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 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 (Alizos 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...
(Alzoni and co-workers, 1976; Bucci, 1977; Bucci and co-workers, 1980; Chanani, 1976; Schijve, 1973). Recently, more emphasis is being placed upon the effects of crack growth and stress corrosion damage on the complex fracture behavior of a variety of high-strength alloys and steels 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 the type of aircraft. FCG resistance for a given material can also vary widely depending on the specific details of load spectra. The cause of difference in FCG resistance for 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 (Brett and co-workers, 1981; Bucci, 1977; Bucci and co-workers, 1980; Chanani, 1976; Sanders and Stailey, 1979). Metallurgical factors found to influence FCG behavior are alloy purity, dispersion 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^-6 m/cycle). For example, overaging (T7) results in a peak in (T6) temper reduced FCG rates by a factor of two at intermediate stress intensities (AK), but increased crack growth rates by a factor of ten at low AK values. These studies have demonstrated that different microstructural features can influence constant-amplitude FCG behavior at different AK values. The level of understanding regarding microstructural effects of FCG under variable amplitude loading does not exist.

The effects of tension overloads superimposed on constant-amplitude loading have been extensively evaluated (Alzoni 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. Some work 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 load amplitude 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 the overload/underload combination (Marris 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_{max} 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_{max}. For this spectrum at the higher level of K_{max}, the result was the same as would be expected from overloads and underloads superimposed on constant-amplitude loading (Marris 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 level of K_{max}, the opposed rate was found. Schijve (1973) reported on spectrum tests with high-amplitude cyclic loading used 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 positive/negative sequence of gust loads was 85 percent of that for the negative/positive 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 (Marrisen 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 microstructural/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 FCG 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. A selected tensile test was conducted in accordance with ASTM Standard Method E857 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 half-pipe tensile (T) or longitudinally oriented (L) specimens. Constant-amplitude fatigue-crack growth tests were conducted over low, intermediate, and high stress intensity ranges on modified T (L-T) specimens (B = 6.35 mm (0.25 in.), W = 64.6 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 loads. This modified spectrum 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 TC2).
Precracking was performed under constant-amplitude fatigue loading at a stress ratio \( R \) of 0.1. The gross maximum peak stress \( \sigma_{\text{hmax}} \) 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)](image)

The constant amplitude fatigue crack growth results are shown in Fig. 4 as \( da/dN \) vs. \( \Delta K \) 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 \( (\Delta K < 0.2 \text{ MPa}\cdot\text{m}/\sqrt{\text{m}}) \), while for higher \( \Delta K \) 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 \( \Delta K \) level for both 2000 and 7000 series alloys.

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 \( K_{\text{hmax}} \) and \( \sigma_{\text{hmax}} \) 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, 90 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.
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/dN vs. K_{max}) 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.
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 – no more than 18 percent difference for any of the alloys except 2020-T651 and 2024-T351, which had 34 and 36 percent differences, respectively.

![Graph showing spectrum growth rates](image)

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

<table>
<thead>
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<th>MATERIAL</th>
<th>TO SPECTRUM</th>
<th>TC SPECTRUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2024-T351</td>
<td>22,190</td>
<td>2024-T351</td>
</tr>
<tr>
<td>7075-T651</td>
<td>19,000</td>
<td>7075-T651</td>
</tr>
<tr>
<td>2020-T651</td>
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<td>2024-T351</td>
</tr>
<tr>
<td>2324-T39</td>
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<td>7075-T651</td>
</tr>
<tr>
<td>7070-T7351</td>
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<td>7075-T7351</td>
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</tr>
<tr>
<td>2024-T851</td>
<td>8,500</td>
<td>2024-T851</td>
</tr>
</tbody>
</table>

**TABLE 1.** Ranking of Alloys for TD and TC Spectra

MAXIMUM PEAK STRESS, $\sigma_{\max} = 145$ MPa (21 ksi) CRACK GROWTH FROM 6mm (0.24 in.) TO FAILURE

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 $\sigma_{\max}$.) These results confirm the damaging effects of compressive loads, even for a very complex, random spectrum.

**TABLE 2.** Ratios of Spectrum Fatigue Lives

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>TO SPECTRUM</th>
<th>TC SPECTRUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020-T651</td>
<td>1.42</td>
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</tr>
<tr>
<td>2024-T351</td>
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<tr>
<td>2024-T851</td>
<td>1.20</td>
<td>1.57</td>
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<td>2124-T851</td>
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<td>1.13</td>
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<tr>
<td>7075-T651</td>
<td>1.22</td>
<td>1.22</td>
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<tr>
<td>7075-T7351</td>
<td>1.21</td>
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<td>7475-T651</td>
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<tr>
<td>7475-T7351</td>
<td>1.12</td>
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</tr>
</tbody>
</table>

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 Willemborg 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

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. FC5 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 the 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.
ACKNOWLEDGEMENTS

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REFERENCES


