NASA TM-86929

NASA Technical Memorandum 86929

NASA-TM-86929 19850009815

A Study of Spectrum Fatigue Crack Propagation in Two Aluminum Alloys I—Spectrum Simplification

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January 1985

NASA

A STUDY OF SPECTRUM FATIGUE CRACK PROPAGATION IN TWO ALUMINUM ALLOYS

I - SPECTRUM SIMPLIFICATION*

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E-2438

SUMMARY

A study of the fatigue crack propagation behavior of two commercial Al alloys was undertaken using spectrum loading conditions characteristic of those encountered at critical locations in high performance fighter aircraft.

A tension dominated (TD) and tension compression (TC) spectrum were employed for each alloy. Using a mechanics-based data analysis, it was suggested that negative loads could be eliminated for the TC spectrum for low to intermediate maximum stress intensities. The suggestion was verified by subsequent testing.

Using fractographic evidence, it was suggested that a further simplification in the spectra could be accomplished by eliminating low and intermediate peak load points resulting in near or below threshold maximum peak stress intensity values.

It was concluded that load interactions become more important at higher stress intensities and more plasticity at the crack tip. These results suggest that a combined mechanics/fractographic mechanisms approach can be used to simplify other complex spectra.

INTRODUCTION

Damage tolerance is a design concept mandated by the U.S. Air Force in the design and maintenance of airframes. In its most basic form, it requires that a crack of approximately 0.13 cm (0.05 in) be assumed at a critical location. This, along with a stress analysis and fracture mechanics methodology is used to compute appropriate inspection intervals.

Implementation of this philosophy requires careful characterization of the fatigue crack propagation (FCP) properties of the material. As a starting point, extensive FCP testing is done under constant load amplitude conditions. Such information, however, can not be directly used in life analysis since real airframes are subject to variable amplitude loading. Thus another important step in evaluating materials and structures is to carry out testing under complex load histories. However, due to the complexity of load

*This work was performed at the University of Cincinnati as part of a masters thesis and was supported by Northrop Aircraft Division.

interaction effects and the higher cost of evaluating a wide variety of spectra, it is desirable to develop simplified load spectra that will none-the-less capture the important interactions. This worthy goal requires an in-depth understanding of load interaction effects as well as microstructural influences on these effects.

The goal of this paper is to examine ways in which spectra can be both better understood and simplified through data analysis as well as fractographic evaluations.

Part II of this study focuses on the effects of various microstructural parameters on FCP under both constant amplitude and spectrum loading and is described in the companion paper.

Dr. G. Chanani and Mr. G. Scarich of Northrop Corporation assisted in supplying materials and test data and gave many helpful suggestions during the course of this study.

EXPERIMENTAL PROCEDURE

Materials and Specimens

The two aluminum alloys used in the program were 7050-T7, which is produced through standard ingot metallurgy (I/M) processing and 7091-T7 produced through powder metallurgy (P/M) process. Both alloys were received in the overaged condition. The detailed alloy composition and heat treatments are shown in table I. Microstructural details are given in Part II.

For constant amplitude testing, compact tension (CT) specimens were used. For spectrum testing center crack tension (CCT) specimens were used so that compressive loads could be applied.

Mechanical Testing

Tensile and constant amplitude FCP testing. - All testing was performed on closed loop, servohydraulic test machines in laboratory environment at room temperature and relative humidity ranging from 40 to 60 percent.

Standard tensile tests were performed to quantify the tensile properties of the alloys. The constant amplitude crack growth testing was performed per ASTM 647 (ref. 1), with load ratio R of 0.33 and a test frequency of 10 Hz. The R ratio was chosen for comparability with other data bases. Visual crack length measurements were made utilizing a 20 X traveling microscope periodically throughout the test.

Spectrum testing. - Two different F-18 aircraft spectra were selected for this program. Portions of these spectra are shown in figure 1. One is a tension-dominated (TD) spectrum representing the lower wing root load history and the other is a tension-compression (TC) spectrum representing the horizontal tail hinge moment load history. Both spectra were computer generated for the two components of the same aircraft assuming an identical sequence of events (ref. 2). One "pass" of this basic event spectrum consists of a sequence of 250 flights representing 300 flight hr.

The spectrum tests were performed in load control using a sinusoidal waveform. The average linear point-to-point load rate (peak to valley or valley to peak) for tests at each maximum peak gross stress (σ_{max}) was constant. A load point is defined as a relative maximum or minimum in the load/time history.

Spectrum testing was conducted at maximum peak stresses (σ_{max}) of 103, 145, and 169 MPa (15, 21, and 24.5 ksi), selected to give wide range of crack growth rates. All of the relative maximum and minimum load points were raised in proportion to the maximum peak load. Graphic description of terms used in connection with spectrum loading is shown in figure 2. All the spectrum tests were performed by Northrop Aircraft Division.

RESULTS AND DISCUSSION

Tensile Properties

The results of tensile tests for both alloys used in the program are shown in table II. For comparison, typical tensile results for these alloys are also shown. Both alloys have almost equivalent tensile properties with 7050 showing approximately 14 MPa (2 ksi) higher tensile and yield strengths than 7091.

Constant Amplitude FCP

The results of the constant amplitude testing are shown in figure 3. As shown, alloy 7050 exhibited slower FCP rates than 7091 alloy. The reasons for this behavior, in terms of microstructural variables, are discussed in part II.

Spectrum Results

Test results for unmodified spectra. - The crack growth rate results of each alloy subjected to the two spectra are shown in figures 4 and 5. The data is plotted in terms of crack growth rate per simulated flight hr (da/dH) versus maximum peak stress intensity (K_{max}). The results lend themselves to an evaluation of effects of various loading histories on FCP rates for each alloy.

It has been shown repeatedly (refs. 3 to 5) that high tensile overloads, such as those encountered in the TD spectrum (fig. 1(a)), produce crack growth retardation due to high residual compressive forces left at the crack tip following an overload. If the high overloads are followed by high compressive loads, such as those occurring in the TC spectrum (fig. 1(b)), the residual compressive stresses are reduced thus increasing the effective stress intensity and the corresponding FCP rates.

If only these well known phenomena are considered, it would be expected that the TD spectrum would result in substantially slower FCP rates than the TC spectrum. However, as is shown in figures 4 and 5 this is not exactly the case. For a given alloy, the crack growth rates are similar for the two spectra at lower K_{max}. This is especially important since the two load histories are very different and yet result in equivalent FCP rates at these lower stress intensities. However, at higher K_{max}, the rates for the two spectra diverge, with the FCP rates of the TC spectrum being faster than those of the TD spectrum in accordance with the various load interaction models (refs. 6 and 7). An important implication of these results is that the load history, and therefore load interactions, are not a major factor affecting spectrum FCG rates at low stress intensities. However, load history becomes a much more important factor in controlling FCP rates when the stress intensities are increased.

Spectrum simplification - mechanics consideration. - To explain the observed results, the effects of the amount of plasticity at the crack tip on load interactions have to be taken into consideration. As was postulated by Willenborg (ref. 6) and Elber (ref. 7), the residual stresses at the crack tip are the result of "squeezing" of the plastically deformed zone at the crack tip by the elastic bulk of the remaining material. The amount of the residual stress is determined by the plastic zone size, (i.e., large plastic zone creates large residual stresses and vice versa).

It can be postulated that for small stress intensities and thus small plastic zone sizes, the residual stresses are relatively small, the load interactions are not very important and thus the applied load history is not the critical factor controlling spectrum FCP rates. Other factors, such as microstructure are probably more important in controlling FCP at low stress intensities. Thus, in the present study, the spectrum FCP rates were the same for a given alloy at low K_{max} even though the alloy was subjected to two entirely different load histories.

At higher stress intensities, the residual stresses are increased and the load history, as a result of the load interactions, plays a much more important role in controlling FCP rates. Thus, at higher K_{max}, the TD spectrum resulted in longer lives than the TC spectrum for both alloys.

The hypothesis that load history has relatively little effect on FCP rates in the lower stress intensity region, can be used to simplify the highly complex spectra if this is the region of interest. As a practical matter this is often the case since the largest portion of fatigue lives occurs at these stress intensities.

In order to evaluate this hypothesis, two spectrum tests were performed on the 7050 alloy using a modified TC spectrum, for which all the negative loads were removed. According to the hypothesis, the elimination of negative loads should not significantly affect spectrum FCP rates at low K_{max}. However, at higher stress intensities where load interactions become important, the elimination of negative loads should result in slower FCP rates for the truncated spectrum, since the absence of compressive loads will not remove residual stresses created by overloads.

The results, shown in figure 6, support the above hypothesis. At lower K_{max} the fatigue lives of the original and modified spectra are roughly equivalent, however at higher K_{max} the modified spectrum exhibits progressively longer relative lives, so much that at high K_{max} the life of the modified spectra is roughly doubled that of the original spectrum.

It should be pointed out that in addition to the level of the applied stress intensity, the yield strength of the material should also be taken into consideration when simplification of spectra is attempted. Thus, for lower yield strength materials (i.e., larger plastic zone size), the maximum applied loads and K_{max} at which load interactions become important are expected to be lower.

Spectrum simplification - fractographic considerations. - In order to better understand the interaction between the applied spectrum load history and the resulting FCP rates, a striation counting technique was used and the results were compared to the measured propagation rates.

The validity of the striation counting technique was evaluated by correlating the striation spacing (fig. 7) of the constant amplitude specimens, with the measured FCP rates. It was assumed that each cycle should result in a striation. The results, shown in table III, indicate good agreement between the observed and calculated growth rates.

It is difficult to determine how many load cycles are present in a given spectrum since many of the load points are just perturbation in a given load cycle. However, for the purpose of analysis, it was assumed (fig. 2) that two load points constitute a "cycle." Thus if each "cycle" resulted in a striation, a one to one ratio of striations to "cycles" would be expected. The analysis was only performed for the 7050 alloy since the striations of the 7091 alloy were too ill-defined to obtain a reliable count. In order to confirm the SEM analysis, some better resolution TEM replicas shown in figure 8 were made. In general, there was a good agreement between the SEM and TEM analysis.

The results of the analysis for both spectra, are shown in figure 9. The data are plotted as a function of the ratio of expected to counted striations versus the maximum peak stress intensity. As seen in that figure, the behavior for both spectra is similar. At low K_{max} the ratio is high, then it rapidly diminishes with increasing K_{max} till a "plateau" is reached. As anticipated, a one to one ratio was never reached.

It is reasonable to assume that striations are created by the higher peak load "cycles", while the "cycles" which did not produce striations consist of lower peak loads. This is supported by the work of others (ref. 8) who have shown a one-on-one correspondence between striations and cycles applied at intermediate higher stress intensities, meanwhile at lower stress intensities frequently no striations are identifiable (ref. 9). The "cycles" which did not produce striations on the fracture surface were probably either perturbations in a given cycle or near a threshold, in a stress intensity region which does not produce striations. These two types of "cycles" probably do not significantly contribute to crack propagation and can be removed without significantly affecting spectrum FCP rates.

It is important to note (fig. 9) that more and more "cycles" produce striations as K_{max} increases. Thus, more of the intermediate and lower load peaks play an important role in determining FCP rates so that the simplification of a spectrum cannot be performed without considering the applied stress intensity. This striation counting technique can be used to identify the type of load points in the spectrum which significantly influence FCP behavior.

Guidelines for Spectrum Simplification

The two major conclusions obtained from this study, i.e., (1) load history and load interactions are not a major factor affecting FCP rates at lower stress intensities and, (2) lower and intermediate load points become progressively more important in affecting FCP rates as stress intensity increases, were used to propose simplified spectra shown in figure 10.

The original spectra are shown in figures 10(a) and (b). In case of the TC spectrum at lower maximum stress intensities, it was shown that all negative loads can be truncated without changing crack growth rates.

Utilizing these observations, a proposed schematic illustration of a simplified version of the TC spectrum, for application at lower maximum stress intensities, is shown in figure 10. The truncation of the low and intermediate load points results in removal of more than half of the load points present in the spectrum (fig. 10(c)). Since the load history does not appear to significantly influence FCP rates, the same truncated spectrum can be used to replace both the TC and TD spectra.

At higher maximum stress intensities, both the compressive loads and intermediate peak load points contribute to FCP behavior and therefore cannot be removed. However, since the ratio of expected to actual striations did not reach a 1:1 correspondence even at high maximum stress intensities, the lower load peaks resulting in below or near threshold stress intensities can probably be removed from both TC and TD spectra without significantly affecting FCP rates. Figures 10(d) and (e) show a schematic representation of such truncation procedure.

The same type of truncation procedure, based on both mechanical and metallurgical observations, can probably be used to simplify many other complex spectra used in FCP and alloy development research.

CONCLUSIONS

Simplified spectra have been proposed based on the following conclusions:

1. There was virtually no difference in FCP rates of the two spectra for a given alloy at lower maximum stress intensities. These results indicate that at these stress intensities, load interaction effects are not a major factor controlling FCP rates.

2. At higher maximum stress intensities, TD type specimens exhibited slower FCP rates than TC type specimens. Thus at higher maximum stress intensities, load interactions became more important in determining FCP behavior.

3. The above two conclusions were explained in terms of the amount of plasticity and thus residual stresses at the crack tip. Load interactions became more important with higher residual stresses and more plasticity at the crack tip.

4. When spectrum simplification was attempted, the applied stress intensity level had to be considered. For instance, removal of negative loads in the TC spectrum did not significantly affect FCP rates at lower K_{max}. However at high K_{max} levels, removal of compressive loads significantly affected spectrum fatigue behavior.

5. The ratio of expected striations spacing to actual striations spacing (obtained by fractographic analysis) for both spectra was high at low K_{max} and dropped significantly as K_{max} increased until a lower limit was reached.

6. The above result can be used to further truncate the spectra:

(a) At lower K_{max}, only high stress peaks control spectrum behavior, thus low and intermediate stress peaks can be eliminated.

(b) At higher K_{max}, load interactions are more important and therefore only the very low stress peaks can be supressed.

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TABLE I. - CHEMICAL COMPOSITION AND HEAT TREATMENT

Chemical Composition								
Material	Limits	Zn	Mg	Cu	Co	Zr	Fe	Si
7050	Measured	6 27	2.3	2.3	---	0.12	0 13	0 07
	Minimum	5 7	1.9	2.0	---	0.08	----	----
	Maximum	6.7	2 6	2.6	---	0.15	0.15	0.12
	Nominal	6.2	2.3	2 3	---	0 1	----	----
7091	Measured	6.53	2.4	1.5	0.4	----	0.05	0.03
	Nominal	6.5	2.5	1.5	0.4	----	----	----

Heat Treatment		
	7050	7091
Solution treatment	2 hr at 488 °C (910 °F) Cold water quench	2 hr at 488 °C (910 °F) Cold water quench
Stretch	1 to 1.5 ϵ_p	1 to 1.5 ϵ_p
Artificial age	24 hr at 121 °C (250 °F) 40 hr at 163 °C (325 °F)	24 hr at 121 °C (250 °F) 14 hr at 163 °C (325 °F)

TABLE II - TENSILE RESULTS - LONGITUDINAL

Alloy		Ultimate strength,		Yield strength,		Elongation ϵ_f(pct)
		MPa	ksi	MPa	ksi	
7050-T73651	Measured	534	77	478	69	15
	Typical	510	74	455	66	11
7091-T7E70	Measured	520	75	464	67	14.5
	Typical	535	78	483	70	11

TABLE III - COMPARISON OF CALCULATED TO ACTUAL STRIATIONS-CONSTANT AMPLITUDE

Alloy	Crack length, mm	Number of expected striations[a] (striations/μm)	Actual striations (striations/μm)
7050-T73651	15.5	5.8	4
			4.5
			5
	16.5	3.6	3.75
			3.5
			3.5
			3.5
	18.5	3.0	3.5
			3.0
			3.25
			3.0
			3.0

[a]Based upon visual crack length measurements and assuming a presence of one striation per each cycle.

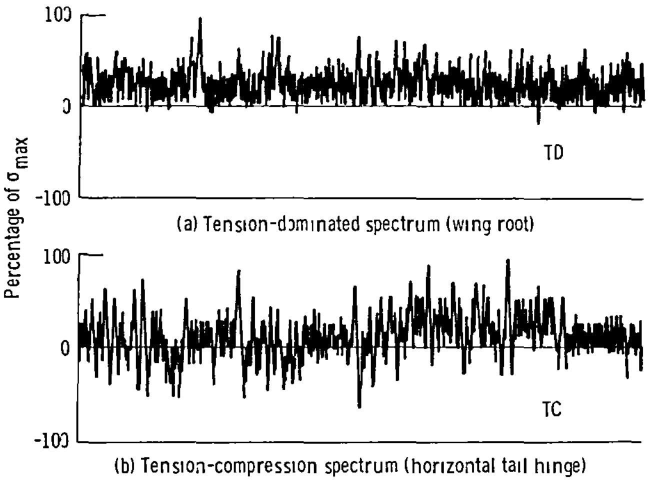


Figure 1 - Representative portions of the spectra used in crack growth testing

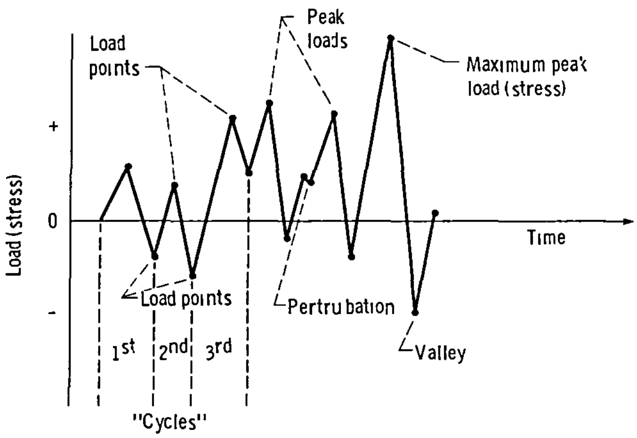


Figure 2 - Definition of terms

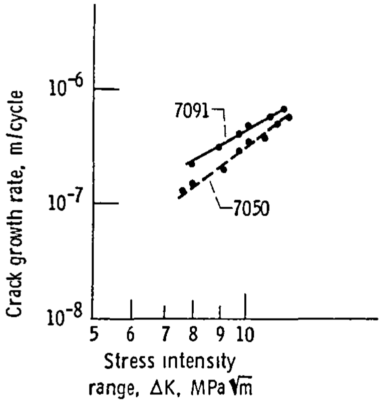


Figure 3 - Results of the constant amplitude testing

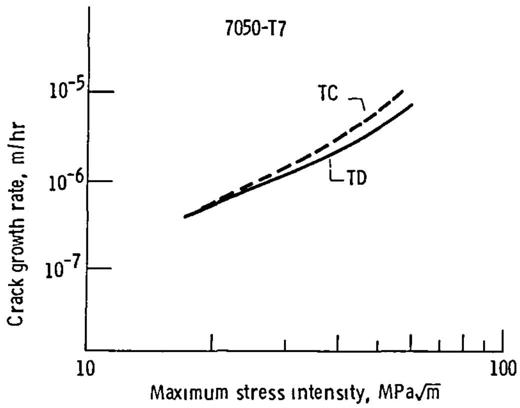


Figure 4 - Spectrum FCG results of the 7050-T7 aluminum alloy

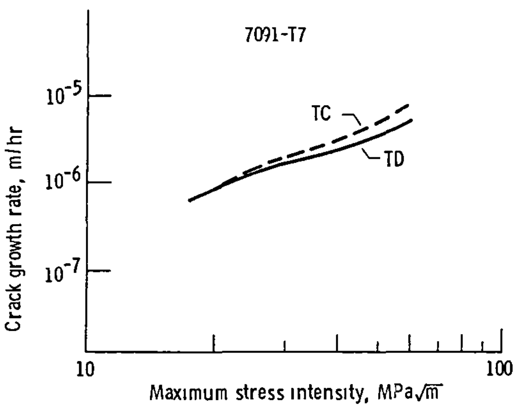


Figure 5 - Spectrum FCG results of the 7091-T7 aluminum alloy

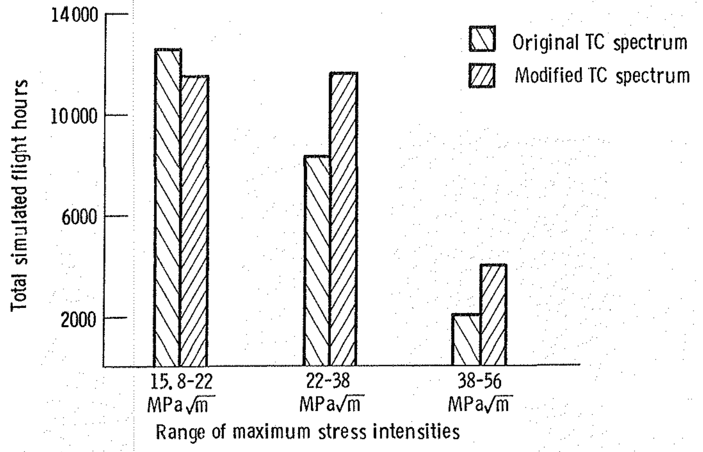


Figure 6. - Fatigue lives in flight hours for various stress intensity ranges for the original and modified TC spectrum.

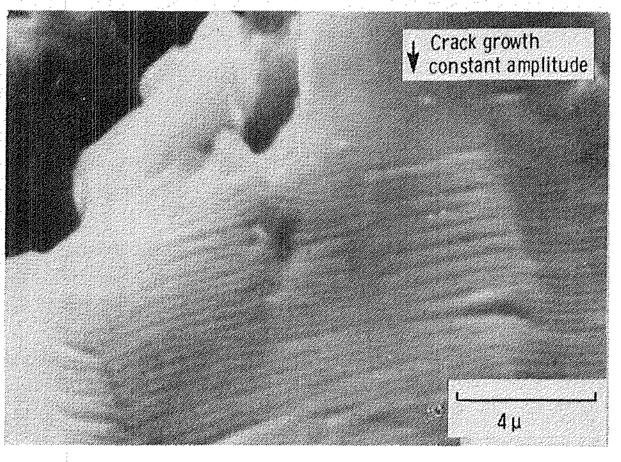
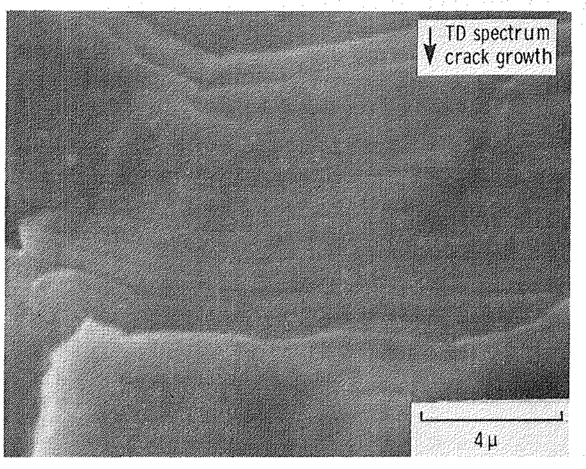
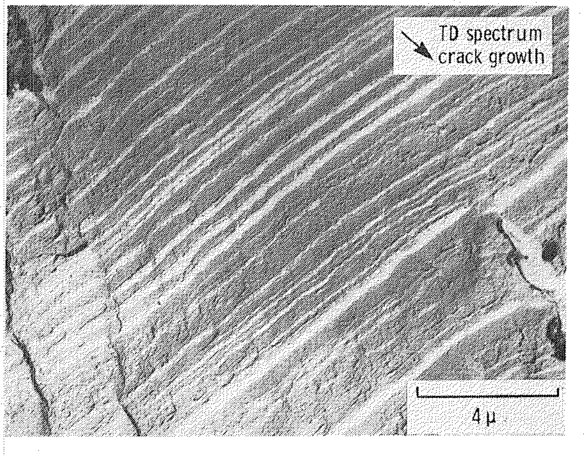


Figure 7. - 7050-T7 alloy. An example of a fractograph used to correlate striation spacing to measured crack growth rates.



(a) SEM.



(b) TEM replica.

Figure 8. - 7050-T7. Comparison of striation spacing by SEM and TEM replica, (different areas).

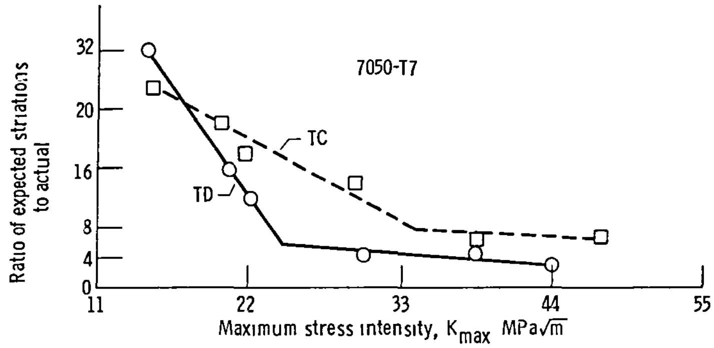


Figure 9 - Relationship between expected and actual striations versus maximum stress intensity

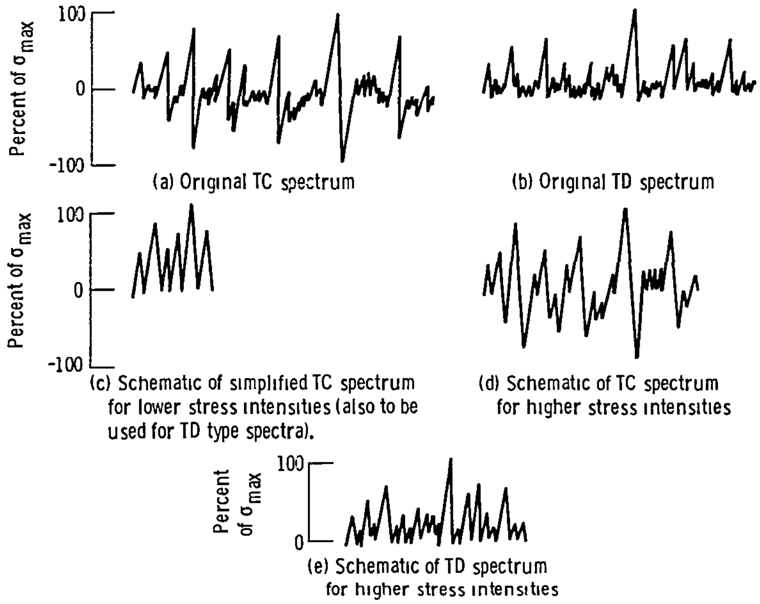


Figure 10 - Proposed schematics to simplify original complex spectra

1 Report No	2 Government Accession No	3 Recipient's Catalog No
NASA TM-86929		

4 Title and Subtitle	5 Report Date
A Study of Spectrum Fatigue Crack Propagation in Two Aluminum Alloys I - Spectrum Simplification	January 1985
	6 Performing Organization Code 505-33-7C
7 Author(s) Jack Telesman and Stephen D. Antolovich	8 Performing Organization Report No E-2348
	10 Work Unit No
9 Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11 Contract or Grant No
	13 Type of Report and Period Covered Technical Memorandum
12 Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14 Sponsoring Agency Code

15 Supplementary Notes

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16 Abstract

A study of the fatigue crack propagation behavior of two commercial Al alloys was undertaken using spectrum loading conditions characteristic of those encountered at critical locations in high performance fighter aircraft. A tension dominated (TD) and tension compression (TC) spectrum were employed for each alloy. Using a mechanics-based data analysis, it was suggested that negative loads could be eliminated for the TC spectrum for low to intermediate maximum stress intensities. The suggestion was verified by subsequent testing. Using fractographic evidence, it was suggested that a further simplification in the spectra could be accomplished by eliminating low and intermediate peak load points resulting in near or below threshold maximum peak stress intensity values. It was concluded that load interactions become more important at higher stress intensities and more plasticity at the crack tip. These results suggest that a combined mechanics/fractographic mechanisms approach can be used to simplify other complex spectra.

17 Key Words (Suggested by Author(s))	18 Distribution Statement
Spectrum loading Fatigue crack propagation Aluminum Powder metallurgy	Unclassified - unlimited STAR Category 26

19 Security Classif (of this report)	20 Security Classif (of this page)	21 No of pages	22 Price*
Unclassified	Unclassified		

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