CORRELATION OF FATIGUE BEHAVIOR WITH MICROSTRUCTURE OF 2XXX AND 7XXX ALUMINUM ALLOYS

G. V. Scarich*, M. J. Gambone*, G. R. Chanani* and P. E. Bretz**

**Northrop Corporation, Aircraft Division, Hawthorne, CA 90250, USA*
***Aluminum Company of America, Alcoa Center, PA 15069, USA*

ABSTRACT

The microstructures and fracture surfaces of a series of 2XXX and 7XXX aluminum alloys were characterized, and correlations with fatigue properties were examined. Some correlations were observed for the 7XXX alloys under constant amplitude and spectral loading, but the 2XXX alloys failed to show the same correlations. It was determined that the presence of large constituents in the microstructure caused an increase in FCG rates, when subjected to both constant amplitude and spectrum loads at high stress intensities. Alloys with Al_3Zr dispersoids are reported to exhibit better FCG resistance than alloys with $Al_{12}Mg_2Cr$ dispersoids under both constant amplitude and spectrum loads; however no relationship between dispersoid and fatigue resistance was observed in this work. The overall fatigue life was affected by the type and size of metastable precipitates present in an alloy. These precipitates are believed to control dislocation movement under strain. The alloy microstructures were observed to have no direct effect on FCG at intermediate stress intensities under constant or variable amplitude loading.

KEYWORDS

Fatigue; microstructure; aluminum alloy; fracture toughness.

INTRODUCTION

The fatigue crack growth (FCG) behavior of an alloy is typically described by its response to constant amplitude cyclic loading. Until recently, it had been assumed that fatigue life under constant amplitude loading adequately described actual loading conditions. However, loads encountered in service are not steady state, but of variable amplitude or spectral in nature. As a result, spectrum fatigue testing is being increasingly used for the selection of materials.

The work of Bucci et al. (1977, 1980), Sanders and Staley (1979) and Starke and Lutjering (1979) has shown that in aluminum precipitation hardening alloys, fatigue life is affected by microstructure. These investigators have shown that the effect of microstructure on FCG behavior changes as the stress intensity varies from near-threshold to high levels. For example, overaging from a T6 temper to a T7 temper can reduce FCG rates by a factor of two at intermediate stress intensities, but can increase FCG rates by a factor of ten at low stress intensities. Therefore, in addition to the nature of applied loads, microstructure is seen to play an important part in alloy FCG behavior.

The objective of this investigation was to characterize the microstructures and fractures of four 2XXX alloys including the Al-Li alloy 2020, and five 7XXX aluminum alloys tested under constant amplitude and spectrum loads. Correlations between microstructure, fractography, and fatigue properties were evaluated in an effort to better understand the role of microstructure in FCG behavior.

TEST MATERIALS AND EXPERIMENTAL METHODS

Commercially produced alloy plates were used in this investigation. The various alloys and tempers evaluated are shown below in Table 1.

TABLE 1

Alloy	Temper
2020	T651
2024	T351, T851
2124	T851
7075	T651, T7351
7475	T651, T7351
7050	T7451

Specimens for optical metallography were taken from the T/4 location in each alloy plate. Standard metallographic techniques were used in preparing all specimens, and etching was done with either Kellers or Graff-Sargent reagents. Limited TEM examination was conducted using thin foils prepared by standard transmission electron microscopy techniques. Specimens for fractographic analysis were ultrasonically cleaned in an acetone bath, rinsed in alcohol, and gold coated. Fractographs of each specimen were obtained at crack lengths of 6.4 and 19 mm using standard SEM methods.

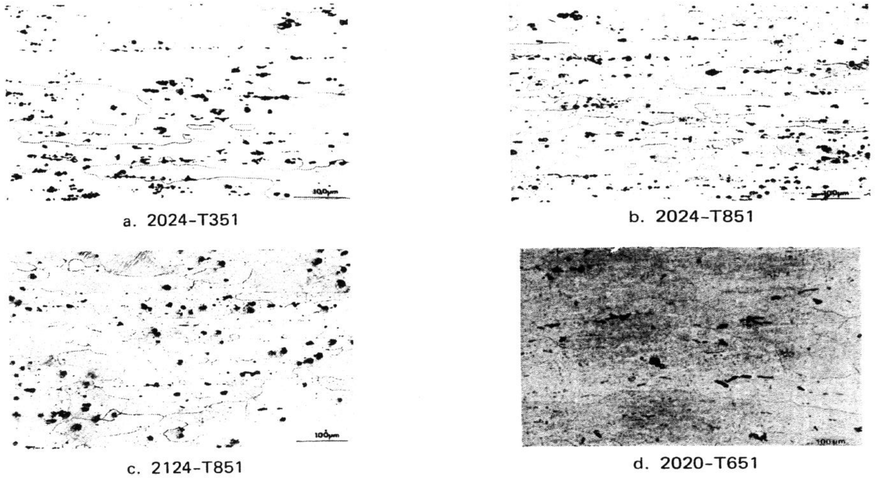
Constant amplitude fatigue crack propagation tests were conducted over low, intermediate and high stress intensities on compact tension C(T) specimens in the longitudinal (L-T) orientation. Spectrum testing was accomplished using two computer-generated spectra from an advanced fighter aircraft. In-depth discussion of the constant amplitude and spectrum testing can be found in a companion paper by Chanani et al. (1984).

RESULTS

Microstructure

2XXX Alloys

Figures 1a, b, c and d are optical photomicrographs of 2024-T351, 2024-T851, 2124-T851 and 2020-T651. The grain structure was observed to be partially recrystallized in three alloys, while being fully recrystallized in the 2020 alloy. Chanani et al. (1982) and Scarich and Bretz (1983) have reported that constituents found in these alloys are insoluble $Al_{12}(Fe,Mn)_3Si$ or Al_7Cu_2Fe. The 2024 and 2124 alloys also contain partially insoluble Mg_2Si and Al_2CuMg. Alloy 2124 with its lower Fe and Si content had fewer constituent particles present (compare Figure 1c with Figures 1a and 1b). In addition, as is illustrated in Figure 2, TEM examination revealed that fully recovered high angle boundaries outlined areas of recovered and partially recrystallized substructure. Past experience indicates that the dispersoid $Al_{20}Cu_2Mn_3$, which is incoherent with the matrix, is present in these alloys (see Figures 2a and 2b, for example). In addition, metastable precipitates were observed in both the T3 and T8 tempers (see Figure 2a). These are believed to be semi-coherent needlelike S' precipitates in the T8 condition and GP zones in the T3 temper. For alloy 2020 strengthening precipitates can barely be resolved in Figure 2b. Stark and Lin (1982) have reported these precipitates to be primarily T_B ($Al_{15}Cu_8Li_2$), θ' (Al_2Cu), T_1 (Al_2CuLi) and S'(Al_3Li).



a. 2024-T351 b. 2024-T851

c. 2124-T851 d. 2020-T651

Fig. 1. Optical micrographs of 2XXX alloys in the longitudinal direction.

7XXX Alloys

Optical photomicrographs of the 7XXX alloys are shown in Figures 3a, b, c, d and e. All five alloys were fully recovered with varying degrees of recrystallization. Again, based on the observations of Chanani et al. (1982) and

Scarich and Bretz (1983) the constituents seen in these alloys were insoluble Al_7Cu_2Fe, partially soluble Mg_2Si and Al_2CuMg. Fewer constituent particles were present in alloys 7475 and 7050, because the Si and Fe contents were lower than 7075 (compare Figures 3a and 3b with 3c, 3d and 3e). TEM examination established that the dispersoids found in 7075 and 7475 were relatively large incoherent $Al_{12}Mg_2Cr$ (Figure 4a), while in 7050 small coherent dispersoids of Al_3Zr are reported by Chanani et al. (1982). Strengthening precipitates can also be seen in Figures 4a and 4b. These precipitates are reported to be a combination of GP zones and semi-coherent η' in the T6 temper and η' and incoherent η in the T7 temper.

a. 2024-T851 showing $Al_{20}Cu_2Mn_3$ dispersoids and needlelike S′ precipitates.

b. 2020-T651 showing $Al_{20}Cu_2Mn_3$ dispersoids and barely visible strengthening precipitates.

Fig. 2. TEM micrographs of 2XXX alloys.

a. 7075-T651

b. 7075-T7351

c. 7475-T651

d. 7475-T7351

e. 7050-T7451

Fig. 3. Optical micrographs of 7XXX alloys in the longitudinal direction.

Fractography

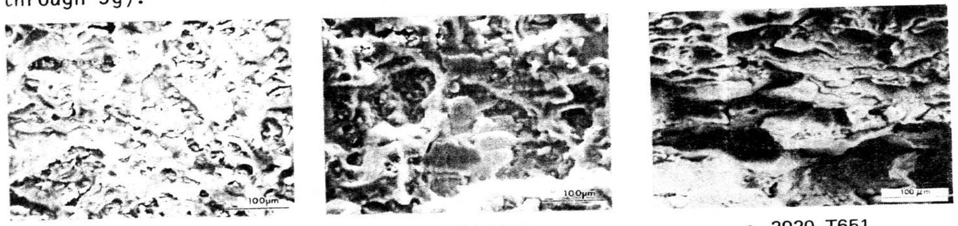
Figures 5a through 5g are SEM fractographs illustrating fracture features of the alloys tested. Macroscopically, the fracture surfaces for all the alloys were flat at short crack lengths with a gradual transition to a slant fracture occurring with longer crack lengths; except for alloy 2020, which had a flat fracture for the entire surface. Also, no beach marks were visible on 2020, while being easily observed on all other alloys.

a. 7075-T651 showing $Al_{12}Mg_2Cr$ dispersoids and strengthening percipitates.

b. 7075-T7351 showing increased precipitate size when compared to the T6 temper.

Fig. 4. TEM micrographs of 7075 specimens.

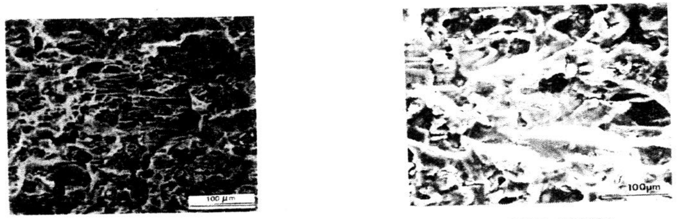
Microscopically, at shorter crack lengths the fractures of alloys tested were characterized by a combination of intergranular fracture, ductile striation formation and void nucleation and growth (compare Figures 5a through 5g).



a. 2024-T851

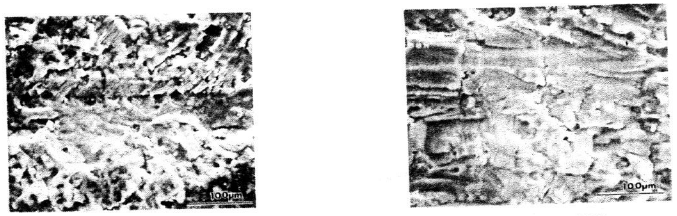
b. 2124-T851

c. 2020-T651



d. 7075-T651

e. 7075-T7351



f. 7475-T651

g. 7475-T7351

Fig. 5. Fracture surfaces of 2XXX and 7XXX specimens.

DISCUSSION

Role of Constituents

Research by Sanders and Staley (1979) indicates that large constituents affect the toughness but not the yield strength of 2XXX and 7XXX aluminum alloys. These constituents tend to fracture or separate from the matrix at high stress intensities. This leads to a preferential crack path ahead of the crack tip and results in lowered FCG resistance. An increase in FCG resistance is obtained at high stress intensities by reducing the volume fraction of constituents in the matrix; however, resistance at intermediate and low stress intensities is unaffected. A comparison of the constant amplitude FCG behavior for alloys 2024 and 2124 in the T851 condition, and 7075 and 7475 in the T7351 temper (see Chanani et al. (1984)) indicates that the high purity alloys 2124 and 7475 exhibit improved FCG behavior at high stress intensities. Similar results were also observed under spectrum loading as is illustrated in Figure 7 of the Chanani et al. (1984) paper. These observations confirm that the volume fraction of constituents plays a strong role in controlling FCG behavior at higher stress intensities in both constant amplitude and spectrum testing.

The role constituents play in controlling FCG behavior can be seen by examination of the spectrum tested fracture surfaces. The fracture surfaces of alloys 2024-T851, 7075-T651 and 7075-T7351 (see Figures 5a, 5d, and 5e) indicate that crack growth occurred by striation formation and void nucleation and growth. Fracture examination of the higher purity alloys 2124-T851 and 7475-T7351, (Fig. 5b, 5f and 5g) indicates that striation formation occurred with little evidence of particle-initiated fracture and void growth. These results suggest that the matrix was unable to accommodate crack tip plastic strains by flowing around constituents at high stress intensities and, therefore, led to fracture or separation of constituents. This resulted in lower FCG resistance at high stress intensities.

Role of Dispersoids

Bucci et al. (1980), and Sanders and Staley (1979) have reported that dispersoids decrease the energy required to propagate monotonically loaded cracks by initiating microvoids, which coalesce into void sheets and link cracks initiated at constituent particles. Dispersoids also influence strength and toughness indirectly, because of their differing abilities to suppress recrystallization in identically fabricated products. Examination of the constant amplitude load curves (see Figure 4, Chanani et al. (1984)) indicate that 7050-T7451 has higher FCG resistance at near-threshold and high stress intensities than 7075-T7351, while at intermediate stress intensities there was no appreciable difference. These results are attributed to the type of dispersoids present in these two alloys, since all other factors are the same. The Al_3Zr dispersoid, which is coherent with the matrix, observed in alloy 7050 is believed to deform with the matrix during plastic deformation, while the incoherent $Al_{12}Mg_2Cr$ dispersoid found in 7075 does not appreciably deform. This leads to stress concentrations and is believed to result in lowered FCG resistance at near-threshold and high stress intensity levels. Under spectrum loads slightly improved FCG resistance was observed in 7050 at higher stress intensities, but the effect of spectrum loading and dispersoid type on FCG resistance is not well understood.

Role of Strengthening Precipitates

The strength of aluminum alloys is dependent upon interactions between dislocations and metastable precipitates. The effect of different strengthening precipitates on FCG rate behavior can be seen by comparing both the T651 and T7351 tempers of alloy 7475 and 7075. Better FCG resistance was exhibited by the T651 temper at near-threshold levels of stress intensity (see Chanani et al. (1984)). This is in agreement with the work of Sanders and Staley (1979), which suggests that GP zones found in the T651 type temper contribute to cyclic hardening, which improves FCG behavior. However, Renaud et al. (1982) indicate the opposite results for near-threshold levels, citing the cause as an oxide or hydroxide film buildup on the fracture surface. At high stress intensities the curves cross and T7351 exhibits better FCG performance. The better performance of this overaged temper is supported by dislocation looping theories discussed by Starke and Lutjering (1979). This dislocation looping of precipitates effectively removes strain localization and results in longer fatigue life. However, comparison of alloy 2024 in the T351 and T851 conditions indicates that the FCG resistance of T351 is better than T851 at all ΔK levels, with the largest difference occurring at near-threshold levels. This inconsistency cannot be explained at this time.

Analysis of the spectrum fatigue crack growth curves in Chanani et al. (1984) indicates that the FCG behavior of 7475-T651 was better than 7475-T7351 at higher stress intensities. At intermediate levels there was no appreciable difference in the FCG behavior. This is a reversal of the trend observed under constant amplitude loads. Bucci et al. (1977, 1980) have suggested that spectrum testing can lead to a reversal of FCG behavior when comparing spectrum test results with constant amplitude test results. This suggests that alloys with higher yield strengths will exhibit better spectrum FCG resistance than overaged alloys, as is the trend observed in the 7475 alloys tested. However, this trend was not observed in the 7075 alloys tested. For 2XXX alloys, 2024-T351 had a lower yield strength and better FCG behavior than 2024-T851. Further work will be necessary to explain this trend reversal.

In alloy 2020 the strengthening precipitates are formed by two separate reactions. The first is the Al-Cu precipitation sequence with θ' (Al_2Cu) being the primary strengthening precipitate, while δ' (Al_3Li) coprecipitates separately from θ'. The spectrum testing performed on this alloy has produced results that reveal improved FCG resistance at lower growth rates with a switch to much lower FCG resistance at higher stress intensities. Nordmark and Kaufman (1972) attributed this lower FCG resistance at high stress intensity to strain localization occurring in precipitate free zones.

SUMMARY AND CONCLUSIONS

Microstructures and fracture surfaces of four 2XXX and five 7XXX series alloys were characterized, and correlations with constant amplitude and spectrum loading were examined. Results of this investigation indicate that alloys 2124-T851 and 7475-T7351 had better FCG resistance than their lower purity counterparts, that is 2024-T851 and 7075-T7351, respectively. The results show that large constituents decrease FCG resistance at high stress intensities and lead to failure by striation formation and void nucleation and growth. The higher purity alloys exhibited markedly less void nucleation even at higher stress intensities.

The dispersoid type appears to affect fatigue behavior, however the effects are not well understood. It was determined that alloy 7050-T7451 had better FCG resistance than 7075-T7351 at both low and high levels of stress intensity under constant amplitude loading and at the higher stress intensities under spectrum testing. It is suggested that the incoherent $Al_{12}Mg_2Cr$ dispersoid present in 7075 does not plastically deform, which would lead to stress relaxation ahead of the growing crack. This would therefore result in stress concentrations, which reduces the FCG resistance.

The FCG resistance of alloys under constant amplitude testing of peak aged alloys was better than overaged alloys at near-threshold levels of stress intensity. This was attributed to cyclic hardening caused by GP zones. At high stress intensities the overaged alloys exhibit better FCG properties, because the precipitates cause dislocation looping, which inhibits strain localization. Spectrum fatigue testing produced the reverse effects for the 7475 alloys, that is, the peak aged 7XXX alloys had better properties at high stress intensities. However, the 7075 alloys did not show this trend.

In summary, the results of this investigation indicate that constituents, dispersoids and metastable precipitates affect fatigue crack growth behavior at near-threshold and high stress intensities. The effects of different microstructures on intermediate levels of stress intensity does not appear to be large. A better overall understanding of microstructural effects at all levels of stress intensity is needed if improved alloys are to be designed.

ACKNOWLEDGMENTS

This work was sponsored by U.S. Naval Air Systems Command under the direction of project manager Mr. M. Valentine. The authors also wish to acknowledge Dr. R.J. Kar of Northrop Aircraft for his support and helpful discussions during various phases of this program.

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