SPECTRUM FATIGUE CRACK GROWTH BEHAVIOR OF ALUMINUM ALLOYS

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ABSTRACT

Constant amplitude and spectrum fatigue crack growth testing was performed on ten commercial 2000 and 7000 series aluminum alloy plate materials. The materials were selected to determine the effects of various alloying approaches including purity (fracture toughness) and temper (yield strength). Two different fighter aircraft spectra were used for testing; one represented the loading on a lower wing root and had predominately tension loads, and the other represented a horizontal tail hinge and had high magnitude compression loads. Spectrum fatigue crack growth life did not correlate with yield strength and only correlated weakly with fracture toughness. In addition, tests were performed with a modification of one of the spectra to determine the effects of compressive loads. These tests showed that compressive loads in this complex, random spectrum significantly reduced the life. Nevertheless, the ranking of the materials was essentially the same for all three spectra.

KEYWORDS

Fatigue crack growth; spectrum fatigue; spectrum loading; aluminum alloys; aircraft; fracture toughness; yield strength.

INTRODUCTION

Fatigue crack growth (FCG) behavior under variable amplitude loading is increasingly being used in the selection of structural materials for aircraft. This is supplanting the selection of materials based on constant-amplitude FCG resistance because the life of an aircraft structure cannot be predicted reliably using constant-amplitude FCG data and existing life prediction techniques. Research in the last decade (Alzos and co-workers, 1976; Bucci, 1977; Bucci and co-workers, 1980; Chanani, 1976; Schijve, 1973, 1976) has shown that load sequences have a considerable effect on FCG behavior. In particular, the application of overloads or a few cycles at high tensile loads may cause retardation; that is, a temporary decrease in FCG rate during subsequent lower-amplitude cycles. Most of the work in the last decade was focused on understanding the effects of single overloads on FCG rates

(Alzos and co-workers, 1976; Bucci, 1977; Bucci and co-workers, 1980; Chanani, 1976; Schijve, 1973). Recently, more emphasis is being placed upon the evaluation of FCG under complex spectrum loading simulating the loading experienced by aircraft structures (Abelkis, 1980; Dill and co-workers, 1980; Schijve, 1976).

The nature of a spectrum can vary widely depending on a particular component and type of aircraft. FCG resistance for a given material can also vary widely depending on the specific details of load spectra. The cause of differences in FCG resistance for the same material in different load spectra is unknown due to the complexities of load spectra and the fact that interactions between alloy microstructure and variable amplitude load histories are not well understood.

Research on high strength aluminum alloys has shown that microstructure affects FCG behavior under constant amplitude loading (Bretz and co-workers, 1981; Bucci, 1977; Bucci and co-workers, 1980; Chanani, 1976; Sanders and Staley, 1979). Metallurgical factors found to influence FCG behavior are alloy purity, dispersoid type, degree of aging (temper), and alloy content. However, the influence of these microstructural features on FCG is not the same at intermediate and high growth rates (10^{-8}m/cycle). For example, overaging (T7) from a peak age (T6) temper reduced FCG rates by a factor of two at intermediate stress intensities (ΔK) but increased crack growth rates by up to a factor of ten at low ΔK. These studies have demonstrated that different microstructural features can influence constant-amplitude FCG behavior at different ΔK values. The same level of understanding regarding microstructural effects on FCG under variable amplitude loading does not exist.

The effects of tension overloads superimposed on constant-amplitude loading has been extensively evaluated (Alzos and co-workers, 1976; Bucci, 1977; Bucci and co-workers, 1980; Chanani, 1976; Schijve, 1973), and it has been well established that the overloads retard fatigue crack growth. Retardation has also been observed in spectrum loading, usually by comparing the spectrum fatigue behavior of a material tested under a spectrum with the behavior under that same spectrum with the highest loads truncated (Schijve, 1976). Some work has been done on the effects of compression loads following overloads in constant-amplitude loading. The effect of the underload is to reduce the retardation, although the resultant constant-amplitude fatigue crack growth rates are still lower than without the overload/underload combination (Marissen and co-workers, 1982; McMillan and Hertzberg, 1968; Mills and Hertzberg, 1976).

The effects of underload/overload sequencing vary for spectrum fatigue. Hsu and McGee (1980) added compression underloads to two spectra which were otherwise all tension. These underloads were added before or after high tension loads. Tests were performed under essentially constant maximum peak stress intensity (defined by K_{hmax} in the present paper) conditions by load shedding, and spectrum crack growth rates were measured. For one of the spectra, results were obtained at two different levels of K_{hmax}. For this spectrum at the higher level of K_{hmax}, the result was the same as would be expected from overloads and underloads superimposed on constant-amplitude loading (Marissen and co-workers, 1982; McMillan and Hertzberg, 1968; Mills and Hertzberg, 1976); that is, a slower spectrum fatigue-crack growth rate for the underload/overload sequence than that for the overload/underload sequence. However, for both spectra at the lower value of K_{hmax}, the opposite was found. Schijve (1973) reported on spectrum tests with (high-amplitude) gust load cycles applied in an otherwise random spectrum in either a negative/positive (underload/overload) sequence or a positive/negative (overload/underload) sequence. He found that spectrum life for the negative/positive sequence of gust loads was 85 percent of that for the positive/negative sequence, which corresponds to a slower spectrum fatigue-crack growth rate for the overload/underload sequence, again opposite to the results for similar evaluations with a constant-amplitude loading baseline (Marissen and co-workers, 1982; McMillan and Hertzberg, 1968; Mills and Hertzberg, 1976). These latter results show that applying results from constant-amplitude fatigue to spectrum fatigue can be misleading.

To better understand the microstructure/FCG relationships, a group of commercial 2000 and 7000 series aluminum alloys was tested under constant amplitude and spectrum loading. This paper describes the results of a comparative analysis and ranking of the alloys tested under constant-amplitude and variable-amplitude loads. Details of the microstructural/fractographic and FCP resistance correlations established are addressed in a companion paper (Scarich and co-workers, 1984).

EXPERIMENTAL PROCEDURE

Commercially produced 2000 and 7000 series aluminum alloy plates in various tempers and ranging in thickness from 19 to 38 mm (0.75 to 1.5 in.) were utilized in the program. The acceptability of each alloy was verified by chemical analysis, tensile tests, and fracture toughness tests. The tensile tests were conducted in accordance with ASTM Standard Method B557 in the longitudinal (L) orientation at the T/4 and 3T/4 locations. The fracture toughness tests were conducted in accordance with ASTM Standard Method E399 using full plate thickness C(T), longitudinally oriented (L-T) specimens. Constant-amplitude fatigue-crack growth tests were conducted over low, intermediate, and high stress intensity ranges on modified C(T) (L-T) specimens (B = 6.35 mm (0.25 in.), W = 64.8 mm (2.55 in.), and H/W = 0.486). All testing was performed on closed loop, servo-hydraulic test machines at a load ratio ($R = P_{min}/P_{max}$) equal to 0.33 and at a test frequency of 25 Hz. Test environment was room temperature laboratory air moistened to a relative humidity of 90 percent. The test procedures adhered to ASTM Standard Test Method E647 for "Constant-Load-Amplitude Fatigue Crack Growth Rates Above 10^{-8} m/Cycle," and to the proposed ASTM standard test practice for measurement of near-threshold growth rates, $da/dN < 10^{-8}$ m/cycle (Bucci, 1981).

For spectrum testing, two different advanced fighter aircraft spectra were used, a tension-dominated (TD) spectrum representing a lower wing root load history and a tension-compression (TC) spectrum representing a horizontal tail hinge moment load history. Representative portions of the stress histories of the two spectra are shown in Fig. 1, and exceedance curves describing the distribution of stress magnitudes in the two spectra are shown in Fig. 2. Both spectra were computer-generated for the two components of the same aircraft, assuming an identical sequence of events. Using these two spectra, the ten materials were evaluated for their spectrum fatigue crack growth behavior. In addition, the TC spectrum was modified to reveal the effects of compression load cycles. This modification consisted of truncating all loads below zero; that is, setting all loads less than zero equal to zero. Seven of the materials were evaluated using the modified spectrum (designated TCZ).

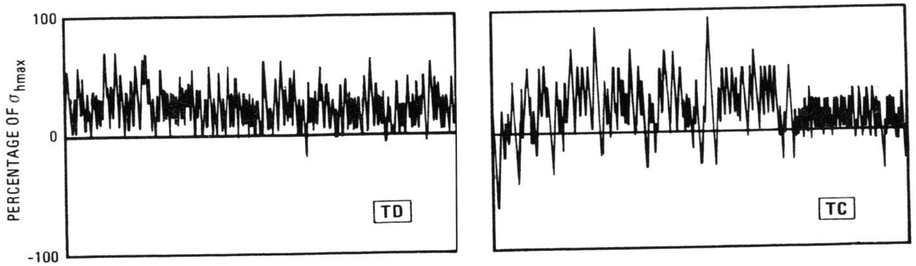

Fig. 1. Representative portions of stress history of the TD and TC spectra.

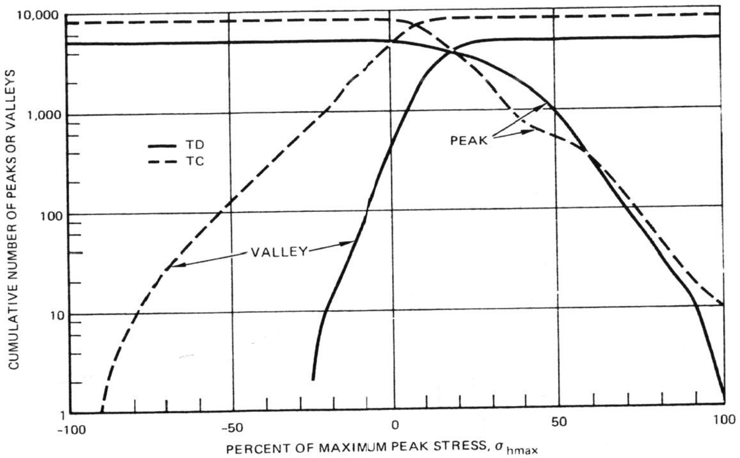

Fig. 2. Exceedance curves

For each of the three spectra, one "pass" of the basic spectrum consisted of a sequence of 250 flights representing 300 flight hours. One pass of the tension-dominated (TD) spectrum had 4,705 load peaks (and an equal number of valleys), the tension-compression (TC) spectrum had 7,852 load peaks and the modified spectrum (TCZ) had 7,713 load peaks. Since the service (design) life of the aircraft is 6,000 hours, one service life was simulated by completion of a total of 20 passes of the above sequence. The aircraft was designed to last four lifetimes, i.e., 24,000 flight hours.

The terminology used in this paper is standard except for K_{hmax} and σ_{hmax} which are the stress intensity factor and stress, respectively, at the highest (largest) peak of the entire spectrum. Spectrum life for purposes of this report is the number of (simulated flight) hours from a (half) crack length of 6 mm (0.24 in.) to fracture of the specimen. The spectrum fatigue specimen was 6.3 mm (0.25 in.) thick, 99 mm (3.9 in.) wide, and 400 mm (15.8 in.) long. All spectrum tests were performed on a computer-controlled servohydraulic machine following the methods of ASTM E647, as appropriate.

Precracking was performed under constant-amplitude fatigue loading at a stress ratio (R) of 0.1. The gross maximum peak stress (σ_{hmax}) was 145 MPa (21 ksi) for all tests. The waveform was sinusoidal. The linear (theoretical) point-to-point load rate (peak to valley or valley to peak) was 220 kN/s (49,000 lb/s) or 20 Hz, whichever was slower. Duplicate tests were performed.

RESULTS AND DISCUSSION

The tensile and fracture toughness results are summarized in Fig. 3, which graphically shows the relationship between fracture toughness and yield strength for the ten materials evaluated. All fracture toughness test results were valid per ASTM E399, except the results for the 2024-T351 and 7475-T651 alloys.

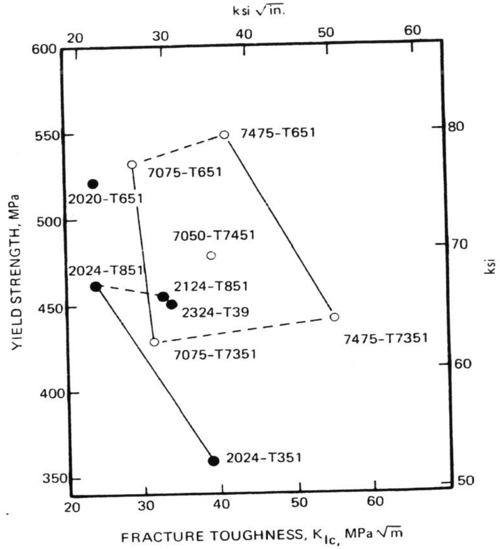

Fig. 3. Yield strength (L) and fracture toughness (L-T)

The constant amplitude fatigue crack growth results are shown in Fig. 4 as da/dN vs. ΔK curves. In addition, the FCGR data are shown in Fig. 5 as the stress intensity required to drive a fatigue crack at a specified rate. In Fig. 5 the results are in descending order of their spectrum fatigue lives within the 2000 and the 7000 series. The data in Fig. 4 show that the variation in FCG resistance among the ten alloys was greatest in the near-threshold regime ($\Delta K < 4$ MPa $\sqrt{m}$), while for higher ΔK levels, crack growth rates varied by no more than a factor of 5. In addition, as can be seen in Fig. 4, the relative rankings in FCG resistance change with ΔK level for both 2000 and 7000 series alloys.

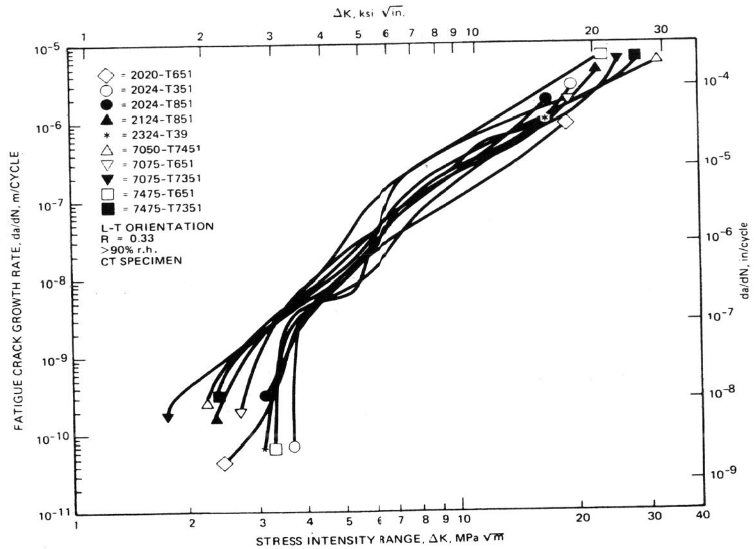

Fig. 4. Constant-amplitude fatigue-crack growth curves

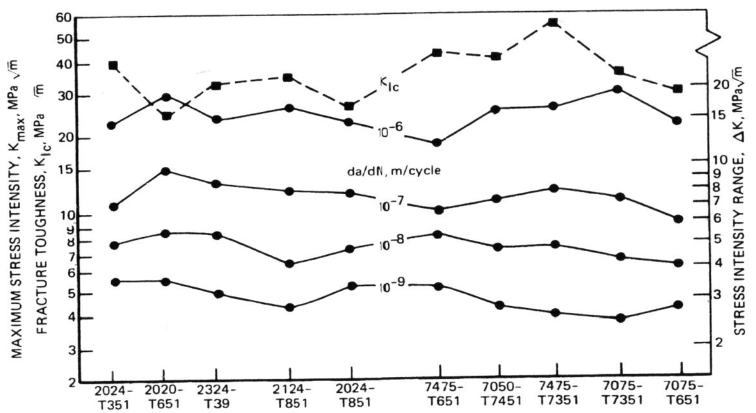

Fig. 5. Stress intensity needed to obtain a given fatigue crack growth rate under constant amplitude loading (R = 0.33, > 90% rh, L-T orientation)

The spectrum fatigue life results for the TD and TC spectra are summarized in Fig. 6. Each bar in the figure is the log mean spectrum fatigue life of two tests. The results were reproducible, with a maximum difference between the lives of the duplicate tests being 21 percent. For comparison, spectrum crack growth rate curves (da/dH vs. K_{hmax}) are shown in Fig. 7 for the TD spectrum. The rates and trends are similar for the TC spectrum. For easier comparison of resistance to spectrum crack growth among all ten materials for both spectra, the maximum peak stress intensities to obtain a given crack growth rate are shown in Fig. 8.

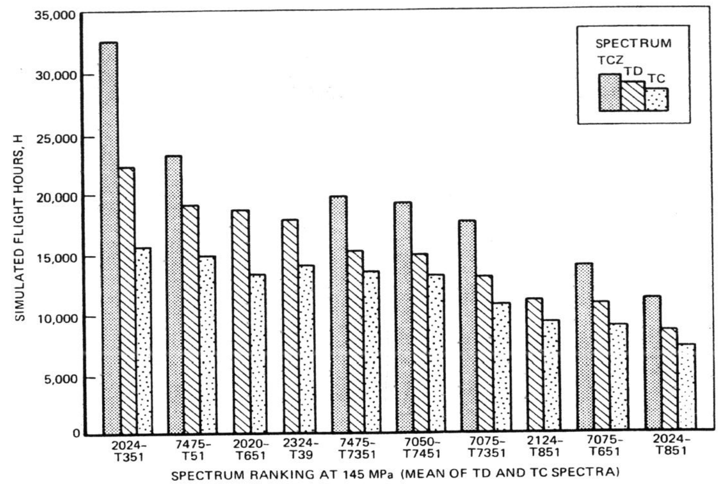

Fig. 6. Spectrum fatigue lives for TCZ, TC, and TD spectra

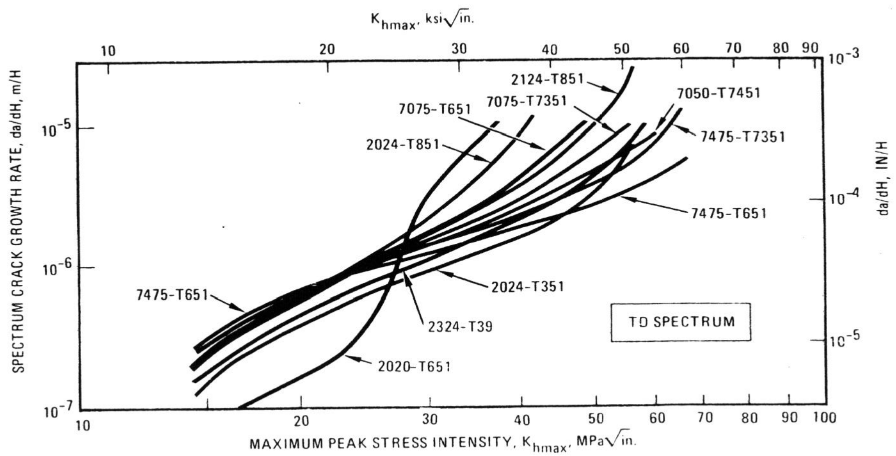

Fig. 7. Spectrum FCGR curves for TD spectrum

A comparison of the results for the TD and TC spectra (Table 1) shows that:

1. The ranking of the ten alloys was the same in the two spectra, except for 2020-T651 for which the ranking under the TC spectrum was lower than for the TD spectrum.

2. For each material the TD spectrum consistently resulted in longer life; and

3. The differences in life for the same material between the two spectra were small — not more than an 18 percent difference for any of the alloys except 2020-T651 and 2024-T351, which had 34 and 36 percent differences, respectively.

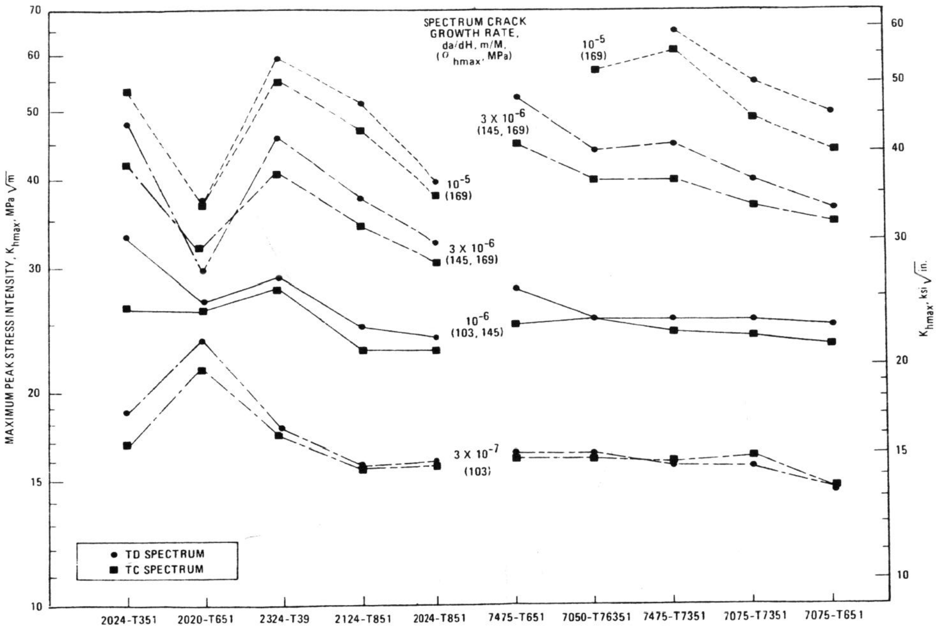

Fig. 8. Maximum peak stress intensity needed to obtain a given spectrum FCGR for TD and TC spectra

TABLE 1. Ranking of Alloys for TD and TC Spectra

MAXIMUM PEAK STRESS, σ_{hmax} = 145 MPa (21 ksi)

CRACK GROWTH FROM 6mm (0.24 in.) TO FAILURE

TD SPECTRUM		TC SPECTRUM	
MATERIAL	SIMULATED FLIGHT HOURS	MATERIAL	SIMULATED FLIGHT HOURS
2024-T351	22,100	2024-T351	15,400
7475-T651	19,000	7475-T651	14,900
2020-T651	18,500	2324-T39	14,400
2324-T39	17,800	7475-T7351	13,400
7475-T7351	15,000	7050-T73651	13,200
7050-T73651	14,900	2020-T651	13,100
7075-T7351	12,900	7075-T7351	10,700
2124-T851	11,200	2124-T851	9,100
7075-T651	10,800	7075-T651	8,900
2024-T851	8,500	2024-T851	7,100

The effects of compression loads on spectrum fatigue life can be seen by comparing the results for the TCZ spectrum to those for the TC spectrum (Fig. 6). This modification resulted in life increases of 46 to 112 percent for the seven alloys (Table 2). Except for the 112 percent increase for 2024-T351, the increases were similar — from 46 to 65 percent. Comparing the results to those for the TD and TC spectra (Fig. 6) shows that the rankings of the alloys are the same as under the two baseline spectra, although the spectrum lives for the TCZ spectrum were longer than those for both the TC and TD spectra. (Note that the TD spectrum had moderate compressive loads — all were less than 35 percent of σ_{hmax}). These results confirm the damaging effects of compressive loads, even for a very complex, random spectrum.

TABLE 2 Ratios of Spectrum Fatigue Lives

MAXIMUM PEAK STRESS, σ_{hmax} = 145 MPa (21 ksi)

CRACK GROWTH FROM 6mm (0.24 in.) TO FAILURE

MATERIAL	RATIO OF SPECTRUM LIVES TD/TC	RATIO OF SPECTRUM LIVES TCZ/TC
2020-T651	1.42	–
2024-T351	1.44	2.12
2024-T851	1.20	1.57
2124-T851	1.23	–
2324-T39	1.24	–
7050-T7451	1.13	1.46
7075-T651	1.22	1.57
7075-T7351	1.21	1.65
7475-T651	1.27	1.54
7475-T7351	1.12	1.47

The spectrum fatigue lives are plotted as a function of yield strength in Fig. 9. These data suggest that there is no general relationship between yield strength and spectrum fatigue life, nor can any relationship be seen by considering the 2000 and 7000 series alloys as two separate groups. This absence of a correlation is in contrast to current life prediction models, such as that developed by Willenborg and co-workers (1971), which assume that decreasing yield strength increases crack growth retardation and lengthens spectrum fatigue life.

The relationship between fracture toughness and spectrum fatigue life is shown in Fig. 10. By itself, increased fracture toughness is expected to lengthen fatigue life by delaying final fracture to a greater crack length. The data in Fig. 10 generally reflect increased fatigue life with higher toughness. Notable exceptions are 2020-T651 and 7475-T7351. Even though 7475-T7351 has the highest fracture toughness of all the materials in this program, it had a spectrum life shorter than four of the nine other materials for the TD spectrum and three of the nine other materials for the TC spectrum. In addition, 7475-T7351, with its superior fracture toughness (K_{Ic} = 55 MPa $\sqrt{m}$), does not have a longer life than 7475-T651 (K_{Ic}= 41 MPa $\sqrt{m}$).

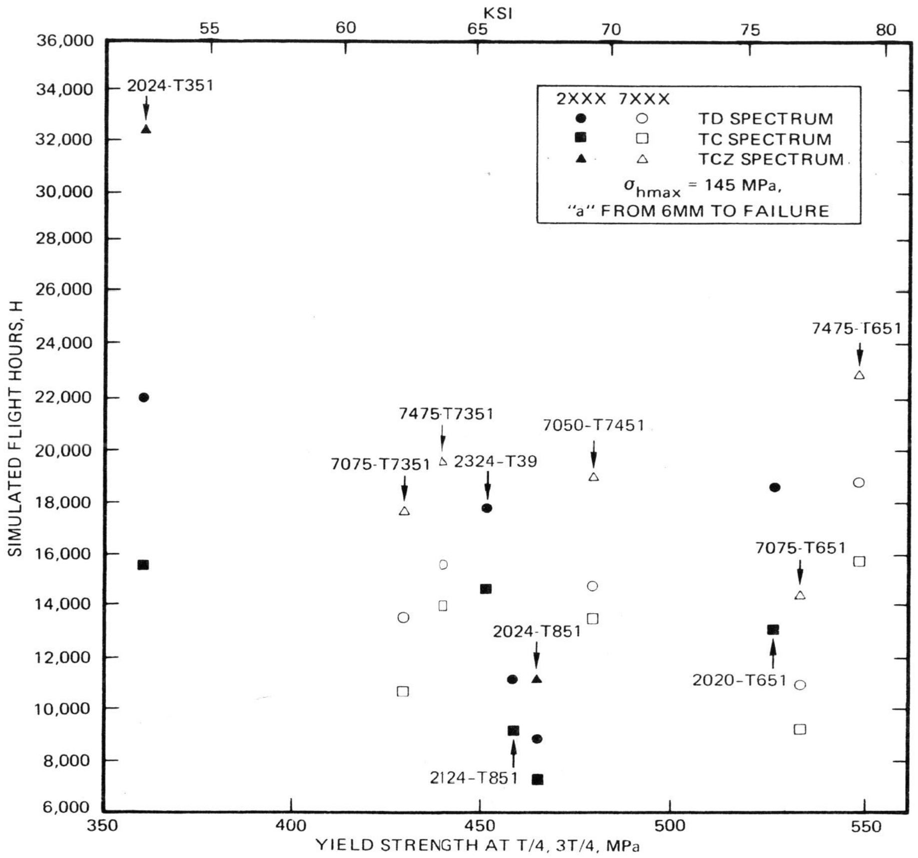

Fig. 9. Spectrum life versus yield strength

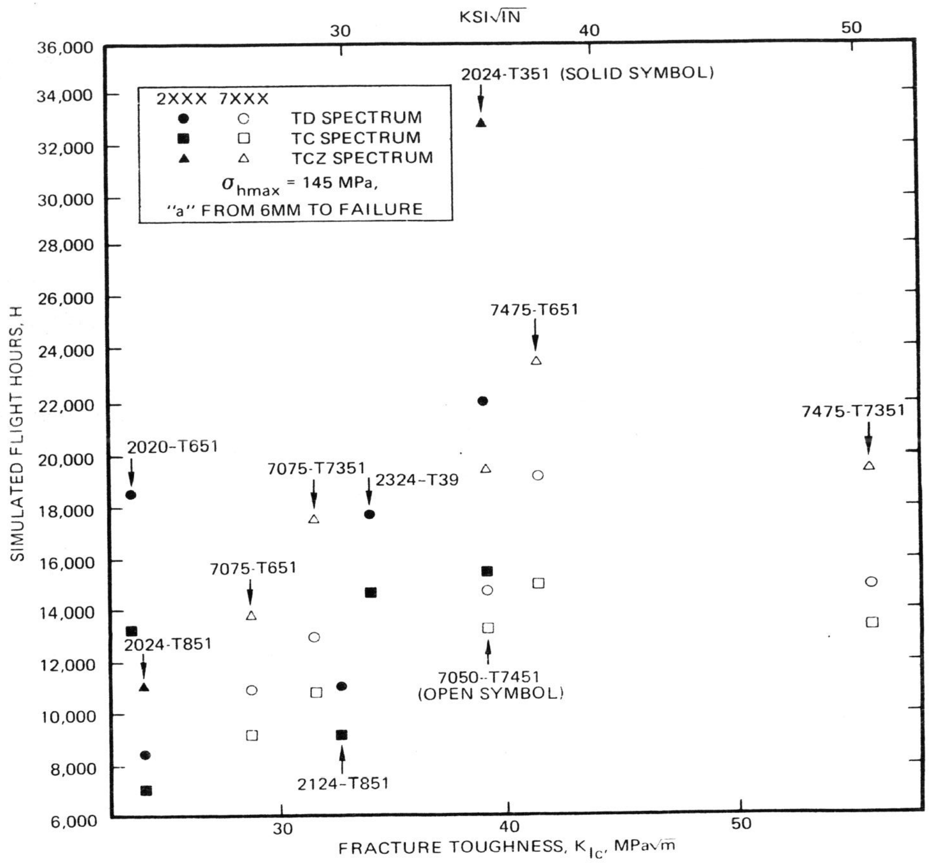

Fig. 10. Spectrum life versus fracture toughness

SUMMARY

Ten commercial 2000 and 7000 series aluminum alloys (2020-T651, 2024-T351, 2024-T851, 2124-T851, 2324-T39, 7050-T7451, 7075-T651, 7075-T7351, 7475-T651 and, 7475-T7351) were evaluated. All ten alloys were characterized with respect to tensile properties and fracture toughness. FCG tests were conducted on specimens of each alloy for both constant-amplitude loading (including the low ΔK region) and two fighter aircraft load spectra and a modification of one of the spectra. The ranking of the materials was essentially the same for the three spectra. This evaluation of the spectrum fatigue crack growth behavior of commercial aerospace alloys shows that this behavior does not correlate with yield strength and correlates weakly with fracture toughness, which is inconsistent with current approaches to developing life prediction models. This suggests that it is necessary to continue to evaluate materials for their spectrum fatigue crack growth behavior until the correlation between metallurgical factors and spectrum behavior (see Scarich and co-workers, 1984) is well understood.

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