The Influence of Material Quality on Airframe Structural Durability

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ABSTRACT

Previous work on Al-Zn-Cu-Mg alloy 7050-T7451 has shown that improved processing to reduce the size of microporosity results in longer fatigue lifetimes. To differentiate this improvement, Alcoa has implemented smooth specimen fatigue testing on a lot release basis to warranty 7050-T7451 thick (5-6 in., 127-153 mm) plate initial fatigue quality. The present study employs a probabilistic fracture mechanics analysis to demonstrate that the material quality improvement verified in the smooth specimen fatigue tests translates to durability performance in actual structures. Microflaw size distributions measured from failed smooth coupon tests serve as the starting point for probabilistic crack growth analysis. Using crack exceedance probability as a basis for durability performance comparison, a hypothetical calculation shows that a fighter aircraft wing fabricated from improved quality metal outperforms the same wing fabricated from unimproved metal.

INTRODUCTION

Reliability and durability of metallic airframe structures are coming under increased scrutiny as efforts are made to increase safety, readiness and supportability [1-6]. Airframe durability often refers to the ability to resist crack-like damage, which if not repaired over time would lead to functional impairment and possibly jeopardize aircraft safety [2]. Air Force studies have shown that a major cause of structural durability problems in aircraft is fatigue [7]. New probabilistic fracture mechanics tools have evolved to assess the safety and economic impacts of initial fatigue quality of airframe structural durability [8,9]. The initial fatigue quality of a structure is dependent on material, manufactured detail and component design. The material component of the initial fatigue quality addressed in this paper refers to populations of microstructural flaws (e.g. microvoids, inclusions) that can neither be eliminated in fabrication nor inspected out. A six month survey of major cracking problems in military aircraft revealed that 24% of the failures originated from material flaws [10]. Consequently, tighter controls on metal processing to reduce severity of flaw populations offers potential for extending life and reducing economic penalties associated with excessive maintenance and overly conservative designs.

In recent work, Alcoa has demonstrated a quality breakthrough on thick 7050-T7451 aluminum alloy plate [11]. In addition to modest improvements in conventional properties, a dramatic improvement was noted in smooth specimen fatigue life. The objective of the current work is to illustrate how material quality improvements detected at the coupon test level relate to component performance. For this purpose, a probabilistic-based durability analysis is used in a structural loading simulation.

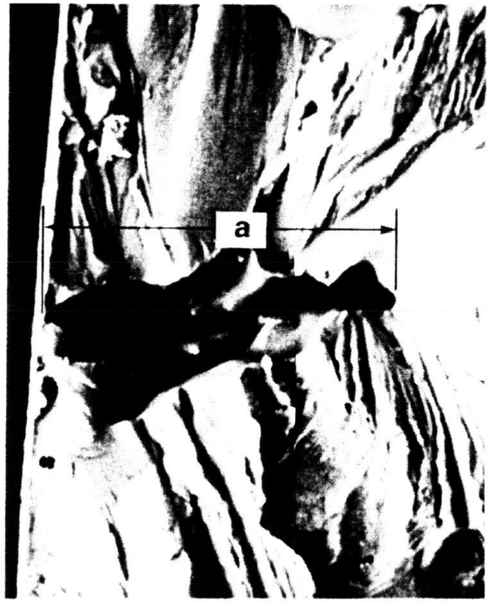
QUALITY-SCREENING SMOOTH FATIGUE TESTING

Improved processing has resulted in reduced microporosity in Alcoa's 7050-T7451 thick plate. As a means of quantifying this improvement, and as a basis for commercial warranty, smooth specimen axial fatigue testing has been implemented as a quality-screening tool for lot-release. In previously reported work on quality improvement in aluminum alloy thick plate, the smooth fatigue test was shown to be more discriminating of initial material quality than other conventional testing approaches [11,12]. During cyclic loading, damage tends to initiate at weakening flaws in the material. The crack initiating flaws may be either extrinsic or intrinsic; extrinsic flaws being machining marks, surface scratches, nicks, etc., and intrinsic flaws being microstructural inhomogeneities such as inclusions, microporosity, grain boundaries, etc. In the absence of gross extrinsic flaws, the fatigue failure process seeks out the weakest microstructural link or intrinsic flaw in the specimen test section [11-20].

The loading conditions selected for Alcoa's 7050-T7451 thick plate quality screening are cycling between a minimum stress of 3.5 ksi (24 MPa) and a maximum stress of 35 ksi (241 MPa) at a frequency of 10 Hz. These particular conditions were selected to produce failures in a reasonable time without the bias of gross cyclic plasticity. The test specimens are 0.500 in. (12.7 mm) diameter rounds taken from the plate midplane (microporosity tends to be most concentrated at the centerline of thick plate) and the long transverse (LT) orientation.

To correlate microporosity and fatigue life, post-test fractography was performed on failed specimens using scanning electron microscopy. In all cases the fracture origin was identified as a single micropore which was located at or just below the specimen surface. Figure 1 shows a typical micropore located at the origin of a smooth fatigue failure. The correlation between the crack-initiating micropore size and fatigue life is shown in Figure 2A. Dimension "a" in the figure corresponds to the largest linear dimension of the crack-initiating micropore as shown in Figure 1. The data of Figure 2A indicate that longer fatigue lives are generally associated with smaller microporosity size, however there is considerable scatter in the data. To examine more closely the relationship between fatigue life and micropore size, a smoothing technique was used on the data to reveal the mean effect of micropore size on fatigue life. The smoothed data, shown in Figure 2B, were obtained by sliding a ten-point average along the original data set ordered by ascending lifetime. These data reveal a strong dependence of the mean fatigue life on micropore size.

The measured crack-initiating micropore size distributions from unimproved and improved materials, produced in 1984 and 1985 respectively, have been fit to Weibull distributions. These distributions are shown in Figure 3. The improvement in material quality from 1984 to 1985 is reflected by a reduction in the occurrence of large micropores (the upper tail portion of the distribution), and a shift in the mode (peak) value to a smaller micropore size. As will be discussed later, these data serve as input into a probabilistic fracture mechanics analysis to



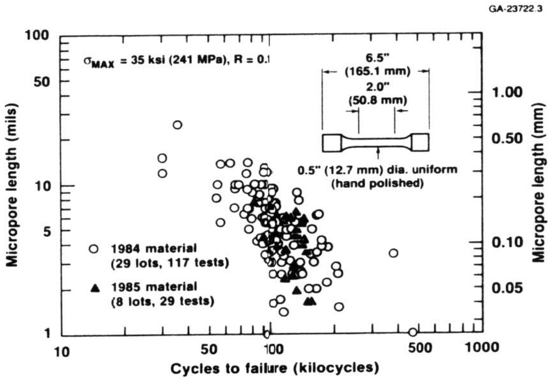
a = 0.0038 in. (0.097 mm)
N_f = 176,000 cycles
Specimen diameter = 0.5 in.
Long transverse test direction
σ_{MAX} = 35 ksi (241 MPa), R = 0.1

Fig. 1. Micropore at the failure origin of a smooth axial fatigue specimen.

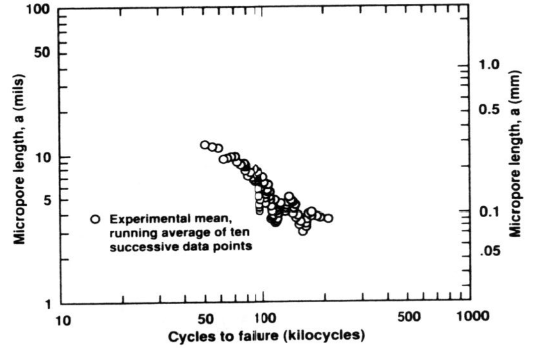
assess the impact of metal quality improvement on aircraft structural durability. It should be noted that in 1985 Alcoa began using the smooth fatigue test for commercial lot-release, and an arbitrary cutoff of 160,000 cycles was imposed to reduce test time in the plant test lab. Considering that the data from specimens which did not fail were omitted from the 1985 material data set, the quality improvement from 1984 to 1985 would be more dramatic than illustrated in Figure 2A and Figure 3.

ADVANCED DURABILITY ANALYSIS

Durability analysis of metallic airframe structures evaluates the probability of small cracks growing large enough to affect maintenance requirements and operational readiness of aircraft



(A) Raw data



(B) Smoothed data (1984 and 1985)

Fig. 2. Micropore length vs. cycles to failure – smooth axial fatigue tests. 7050-T7451 thick plate (5.7-5.9 in, 145-150 mm), long transverse, T/2 test location.

[3-5,8,9]. A starting point for this analysis is the initial fatigue quality of the component or structure prior to service. The initial fatigue quality is represented by an equivalent initial flaw size (EIFS) distribution which can be either correlated directly to actual failure origins, e.g. Figure 2A, or extrapolated from fatigue test lifetimes [9,11]. Factors which influence the initial fatigue quality are material quality, manufactured detail and component design. Once defined, the distribution of initial flaws are grown forward using a probabilistic crack growth model under the service load spectrum of interest. The durability analysis yields the probability of obtaining a given flaw size after a specified service time [8,9]. Unlike deterministic analyses which rely on a worst case flaw assumption, the probabilistic approach is able to quantify at the design stage performance enhancements resulting from material or manufacturing quality improvement.

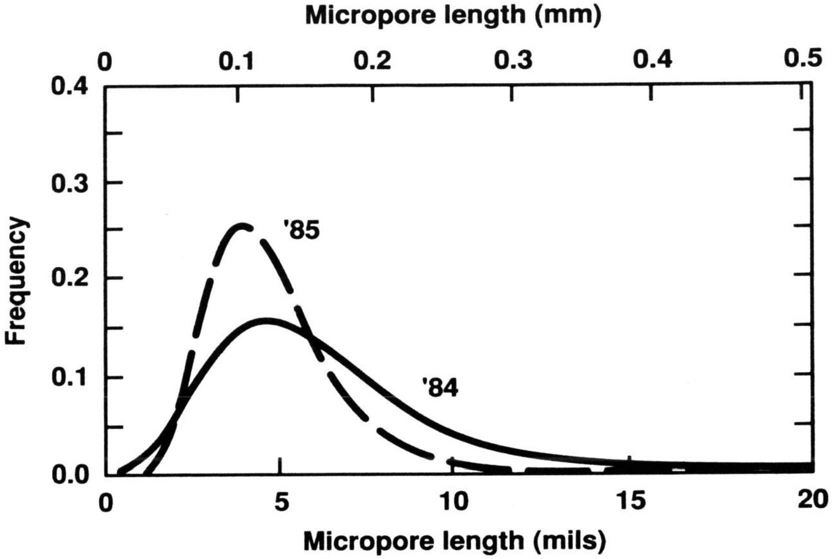


Fig. 3. Initial material micropore size distributions for 1984 and 1985 quality 7050 thick plate (as determined by post fatigue test fractography).

To demonstrate the potential impact of material quality improvement on aircraft durability, a hypothetical analysis was performed by the Air Force. The Air Force durability analysis approach, described in [8,9], calculates the probability of obtaining a given size flaw extending out of a fastener hole after a specified service time. The analysis in this paper uses the equivalent initial flaw size (EIFS) distributions developed for 7050-T7451 thick plate and representative loading for an F-16 fighter lower wing skin [21]. The initial micropore size distributions measured from smooth fatigue failures of 1984 and 1985 material (Figure 3) were supplied as input to the Air Force analysis [22]. The probability of flaw sizes exceeding 0.03, 0.05, 0.1 and 0.2 in. (0.76, 1.27, 2.54, and 5.08 mm) were calculated for service times of 8,000 and 16,000 flight hours; one and two times the design life respectively. The flaw exceedance probabilities have been converted into the number of flaw size exceedances expected per 1,000 fastener holes in the lower wing skin. These data for both initial micropore size distributions are shown in Table 1. From the data it can be seen that the quality improvement from 1984 to 1985 has a large influence on the expected number of crack exceedances. After 8,000 flight hours, the 1984 material had 196 cracks expected in excess of 0.03 in. and two cracks larger than 0.05 in., while the 1985 material had only two cracks larger than 0.03 in. and no cracks larger than 0.05 in.. Both materials had no cracks expected greater than 0.1 in. after 8,000 flight hours. A similar effect of material quality is observed after 16,000 flight hours for cracks expected in excess of 0.1 and 0.2 in. The 1984 material gave 195 and three crack exceedances and the 1985 material gave three and zero crack exceedances for crack sizes of 0.1 and 0.2 in., respectively.

Table 1. Hypothetical calculation showing how improvement in material quality can be translated to airframe durability.

Number of flaw size exceedances per 1000 fastener holes

Flaw size in. (mm)	8000 flt. hrs. 1 service lifetime		16000 flt. hrs. 2 service lifetimes	
	1984 material	1985 material	1984 material	1985 material
0.03 (0.76)	196	3	–	–
0.05 (1.27)	2	0	–	–
0.10 (2.54)	0	0	195	3
0.20 (5.08)	0	0	3	0

The results of the USAF durability analysis illustrate the influence that quality improvement can have on aircraft structural durability. Moreover, the probabilistic-based durability analysis enables performance benefit to be captured at the design stage. In contrast, traditional deterministic fracture mechanics approach based on a worst case flaw assumption would fail to differentiate the impact of superior quality on performance. Thus, smooth fatigue testing in concert with probabilistic fracture mechanics enables computational trade studies for design and life management as illustrated conceptually in Figure 4.

SUMMARY

Increasing demands for aircraft structural durability requires improved materials and manufacturing to avoid excessive costs due to maintenance and downtime associated with cracking. As demonstrated here for Alcoa material produced in 1984 prior to process improvement and higher quality 1985 material, the smooth coupon fatigue test can be used as a tool to discriminate material quality. The benefits of the quality improvement on structural integrity of aircraft were demonstrated by a hypothetical USAF probabilistic-based durability analysis. The use of a probabilistic-based approach for durability assessment enables the benefits due to increased quality/performance to be captured in design. This is an inherent advantage over traditional deterministic based fracture mechanics analyses which assumes a worst case flaw, independent of initial material quality.

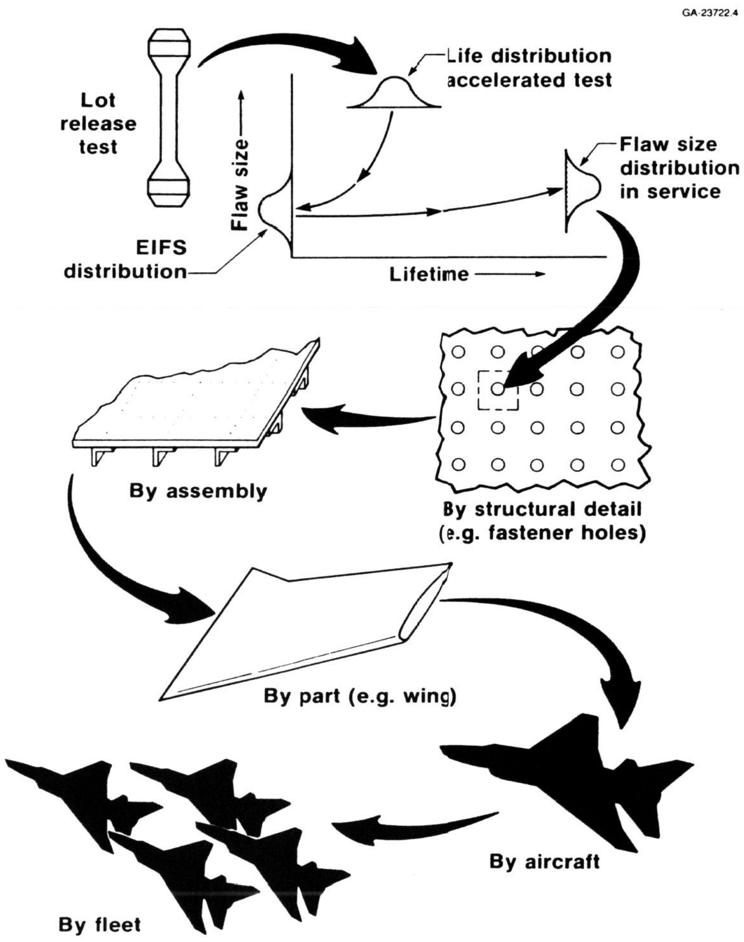


Fig. 4. The EIFS distribution – starting point for life management at various structural levels.

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