
6. The measured crack growth rate of program and random load crack propagation tests were compared with rates calculated by a computer program. The computed rates are not conservative but they do not differ from the measured rates by a factor of more than two. The application of Miner's rule resulted in $\sum \frac{n}{N}$ values of the order of .650 for the constant maximum load programs and of .850 for the variable maximum load programs.

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APPENDIX I - TEST DATA

Program P1 Alloy 7075 T6		Program P6 Alloy 7075 T6		Program P2 Alloy 7075 T6		Program P7 Alloy 7075 T6	
Periods Number	Crack Length	Periods Number	Crack Length	Periods Number	Crack Length	Periods Number	Crack Length
N	2a	N	2a	N	2a	N	2a
0	0.494	0	0.502	0	0.539	0	0.505
375	0.506	200	0.510	200	0.549	300	0.529
475	0.535	300	0.523	506	0.594	500	0.377
550	0.553	450	0.547	750	0.619	700	0.619
650	0.575	600	0.582	1000	0.657	900	0.691
750	0.599	750	0.624	1250	0.663	1100	0.765
850	0.645	900	0.652	1500	0.734	1300	0.849
950	0.673	1050	0.692	1750	0.811	1500	0.956
1100	0.756	1200	0.733	2050	0.946	1720	1.076
1250	0.828	1400	0.790	2300	1.072	1900	1.198
1400	0.912	1600	0.855	2550	1.163	2100	1.418
1550	0.990	1820	0.941	2750	1.366	2200	1.529
1700	1.124	2000	1.028	2850	1.455	2350	1.814
1850	1.256	2150	1.118	2952	1.561	2400	1.986
1950	1.365	2250	1.170	3100	1.724	2450	2.268
2050	1.492	2400	1.230	3250	1.896	2499	
2150	1.649	2550	1.457	3500	2.248		
2250	1.818	2650	1.484	3600	2.432		
2350	2.063	2700	1.547	3750	2.700		
2450	2.318	2800	1.592	3850	3.042		
2550	2.686	2900	1.691	3950	3.686		
2600	2.923	3000	1.821	3981			
2650	3.254	3100	2.011				
2700	4.080	3150	2.133				
2712		3200	2.280				
		3225	2.431				
		3250	2.573				
		3275	2.718				
		3300	2.942				
		3315					

Program P1 Alloy 2024 T3			Program P2 Alloy 2024 T3		Program P3 Alloy 2024 T3		Program P4 Alloy 2024 T3	
Periods Number N	Crack Length 2a		Periods Number N	Crack Length 2a	Periods Number N	Crack Length 2a	Periods Number N	Crack Length 2a
0	0,498	0,249	0	0.509	0	0.492	0	0.521
250	0.517	0.258	500	0.537	250	0.502	125	0.530
600	0.566	0.283	1125	0.643	500	0.555	200	0.545
1000	0.628	0.314	1750	0.833	600	0.589	275	0.568
1600	0.764	0.382	2300	0.982	750	0.643	350	0.586
2000	0.914	0.457	2750	1.149	900	0.684	475	0.654
2500	1,110	0.550	3550	1.540	1050	0.730	550	0.702
3100	1,466	0.733	4000	1.933	1200	0.798	650	0.778
3500	1,784	0.892	4500	2.548	1400	0.886	750	0.865
4100	2,479	1.240	5000	3.642	1600	0.983	850	0.958
4400	3,001	1,500	5250	4.80	1850	1.121	950	1.070
4500	3,233	1,616	5300	5.27	2050	1.279	1050	1.203
4750	4,051	2,025	5325	5.55	2175	1.371	1150	1.346
4850	4,646	2,323	5355	6.40	2275	1.467	1225	1.479
4925	5,326	2,663	5360		2375	1.573	1375	1.789
4940	5,75	2,87			2475	1.655	1400	1.855
4945	5,85	2,92			2600	1.800	1475	2.063
4950	6,00	3,00			2700	1.916	1550	2.303
4955					2800	2.050	1600	2.519
					2900	2.206	1650	2.751
					3000	2.386	1700	3.020
					3125	2.650	1750	3.389
					3200	2.830	1800	3.87
					3300	3.128	1825	4.18
					3400	3.490	1850	4.63
					3450	3.77	1875	5.42
					3550	4.50		
					3575	4.80		
					3590	5.00		
					3595	5.08		
					3600	5.18		
					3605	5.26		
					3610	5.37		
					3615	5.48		
					3620	5.59		
					3625	5.77		
					3630	5.95		
					3635	6.33		
					3639	Failed		

Program P5 Alloy 2024 T3		Program P6 Alloy 2024 T3		Program P7 Alloy 2024 T3		Program P8 Alloy 2024 T3	
Periods Number N	Crack Length 2a	Periods Number N	Cracks Length 2a	Periods Number N	Crack Length 2a	Periods Number N	Crack Length 2a
0	0.512	0	0.513	0	0.501	0	0.5254
350	0.529	500	0.524	900	0.531	300	0.5574
450	0.552	1000	0.550	1200	0.547	650	0.637
650	0.596	1600	0.602	1600	0.582	1000	0.729
775	0.627	2000	0.618	2000	0.620	1375	0.859
910	0.677	2500	0.672	2450	0.664	1700	0.993
1050	0.716	3000	0.733	2900	0.719	1975	1.131
1200	0.775	3500	0.807	3500	0.804	2250	1.312
1350	0.831	4000	0.876	4118	0.907	2500	1.534
1550	0.941	4500	0.975	4500	0.951	2775	1.817
1710	1.025	5000	1.077	5400	1.120	3000	2.123
1850	1.104	5500	1.184	5800	1.184	3200	2.460
2000	1.203	6000	1.318	6307	1.295	3300	2.687
2100	1.287	6750	1.539	6800	1.444	3400	2.882
2200	1.358	7500	1.817	7300	1.569	3550	3.35
2325	1.473	8100	2.083	7700	1.718	3650	3.75
2450	1.592	8600	2.383	8000	1.835	3725	4.13
2560	1.722	9200	2.798	8300	1.958	3750	4.29
2650	1.843	9800	3.426	8600	2.072	3775	4.47
2775	2.010	10125	3.821	9400	2.475	3800	4.77
2875	2.177	10250	4.036	9800	2.650	3815	5.02
3000	2.417	10300	4.16	10000	2.818	3830	5.20
3100	2.650	10350	4.24	10200	2.956	3840	5.45
3150	2.780	10450	4.48	10400	3.122	3850	5.70
3200	2.920	10525	4.71	10600	3.299	3860	5.92
3250	3.093	10650	5.12	10800	3.466	3867	
3310	3.310	10675	5.25	11000	3.684		
3350	3.479	10700	5.37	11200	3.925		
3400	3.750	10725	5.55	11405	4.245		
3425	3.880	10750	5.74	11600	4.588		
3450	4.020	10775	6.04	11900	5.722		
3475	4.180	10780	6.14	11921			
3500	4.350	10785	6.24				
3525	4.620	10790					
3540	4.750						
3570	5.150						
3580	5.320						
3590	5.520						
3600	5.800						
3605	6.010						
3610	6.270						
3613							

Program P9 Alloy 2024 T3		Program P10 Alloy 2024 T3		Program P11 Alloy 2024 T3		Program P12 Alloy 2024 T3	
Periods Number	Crack Length	Periods Number	Crack Length	Periods Number	Crack Length	Periods Number	Crack Length
N	2a	N	2a	N	2a	N	2a
0	0.499	0	0.511	0	0.505	0	0.492
250	0.525	150	0.524	250	0.513	400	0.505
500	0.572	300	0.567	500	0.519	800	0.585
750	0.643	500	0.622	750	0.525	1125	0.626
1000	0.723	700	0.713	1000	0.543	1725	0.762
1250	0.823	950	0.845	1250	0.570	1825	0.785
1500	0.931	1125	0.967	1500	0.592	2000	0.848
1750	1.066	1250	1.050	1750	0.620	2250	0.930
2000	1.240	1400	1.189	2000	0.648	2400	0.977
2250	1.438	1550	1.380	2200	0.675	2600	1.070
2600	1.792	1700	1.573	2500	0.722	2925	1.230
2800	2.077	1900	1.878	2750	0.751	3250	1.417
3000	2.382	2110	2.322	3100	0.815	3525	1.636
3208	2.819	2275	2.844	3400	0.870	3850	1.921
3303	3.072	2400	3.50	3700	0.941	4100	2.210
3406	3.402	2520	4.73	4050	1.023	4350	2.575
3452	3.600	2553		4350	1.108	4500	2.859
3504	3.88			4700	1.239	4625	3.19
3575	4.28			5050	1.329	4700	3.38
3625	4.70			5500	1.508	4800	3.71
3675	5.37			5900	1.700	4900	4.18
3700	Failed			6200	1.858	5000	4.90
				6500	2.039	5025	5.20
				6950	2.372	5050	5.62
				7200	2.585	5070	6.30
				7900	2.893		

Program P13
Alloy 2024 T3

Periods Number N	Crack Length 2a
0	0.504
300	0.511
600	0.592
700	0.626
850	0.674
1000	0.760
1175	0.815
1400	0.961
1605	1.070
1800	1.225
1925	1.335
2075	1.480
2200	1.623
2350	1.825
2450	1.976
2605	2.247
2680	2.405

APPENDIX II - COMPUTER PROGRAMS

PROGRAM P1 CRACK GROWTH IN 2024 T3 PANELS

FOR THIS SET OF CONDITIONS,

THE NUMBER OF FLIGHTS TAKEN IS 7968

THE CRACK LENGTH REACHED IS 3.27102 INCHES

THE CONTROL CRACK LENGTH SPECIFIED IS 3.25000 INCHES

FLIGHT,	CRACK LENGTH	FLIGHT	CRACK LENGTH
159	0.255001	4293	0.515707
318	0.260228	4452	0.534070
477	0.265695	4611	0.553572
636	0.271416	4770	0.574308
795	0.277408	4929	0.596378
954	0.283688	5088	0.619890
1113	0.290276	5247	0.644876
1272	0.297201	5406	0.671515
1431	0.304488	5565	0.700916
1590	0.312144	5724	0.732789
1749	0.320192	5883	0.767326
1908	0.328652	6042	0.804890
2067	0.337545	6201	0.845348
2226	0.346890	6360	0.889468
2385	0.356708	6519	0.938342
2544	0.367015	6678	0.993105
2703	0.377825	6837	1.055434
2862	0.389151	6996	1.128334
3021	0.400710	7155	1.217298
3180	0.412714	7314	1.327602
3339	0.425281	7473	1.470291
3498	0.438459	7632	1.668310
3657	0.452299	7791	1.990210
3816	0.466860	7950	2.887476
3975	0.482211	7968	3.271015
4134	0.498429		

PROGRAM P2 CRACK GROWTH IN 2024 T3 PANELS

FOR THIS SET OF CONDITIONS,

THE NUMBER OF FLIGHTS TAKEN IS 7968

THE CRACK LENGTH REACHED IS 3.26254 INCHES

THE CONTROL CRACK LENGTH SPECIFIED IS 3.25000 INCHES

FLIGHT,	CRACK LENGTH	FLIGHT	CRACK LENGTH
156	0.255002	4293	0.515720
316	0.260229	4452	0.534084
477	0.265695	4611	0.553587
636	0.271417	4770	0.574324
795	0.277409	4929	0.596395
954	0.283690	5088	0.619909
1113	0.290278	5247	0.644895
1272	0.297204	5406	0.671535
1431	0.304491	5565	0.700939
1590	0.312148	5724	0.732814
1749	0.320197	5883	0.767353
1908	0.328657	6042	0.804918
2067	0.337550	6201	0.845379
2226	0.346896	6360	0.889501
2385	0.356715	6519	0.938378
2544	0.367022	6678	0.993142
2703	0.377833	6837	1.055470
2862	0.389159	6996	1.128352
3021	0.400718	7155	1.217305
3180	0.412722	7314	1.327593
3339	0.425291	7473	1.470257
3498	0.438468	7632	1.668215
3657	0.452304	7791	1.989930
3816	0.466871	7950	2.884441
3975	0.482223	7968	3.262541
4134	0.498441		

PROGRAM P3 CRACK GROWTH IN 2024 T3 PANELS

FOR THIS SET OF CONDITIONS,

THE NUMBER OF FLIGHTS TAKEN IS 5526

THE CRACK LENGTH REACHED IS 3.26622 INCHES

THE CONTROL CRACK LENGTH SPECIFIED IS 3.25000 INCHES

FLIGHT,	CRACK LENGTH	FLIGHT	CRACK LENGTH
111	0.254990	2886	0.498631
222	0.260203	2997	0.516248
333	0.265653	3108	0.534999
444	0.271354	3219	0.554954
555	0.277323	3330	0.576216
666	0.283575	3441	0.598894
777	0.290129	3552	0.623108
888	0.297006	3663	0.648890
999	0.304226	3774	0.676511
1110	0.311808	3885	0.707173
1221	0.319773	3996	0.740365
1332	0.328144	4107	0.776412
1443	0.336942	4218	0.815694
1554	0.346191	4329	0.857720
1665	0.355912	4440	0.903897
1776	0.366126	4551	0.955213
1887	0.376854	4662	1.012947
1998	0.388113	4773	1.079113
2109	0.399705	4884	1.157810
2220	0.411762	4995	1.254227
2331	0.424416	5106	1.375048
2442	0.437718	5217	1.533539
2553	0.451723	5328	1.760944
2664	0.466495	5439	2.165308
2775	0.482104	5526	3.266218

PROGRAM P5 CRACK GRWTH IN 2024 T3 PANELS

FOR THIS SET OF CONDITIONS,

THE NUMBER OF FLIGHTS TAKEN IS 5526

THE CRACK LENGTH REACHED IS 3.25610 INCHES

THE CONTROL CRACK LENGTH SPECIFIED IS 3.25000 INCHES

FLIGHT,	CRACK LENGTH	FLIGHT	CRACK LENGTH
110	0.254943	2970	0.511694
220	0.260104	3080	0.529981
330	0.265496	3190	0.549423
440	0.271134	3300	0.570120
550	0.277034	3410	0.592178
660	0.283211	3520	0.615708
770	0.289684	3630	0.640774
880	0.296472	3740	0.667515
990	0.303595	3850	0.696911
1100	0.311073	3960	0.728938
1210	0.318924	4070	0.763656
1320	0.327172	4180	0.801417
1430	0.335836	4290	0.842060
1540	0.344941	4400	0.886198
1650	0.354505	4510	0.935012
1760	0.364552	4620	0.989602
1870	0.375099	4730	1.051578
1980	0.386165	4840	1.123748
2090	0.397608	4950	1.211695
2200	0.409449	5060	1.320150
2310	0.421868	5170	1.459127
2420	0.434913	5280	1.648398
2530	0.448637	5390	1.946119
2640	0.463100	5500	2.661111
2750	0.478369	5526	3.256102
2960	0.494519		

PROGRAM P6 CRACK GROWTH IN 2024 T3 PANELS

FOR THIS SET OF CONDITIONS,

THE NUMBER OF FLIGHTS TAKEN IS 12151

THE CRACK LENGTH REACHED IS 2.90380 INCHES

THE CONTROL CRACK LENGTH SPECIFIED IS 2.90000 INCHES

FLIGHT,	CRACK LENGTH	FLIGHT	CRACK LENGTH
243	0.254394	6561	0.485921
486	0.258963	6904	0.504106
729	0.263717	7047	0.523605
972	0.268665	7290	0.544562
1215	0.273822	7533	0.567085
1458	0.279201	7776	0.591191
1701	0.284816	8019	0.617153
1944	0.290670	8262	0.644787
2187	0.296788	8505	0.674525
2430	0.303200	8748	0.707847
2673	0.309892	8991	0.744386
2916	0.316911	9234	0.784597
3159	0.324283	9477	0.829064
3402	0.332033	9720	0.878628
3645	0.340191	9963	0.934171
3888	0.348790	10206	0.997013
4131	0.357865	10449	1.068944
4374	0.367455	10692	1.152425
4617	0.377588	10935	1.251246
4860	0.388321	11178	1.371102
5103	0.399700	11421	1.522059
5346	0.411789	11664	1.725326
5589	0.424669	11907	2.045630
5832	0.438460	12150	2.895330
6075	0.453198	12151	2.903804
6318	0.468979		

PROGRAM P7 CRACK GROWTH IN 2024 T3 PANELS

FOR THIS SET OF CONDITIONS,

THE NUMBER OF FLIGHTS TAKEN IS 13517

THE CRACK LENGTH REACHED IS 2.90526 INCHES

THE CONTROL CRACK LENGTH SPECIFIED IS 2.90000 INCHES

FLIGHT,	CRACK LENGTH	FLIGHT	CRACK LENGTH
270	0.254257	7290	0.493558
540	0.258693	7560	0.513151
810	0.263320	7830	0.534234
1080	0.269149	8100	0.556961
1350	0.273196	8370	0.581319
1620	0.278477	8640	0.607525
1890	0.284008	8910	0.635692
2160	0.289811	9180	0.665994
2430	0.295918	9450	0.699478
2700	0.302353	9720	0.736427
2970	0.309092	9990	0.776953
3240	0.316189	10260	0.821518
3510	0.323673	10530	0.870501
3780	0.331576	10800	0.924568
4050	0.339931	11070	0.984756
4320	0.348774	11340	1.052260
4590	0.358148	11610	1.128636
4860	0.368094	11880	1.216141
5130	0.378623	12150	1.317953
5400	0.389821	12420	1.438771
5670	0.401735	12690	1.587177
5940	0.414448	12960	1.782270
6210	0.428071	13230	2.082376
6480	0.442718	13500	2.801352
6750	0.458439	13517	2.905261
7020	0.475339		

PROGRAM P8 CRACK GROWTH IN 2024 T3 PANELS

FOR THIS SET OF CONDITIONS,

THE NUMBER OF FLIGHTS TAKEN IS 4440

THE CRACK LENGTH REACHED IS 2.90840 INCHES

THE CONTROL CRACK LENGTH SPECIFIED IS 2.90000 INCHES

FLIGHT,	CRACK LENGTH	FLIGHT	CRACK LENGTH
89	0.254570	2314	0.492571
178	0.259339	2403	0.511530
267	0.264321	2492	0.531782
356	0.269529	2581	0.553454
445	0.274980	2670	0.576589
534	0.280692	2759	0.601304
623	0.286682	2848	0.627685
712	0.292975	2937	0.655711
801	0.299612	3026	0.686175
890	0.306586	3115	0.719826
979	0.313922	3204	0.756426
1068	0.321654	3293	0.796337
1157	0.329814	3382	0.839929
1246	0.338431	3471	0.887543
1335	0.347540	3560	0.940017
1424	0.357176	3649	0.998263
1513	0.367377	3738	1.063474
1602	0.378128	3827	1.137188
1691	0.389513	3916	1.221763
1780	0.401578	4005	1.320636
1869	0.414397	4094	1.439226
1958	0.428055	4183	1.588485
2047	0.442640	4272	1.792941
2136	0.458201	4361	2.127930
2225	0.474816	4440	2.908402

PROGRAM. P9 CRACK GROWTH IN 2024 T3 PANELS

FOR THIS SET OF CONDITIONS,

THE NUMBER OF FLIGHTS TAKEN IS 4466

THE CRACK LENGTH REACHED IS 2.90974 INCHES

THE CONTROL CRACK LENGTH SPECIFIED IS 2.90000 INCHES

FLIGHT,	CRACK LENGTH	FLIGHT	CRACK LENGTH
89	0.254548	2403	0.510834
178	0.259296	2492	0.530969
267	0.264256	2581	0.552501
356	0.269443	2670	0.575478
445	0.274874	2759	0.600005
534	0.280566	2848	0.626183
623	0.286538	2937	0.653969
712	0.292819	3026	0.684080
801	0.299448	3115	0.717364
890	0.306419	3204	0.753528
979	0.313753	3293	0.792911
1068	0.321486	3382	0.835869
1157	0.329647	3471	0.882696
1246	0.338268	3560	0.934154
1335	0.347382	3649	0.991080
1424	0.357022	3738	1.054546
1513	0.367226	3827	1.125833
1602	0.377970	3916	1.206865
1691	0.389341	4005	1.300736
1780	0.401377	4094	1.412004
1869	0.414154	4183	1.549582
1958	0.427760	4272	1.733445
2047	0.442284	4361	2.013495
2136	0.457773	4450	2.642915
2225	0.474312	4466	2.909745
2314	0.491979		

PROGRAM P11 CRACK GROWTH IN 2024 T3 PANELS

FOR THIS SET OF CONDITIONS,

THE NUMBER OF FLIGHTS TAKEN IS 9741

THE CRACK LENGTH REACHED IS 2.90281 INCHES

THE CONTROL CRACK LENGTH SPECIFIED IS 2.90000 INCHES

FLIGHT,	CRACK LENGTH	FLIGHT	CRACK LENGTH
195	0.254486	5070	0.492681
390	0.259166	5265	0.511706
585	0.264053	5460	0.531950
780	0.269163	5655	0.553602
975	0.274512	5850	0.576788
1170	0.280117	6045	0.601645
1365	0.285998	6240	0.628270
1560	0.292174	6435	0.656700
1755	0.298719	6630	0.687700
1950	0.305635	6825	0.721946
2145	0.312930	7020	0.759219
2340	0.320634	7215	0.799912
2535	0.328778	7410	0.844277
2730	0.337395	7605	0.892808
2925	0.346520	7800	0.946437
3120	0.356192	7995	1.006084
3315	0.366451	8190	1.073019
3510	0.377303	8385	1.149018
3705	0.388815	8580	1.236414
3900	0.400998	8775	1.338075
4095	0.413938	8970	1.458038
4290	0.427715	9165	1.603785
4485	0.442399	9360	1.797256
4680	0.458063	9555	2.111245
4875	0.474801	9741	2.902808

PROGRAM P12 CRACK GROWTH IN 2024 T3 PANELS

FOR THIS SET OF CONDITIONS,

THE NUMBER OF FLIGHTS TAKEN IS 6942

THE CRACK LENGTH REACHED IS 2.90175 INCHES

THE CONTROL CRACK LENGTH SPECIFIED IS 2.90000 INCHES

FLIGHT,	CRACK LENGTH	FLIGHT	CRACK LENGTH
139	0.254758	3614	0.502688
274	0.259730	3753	0.522007
417	0.264931	3892	0.542628
556	0.270376	4031	0.564654
695	0.276084	4170	0.588189
834	0.282072	4309	0.613341
973	0.288362	4448	0.639793
1112	0.294994	4587	0.667934
1251	0.301979	4726	0.698832
1390	0.309335	4865	0.732413
1529	0.317089	5004	0.768759
1668	0.325267	5143	0.808208
1807	0.333898	5282	0.851061
1946	0.343011	5421	0.897687
2085	0.352636	5560	0.948859
2224	0.362805	5699	1.005336
2363	0.373497	5838	1.068157
2502	0.384719	5977	1.138275
2641	0.396583	6116	1.217803
2780	0.409140	6255	1.310178
2919	0.422450	6394	1.420749
3058	0.436575	6533	1.562275
3197	0.451584	6672	1.762242
3336	0.467552	6811	2.086557
3475	0.484560	6942	2.901749

PROGRAM P1 CRACK GROWTH IN 7075 T6 PANELS

FOR THIS SET OF CONDITIONS,

THE NUMBER OF FLIGHTS TAKEN IS 5623

THE CRACK LENGTH REACHED IS 2.50277 INCHES

THE CONTROL CRACK LENGTH SPECIFIED IS 2.50000 INCHES

FLIGHT,	CRACK LENGTH	FLIGHT	CRACK LENGTH
112	0.255822	3024	0.539007
224	0.261876	3136	0.559019
336	0.268170	3248	0.580283
448	0.274720	3360	0.602909
560	0.281538	3472	0.627018
672	0.288640	3584	0.652744
784	0.296039	3696	0.680402
896	0.303753	3808	0.710873
1008	0.311797	3920	0.743711
1120	0.320190	4032	0.779159
1232	0.328950	4144	0.816727
1344	0.338096	4256	0.857094
1456	0.347647	4368	0.900998
1568	0.357625	4480	0.948999
1680	0.367948	4592	1.001794
1792	0.378685	4704	1.060311
1904	0.389914	4816	1.125767
2016	0.401671	4928	1.200275
2128	0.413993	5040	1.286828
2240	0.426922	5152	1.390317
2352	0.440504	5264	1.520710
2464	0.454790	5376	1.694984
2576	0.469835	5488	1.955872
2688	0.485701	5600	2.376551
2800	0.502456	5623	2.502770
2912	0.520177		

PROGRAM P2 CRACK GROWTH IN 7075 T6 PANFLS

FOR THIS SET OF CONDITIONS,

THE NUMBER OF FLIGHTS TAKEN IS 5623

THE CRACK LENGTH REACHED IS 2.50147 INCHES

THE CONTROL CRACK LENGTH SPECIFIED IS 2.50000 INCHES

FLIGHT,	CRACK LENGTH	FLIGHT	CRACK LENGTH
112	0.255822	3024	0.539010
224	0.261876	3136	0.559022
336	0.268170	3248	0.580286
448	0.274720	3360	0.602912
560	0.281539	3472	0.627022
672	0.288640	3584	0.652748
784	0.296040	3696	0.680406
896	0.303753	3808	0.710377
1008	0.311798	3920	0.743715
1120	0.320191	4032	0.779164
1232	0.328951	4144	0.816730
1344	0.338097	4256	0.857096
1456	0.347649	4368	0.900999
1568	0.357626	4480	0.948998
1680	0.367950	4592	1.001791
1792	0.378687	4704	1.060306
1904	0.389917	4816	1.125755
2016	0.401674	4928	1.200252
2128	0.413996	5040	1.286780
2240	0.426925	5152	1.390233
2352	0.440508	5264	1.520556
2464	0.454793	5376	1.694715
2576	0.469838	5488	1.955370
2688	0.485704	5600	2.375599
2800	0.502460	5623	2.501473
2912	0.520181		

PROGRAM P6 CRACK GROWTH IN 7075 T6 PANELS

FOR THIS SET OF CONDITIONS,

THE NUMBER OF FLIGHTS TAKEN IS 346A

THE CRACK LENGTH REACHED IS 1.35107 INCHES

THE CONTROL CRACK LENGTH SPECIFIED IS 1.35000 INCHES

FLIGHT,	CRACK LENGTH	FLIGHT	CRACK LENGTH
69	0.255165	1863	0.486235
138	0.260501	1937	0.501256
207	0.266019	2001	0.517029
276	0.271725	2070	0.533614
345	0.277630	2139	0.551071
414	0.283744	2208	0.569380
483	0.290079	2277	0.588517
552	0.296645	2346	0.608720
621	0.303454	2415	0.630103
690	0.310519	2484	0.652798
759	0.317854	2553	0.677045
828	0.325472	2622	0.704036
897	0.333389	2691	0.733149
966	0.341521	2760	0.764688
1035	0.350184	2829	0.798892
1104	0.359097	2898	0.835951
1173	0.368366	2967	0.876334
1242	0.378015	3036	0.920221
1311	0.388075	3105	0.968262
1380	0.398552	3174	1.021718
1449	0.409481	3243	1.082657
1518	0.420880	3312	1.152640
1587	0.432784	3381	1.233812
1656	0.445234	3450	1.325417
1725	0.458267	346A	1.351066
1794	0.471970		

PROGRAM P7 CRACK GROWTH IN 7075 T6 PANELS

FOR THIS SET OF CONDITIONS,

THE NUMBER OF FLIGHTS TAKEN IS 3679

THE CRACK LENGTH REACHED IS 1.35056 INCHES

THE CONTROL CRACK LENGTH SPECIFIED IS 1.35000 INCHES

FLIGHT,	CRACK LENGTH	FLIGHT	CRACK LENGTH
73	0.255282	1971	0.493373
146	0.260742	2044	0.509094
219	0.266389	2117	0.525624
292	0.272221	2190	0.543045
365	0.278250	2263	0.561391
438	0.284494	2336	0.580549
511	0.290965	2409	0.600725
584	0.297675	2482	0.622031
657	0.304635	2555	0.644567
730	0.311861	2628	0.668445
803	0.319365	2701	0.694454
876	0.327163	2774	0.722489
949	0.335270	2847	0.752536
1022	0.343705	2920	0.784868
1095	0.352486	2993	0.819419
1168	0.361630	3066	0.856543
1241	0.371141	3139	0.896477
1314	0.381056	3212	0.939160
1387	0.391403	3285	0.985526
1460	0.402180	3358	1.036569
1533	0.413441	3431	1.093784
1606	0.425254	3504	1.158316
1679	0.437621	3577	1.231971
1752	0.450578	3650	1.314918
1925	0.464161	3679	1.350557
1998	0.478411		