Aluminum Quality Breakthrough for Aircraft Structural Reliability

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In 1983, Alcoa's Davenport Works initiated a statistically designed experiment to evaluate effects of processing on thick plate metal quality. An outgrowth of this program is a breakthrough in quality and resultant property improvements that can be exploited for fatigue and fracture-critical structures. This paper describes the statistical quality control effort, and gives evidence of the improved capabilities typical of recently produced high-quality material. Among conventional mechanical property tests, the smooth fatigue test is shown to be the most discriminating for initial metal quality. Data are shown correlating longer lifetimes to reduced microporosity size in the improved plate. Replicate fatigue tests enable definition of a "characteristic" initial flaw size distribution that can serve as a starting point for flaw growth analysis and life management. These findings are discussed relative to initial fatigue quality guarantees and compatibility with emerging U.S. Air Force durability analysis methodology. In summary, it is shown that the combination of more discriminating testing and a superior product offers considerable promise for reliability improvement in aircraft structural designs of the future.

Introduction

FUTURE aircraft designs will reflect more stringent reliability demands to contain mounting costs associated with maintenance and downtime.[1-5] A survey of U.S. Air Force (USAF) logistic and maintenance centers revealed that most structural durability problems are the result of cracking.[6] Consequently, during design, assurance is sought that the structure will not crack excessively in service leading to functional impairment affecting the aircraft readiness.[2-5,7-11] Durability design begins with quality of the starting material. Under fatigue loading, for example, surface scratches, inclusions, or micropores can greatly accelerate the crack initiation process, and though cracks emanating from these origins are not an immediate safety hazard, they affect structural maintenance requirements.

The Al-Zn-Cu-Mg alloy 7050 was developed by Alcoa to provide a superior combination of strength, stress corrosion resistance, and fracture toughness, particularly in thick plate sections. Since the mid-1970's, Alcoa has supplied millions of pounds of thick 7050-T7451 plate for fatigue and fracture-critical aircraft structures, such as fuselage bulkheads and wing box applications. In 1983, Alcoa's Davenport Works implemented a statistically designed experiment with the objective of improving quality and engineering characteristics of 3–6-in. thick 7050-T7451 plate. While the current product was capable of meeting existing aircraft material specifications, improvements were sought to satisfy the higher integrity needs of future applications.

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In carrying out this investigation, smooth coupon fatigue testing coupled with post-test fractography was used to characterize members of the microflaw population with the greatest likelihood of originating detectable cracks in service. This promising technique is appropriately sensitive and well suited to the needs of emerging USAF guidelines for reducing cracking problems in metallic aircraft structures.[3-5,8,11,12]

Though the effort described in this paper focuses on aluminum alloy 7050 thick plate, the statistical quality control and fatigue test methodologies utilized are transportable to other high-strength aluminum alloy systems. As a result, the 7050 alloy quality improvements demonstrated herein have also benefited other 2XXX and 7XXX aluminum plate alloy systems.

Statistical Quality Control Experiment

While not new conceptually,[13-15] statistical quality control tools have not been incorporated extensively in problem-solving methodology at the plant level. Once the commitment to improving quality had been established, the first task was to determine where to start. Process improvement opportunities on the shop floor are seemingly unlimited, so five process variables considered to be most critical were selected for initial investigation, using a statistically designed experiment. Statistical quality control efforts focus on the current process, making improvements through reduction in variation. The focus of this paper is on the measurable improvements resulting from this effort, and mention of specific process variables is avoided in the interest of maintaining the proprietary advantage this commitment has achieved.

A statistically designed experiment provides the means of separating the "vital few" process variables from the "trivial many."[16] For this experiment, a 2^{5-1} fractional factorial (five variable, two-level) design was selected (Fig. 1). This design assured that all main effects and two-factor interactions are clear and not confounded with other main effects and two-factor interactions. A total of 20-runs were performed for the experiment—16 for the design and 4 replicated at the midpoints to provide a measure of experimental error. About 300,000 lb of metal were produced for the 20 run experiment. The experiment proved successful in identifying the most significant process variables.

Following completion of the designed experiment, efforts were directed at bringing the variables into a state of statistical control. Figure 2 is a composite Shewhart run chart[15] showing the relative values of a significant process variable before and after incorporating the quality control effort. As shown, the mean level ($\bar{x}$) was lowered by 60%, and the variation as defined by the upper and lower control limits (UCL and LCL, respectively) was reduced 3.4 times. This activity was repeated many times over, and as quality improvements were realized additional process variables were targeted for statistical control.

Quality Improvements

Process improvements are directly reflected by improvements in the product.[15] While some improvements were realized following the breakthrough achieved from the initial effort, quality improved progressively over time as new variables were brought under control. As a result, some quality and engineering characteristic improvements were immediately apparent, while others became evident only after additional process improvements were made.

Ultrasonic Inspection

Ultrasonic indications in thick plate correlate to the degree of microporosity present. One of the first benefits realized from the quality improvement effort was the elimination of class B[18] indications, as shown in Table 1.

In May 1985, this improvement led to a guarantee that Alcoa would no longer furnish plate with class B indications, and that all plate for aerospace applications would meet class A inspection limits. Even with the acceptance of the tighter class A limits, ultrasonic inspection recovery continued to improve, exceeding 99% for the past three years. While ultrasonic inspection does not present a total picture of the micropore distribution, it does portray the "worst cases" comprising the distribution tail. The quality improvement, as determined through the class frequency present in the distribution tails, is shown graphically in Fig. 3. In 1981, the average 7050-T7451 plate lot sampled contained 0.8 class A indications and 4.8 class AA indications. By 1985, the distribution tail had shifted to the point that the average lot sampled contained no class A indications and only 0.02 class AA indications. As such, it is evident that 7050-T7451 plant class AA inspection can now be guaranteed on request. More recently, class AA capability has been demonstrated for all Alcoa plate alloys with controlled fracture toughness requirements for aerospace.

Reduction in the degree of centerline microporosity with time has been verified by an internal quality check. Since 1976, Alcoa has performed a separate ultrasonic scan for aerospace alloys in thick gages (> 3 in.), where rolling may be insufficient to heal microporosity. The scan consists of inspection for a continuous response at the midplane (location of greatest microporosity) using a 3/4-in. diam 5 MHz crystal set to 100% response of a class A test block. An internal response limit of 15% was selected as a means of ensuring plate

Table 1 Ultrasonic classes for single discontinuity response

Class	Response, in.
AA	3/64
A	5/64
B	8/64

Any discontinuity with an indication greater than the response from a reference flat-bottom hole of the size given (diameter) is not acceptable.

Design order	1	2	3	4	5
1	+	−	−	−	−
2	−	+	−	−	−
3	−	−	+	−	−
4	+	+	+	−	−
5	−	−	−	+	−
6	+	+	−	+	−
7	+	−	+	+	−
8	−	+	+	+	−
9	−	−	−	−	+
10	+	+	−	−	+
11	+	−	+	−	+
12	−	+	+	−	+
13	+	−	−	+	+
14	−	+	−	+	+
15	−	−	+	+	+
16	+	+	+	+	+
			Replicates		
17	MP*	MP	MP	−	MP
18	MP	MP	MP	+	MP
19	MP	MP	MP	−	MP
20	MP	MP	MP	+	MP

*MP = Midpoint in range

Fig. 1 7050-T7451 plate improvement 2^{5-1} fractional factorial design with resolution V.

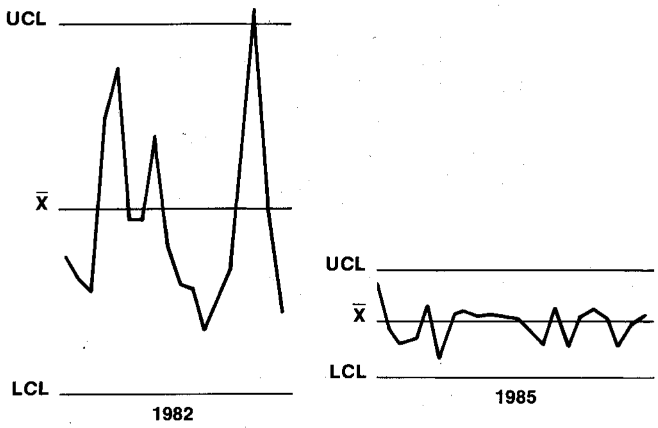

Fig. 2 Run chart of the most significant 7050-T7451 process variable.

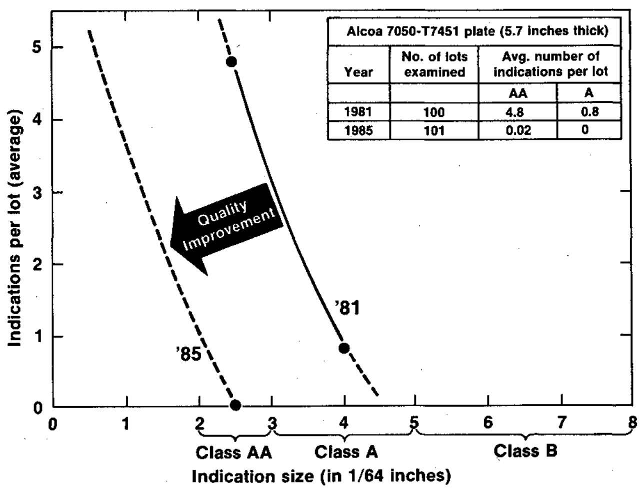

Fig. 3 Thick 7050-T7451 plate ultrasonic quality improvement.

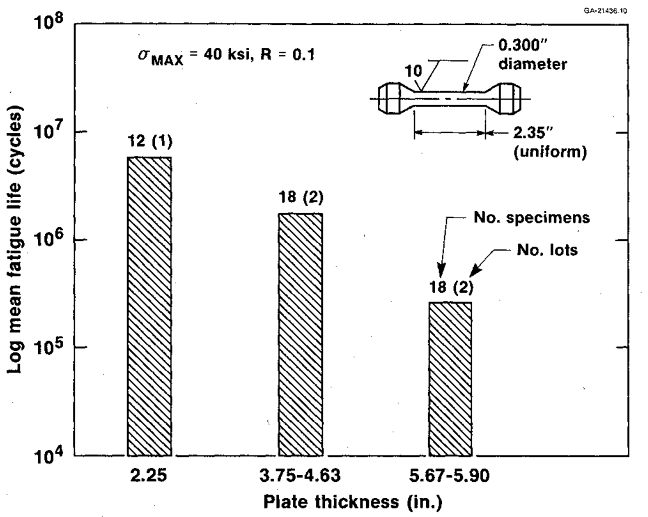

Fig. 4 Smooth axial fatigue performance at *T*/2 test location in 7050-T7451 plate of varying thicknesses (long transverse).

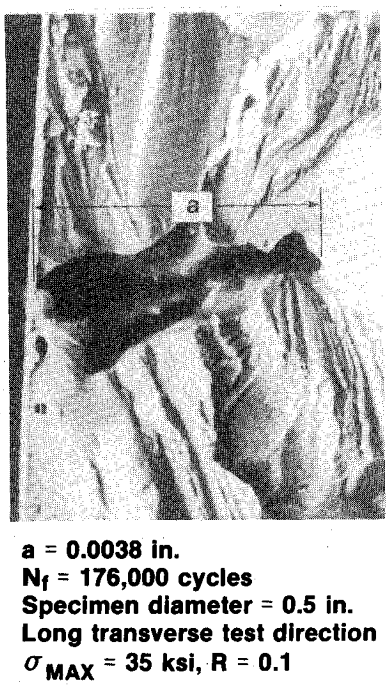

Fig. 5 Micropore failure origin of smooth axial fatigue specimen. Removed from *T*/2 test location of 5.9 in. thick 7050-T7451 plate (specimen 676951–6).

integrity. (This limit is much tighter than that of MIL-STD-2154,[18] which states that loss of back reflection exceeding 50% shall be cause for rejection.) Following the quality control efforts, Alcoa's internal inspection limit was lowered to 2% (threshold for detection) to reflect the improved product integrity.

Fluorescent Penetrant Inspection

The reduction of plate centerline microporosity was also verified by fluorescent penetrant response. Prior to incorporating the quality effort, banding of centerline penetrant indications was generally noted in thick plate. For 6-in.-thick plate, the band would be centered on the midthickness (*T*/2) plane and approximately 1 in. wide. Following the quality control effort, the band was no longer evident, and the indications present were distributed throughout the thickness.

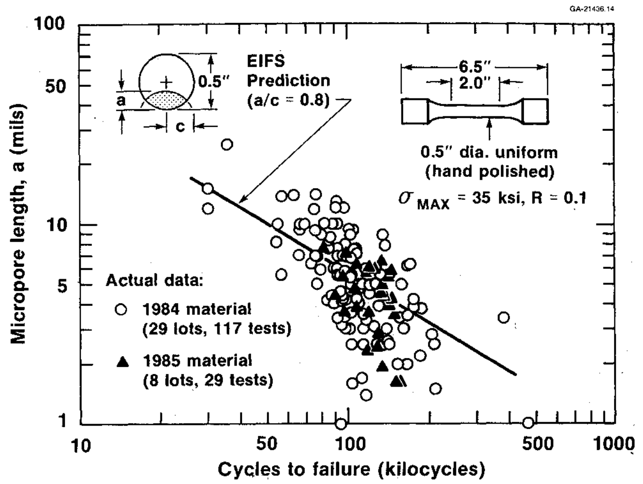

Fig. 6 Micropore length vs cycles to failure. Smooth axial fatigue tests, 7050-T7451 thick plate (5.7–5.9 in.) (long transverse, *T*/2 test location).

Mechanical Properties

The first production runs of 7050-T7451 thick plate, following quality control improvements implemented in 1984, showed a dramatic shift in both the mean and variation of short transverse elongation values. The mean increased from the historic level of 3.8 to 4.8%—a 26% increase, whereas the lower 95–99% limit increased from 2 to 3%—a 50% increase. Over the same time span, tensile and yield minimum strength values increased by 1 to 4 ksi, and minimum fracture toughness values increased by 1 to 5 ksi $\sqrt{in^2}$. These improvements have been documented[19] and are being incorporated as revisions to AMS-4050D[20] and MIL-HDBK-5,[21] as well as to customer specifications.

Fatigue

Most early life fatigue failures originate from pre-existing defects. Preservice inspection attempts to reduce both the magnitude and severity of these flaws. However, traditional nondestructive methods are suspect for the more demanding microdefect screening required by new aircraft and engine structural durability guidelines.[3–5,8,11,12] Over the years, much effort has been devoted to characterizing fatigue behavior using statistics of extreme values.[22–25] A rationale behind these studies is that materials contain weakening flaws, and though the flaw size spectrum may be wide, the fatigue process seeks out the dominant flaw (weakest link). Therefore, controlling the distribution of all flaws is not as important as controlling the size of the largest flaws (the extreme values). The smooth axial fatigue test is appropriately sensitive for screening initial metal quality, as the failure process seeks out the weakest microstructural feature.[26] The test is also simple and relatively inexpensive, thereby making it attractive for use in a production environment.

Figure 4 shows that smooth fatigue lifetimes of 7050 plate increase progressively with thickness reduction. Added rolling to thinner plate gages facilitates healing of pre-existing micropores. Fractures associated with the 7050 plate data revealed that failure for the heavier plate gages, in all cases, originated from a micropore located at or just beneath the specimen surface, e.g., Fig. 5. Consequently, the fatigue quality screening focused on samples from the *T*/2 midthickness location where micropore concentration is greatest in heavy gage plate (5-0–5.9 in). Fatigue specimens were oriented in the long transverse test direction so that loading would be normal to the elongated direction of the micropores. After some preliminary testing, a 3.5 ksi minimum to 35 ksi maximum cyclic stress range was selected to produce failures in a reasonable time. Early in the investigation, broken specimens

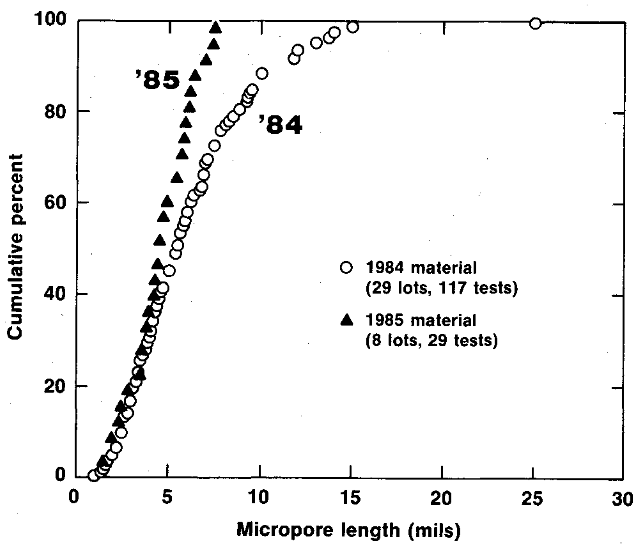

Fig. 7 Cumulative micropore size distribution. Smooth specimen fatigue failure origins, 7050-T7451 thick plate (5.7–5.9 in.) manufactured in 1984 and 1985.

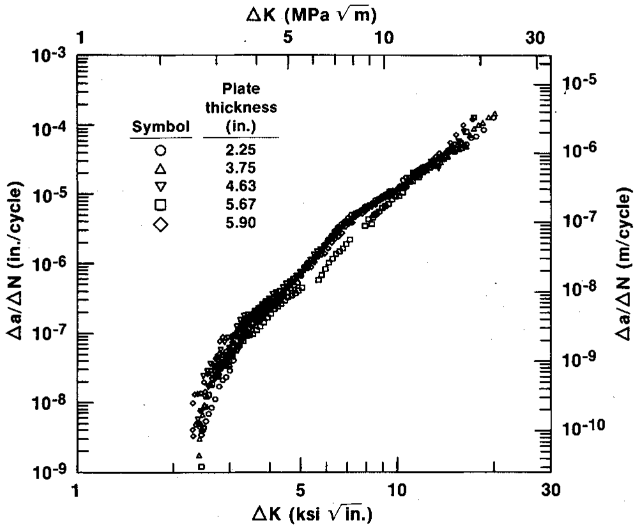

Fig. 9 Fatigue crack growth rates. Varying thickness 7050-T7451 plate, long transverse, $T/2$ test location, $R = 0.33$, humid air (R.H. > 90%).

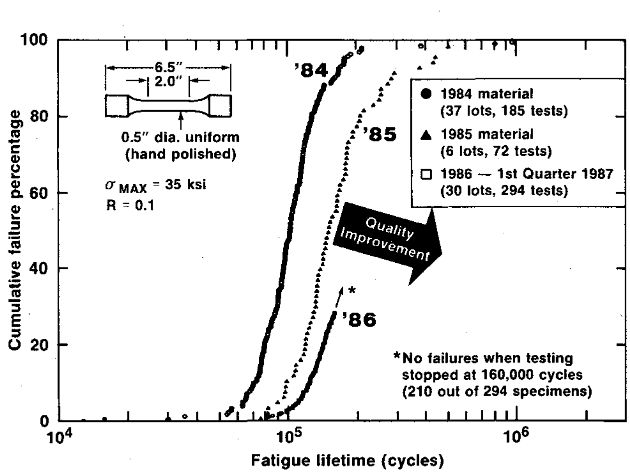

Fig. 8 Cumulative fatigue failure distributions for 7050-T7451 thick plate (5.7–5.9 in.) produced over 1984 to first quarter 1987 time period (long transverse, $T/2$ test direction).

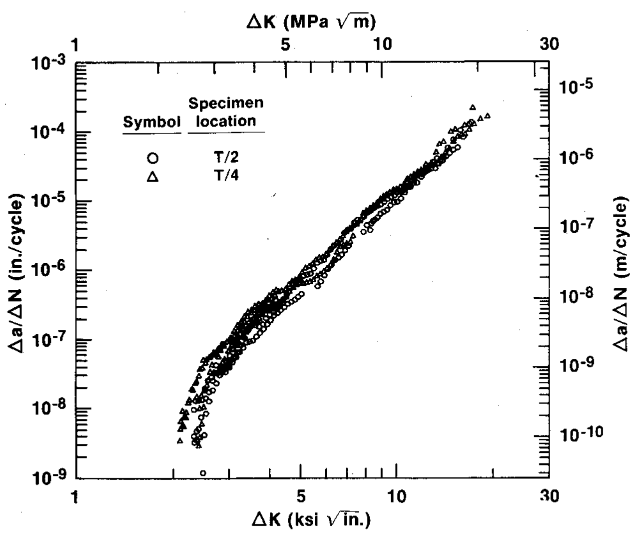

Fig. 10 Fatigue crack growth rates. 7050-T7451 plate (5.67 and 5.90 in. thick). Long transverse, $T/2$ and $T/4$ test locations, $R = 0.33$, humid air (R.H. > 90%).

were examined in an attempt to correlate fatigue life and size of the microvoid at the failure origin. Figure 6 shows data established for commercial plate lots fabricated from 1984 to 1985. The micropore size corresponding to the plotted data is the maximum pore dimension measured from an SEM photograph of the specimen fracture (dimension "a" of Fig. 5, for example). As expected, longer fatigue lifetimes tend to be associated with the smaller micropore origins, and Figs. 6 and 7 show that 1985 process improvements successfully diminished occurrence of larger micropores responsible for early failures in the 1984 material. Fatigue testing is now a part of Alcoa's process monitoring strategy for thick 7050 plate, and the cumulative experience given in Fig. 8 shows the quality improvement since implementation of this practice. Quality has improved to the point that the majority of specimens tested from 1986 to date survive an arbitrary 160 kilocycle truncation imposed to shorten test times for production material lot release.

Fatigue crack growth tests in accordance with ASTM E647[27] were also conducted to determine the effect of microporosity degree on crack propagation behavior. Comparable growth rates (da/dN) were obtained from specimens removed at the $T/2$ location of various thickness 7050 plates (Fig. 9), and from material at both the $T/2$ (high microporosity) and $T/4$ (low microporosity) locations of thick 7050 plate (Fig. 10). It is concluded from these results that crack propagation rates are insensitive to microporosity degree when the size of the crack is much larger than the scale of the microstructure. In contrast, the preceding smooth specimen results of Figs. 4, 6, and 8 imply that microporosity degree has significant influence on crack nucleation and early stage growth.

Quality Implications on Structural Reliability and Life Management

Total cost of ownership is becoming more important in selection and qualification decisions on aircraft materials and manufacturing processes.[1] When averaged over the life of a part, structure, or entire fleet, maintenance and downtime costs can become a driving force for change. Consequently, design and diagnostic life management strategies are needed to ensure longevity and safety without incurring excessive cracking problems over the design life period. Life assurance begins with controls on manufacturing, since life and consistency of performance are quality dependent. The conceptual drawing of Fig. 11 illustrates that lifetime to grow a crack to size "a" can, on average, be extended and be reproduced more consistently by decreasing size of the largest pre-existing flaws.

Aircraft structural durability requirements are concerned with reducing the probability of relatively small (0.0005–0.05 in.) flaws (of whatever origin) growing to sizes resulting in functional impairment and high life-cycle costs. Analytical procedures for predicting fatigue crack exceeding probabilities as a function of time in service have recently been developed by the USAF[8] and verified on full-scale structures.[4,5] These procedures employ probabilistic fracture mechanics and correlate structural cracking to initial fatigue quality represented as an equivalent initial flaw size (EIFS) distribution.[3–5,8] An equivalent initial flaw is a hypothetical crack assumed to exist prior to service. The EIFS distribution can be back-calculated from smooth coupon specimen fatigue lives and the appropriate crack growth rate data, as conceptually illustrated in Fig. 12. An EIFS vs fatigue life curve calculated in this manner for the test conditions of Fig. 6 is shown to fit the actual data.

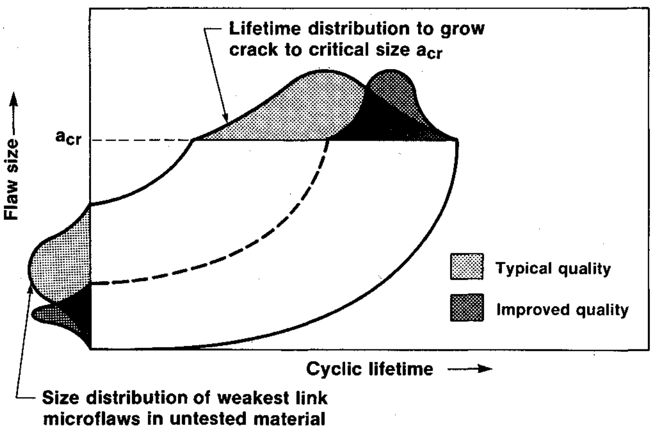

Fig. 11 Conceptual drawing showing that quality improvement translates to longer mean fatigue life and reduced variability.

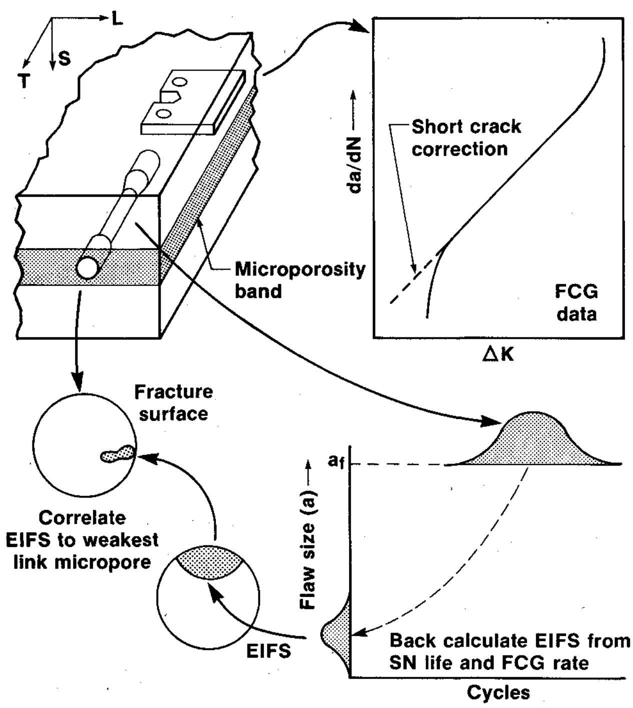

Fig. 12 Fatigue quality screening approach used for 7050-T7451 thick plate.

More impressive is agreement between the EIFS prediction and smoothed experimental data representing the mean micropore size vs life relationship separated from the scatter (Fig. 13). The smoothed test results of Fig. 13 were obtained by sliding a ten-point average along the original data set (Fig. 6) ordered by ascending lifetime. The EIFS computation shown in Figs. 6 and 13 assumed a semielliptical surface crack of depth a and length $2c$, with stress intensity factor given by the solution of Raju and Newman.[28] An aspect ratio (a/c) of 0.8 was chosen since it approximates the equilibrium shape partial-thickness crack of a uniformly loaded round tensile bar.[28,29] It has been observed repeatedly in the literature [30–33] that small cracks grow faster than rates predicted by near-threshold data obtained from long crack specimens of the current standard ASTM practice.[27] For simplicity and to compensate for the small crack effect, the EIFS curve in Fig. 6 was calculated using 7050 growth rate data ($R = 0.1$) corrected by linear extrapolation to low da/dN, as illustrated in Fig. 12. Refinements to improve further the computational accuracy of the EIFS model are presently being evaluated. The concepts incorporated into these enhancements are described elsewhere[33–35] and are outside the scope of this discussion.

A major point in the preceding example is that fracture mechanics interpretation of smooth fatigue data enables quantification of initial (weakest link) microdefect sizes in a manner consistent with new USAF durability analysis guidelines.[3–5,8] Once determined, the EIFS distribution can be viewed as a quality characteristic of the starting material, independent of specimen type and load history biases inherent to comparative analyses of cyclic lifetimes. Thus, in principle, the EIFS distribution can serve as a starting point for incorporating initial metal quality into computational trade studies for design and life management, e.g., Fig. 14.

In reality, initial fatigue quality needs to be discriminated at three levels: material, manufactured detail, and component. Unfortunately for material suppliers, current airframe specifications do not discriminate initial metal quality as a requirement for long-term durability. At the procurement stage, where high marks are given for low cost, the inability to pin a value on quality improvement reduces supplier incentive for consistently producing the highest quality product. In order to determine the extent to which improved material quality translates into long-term performance of parts, Alcoa has engaged in a cooperative test program with the Air Force. In this program, improved and unimproved (but still accepted by current specifications) 7050 thick plate will be furnished for fatigue evaluation. The program will characterize fatigue performance of increasingly complex specimens, beginning with

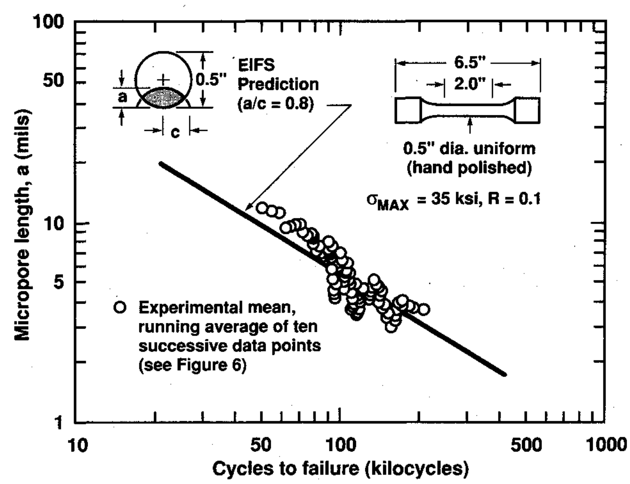

Fig. 13 Smoothed vs predicted relationship of micropore length and cyclic life, 7050-T7451 thick plate (5.7–5.9 in.) (long transverse, $T/2$ test location).

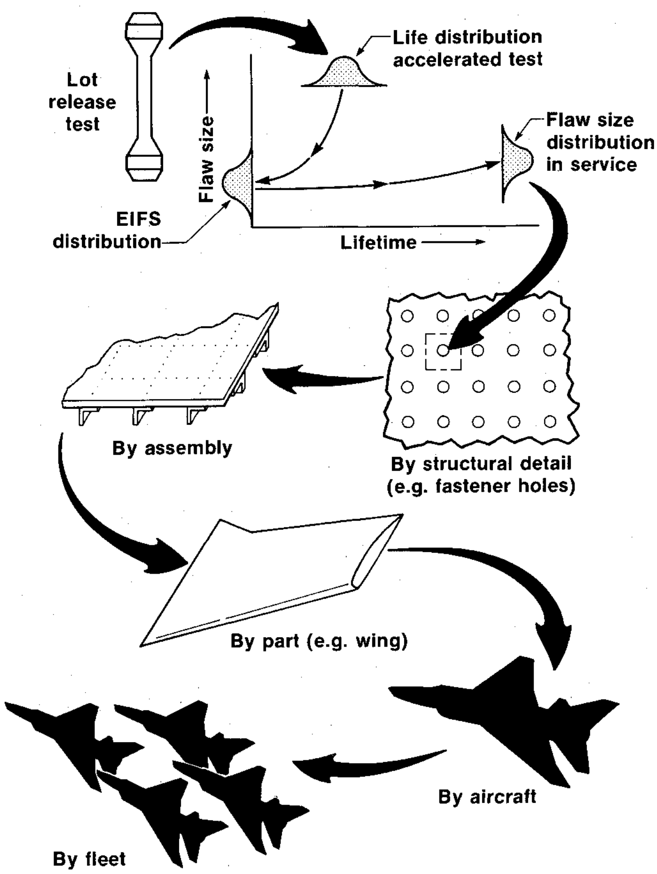

Fig. 14 The EIFS distribution—starting point for life management at various structural levels.

smooth axial fatigue specimens and leading to component parts. Ultimately, finished parts will be made and tested for final verification. The test program is intended to provide convincing evidence to support inclusion of fatigue lot release tests in specifications referencing initial material quality guarantees as a means of assuring airframe durability. The work presented in this paper represents a beginning step toward accomplishing this end.

Summary

Structural reliability and maintainability are becoming important tradeoff considerations in the design of advanced metallic aircraft. To meet future needs, improved materials and quality assurances will be necessary to avoid excessive costs of maintenance associated with cracking problems in the field. Conventional lot release testing of mechanical properties is not sufficiently discriminating of initial metal quality in relation to reliability performance objectives. Smooth fatigue testing exhibits a level of discrimination to quantify material reliability in terms useful to design. The coupon test lifetime distribution can then be transposed to an equivalent initial flaw size distribution as a starting point for flaw growth analysis and life management. Thus, in addition to use for warranty of metal quality and consistency on a lot-by-lot basis, the smooth fatigue test gives data enabling reliability assessment of well-designed parts.

A quality breakthrough made on thick 7050-T7451 aluminum alloy plate was demonstrated with respect to various reliability criteria established at the material producer level. The statistical quality control methods adopted on a plant-wide basis at Alcoa's Davenport Works resulted in significant improvements in conventional quality indices and smooth fatigue specimen test results. The demonstrated combination of more discriminating testing and a superior quality product offers promising new options for incorporating reliability into aircraft structural designs of the future.

Acknowledgments

This work represents over five years of accumulated effort by many Alcoa individuals, and any list of names is likely to miss valued contributors. In reality, it is the commitment to excellence of the organization for which they all work. Particular acknowledgment is owed to R. W. Westerlund, K. P. Young, D. F. Skluzak, M. A. Green, D. W. Barber, and D. S. Shryack of Alcoa Davenport Works for technical support on various aspects of the plant experiments; to G. Sowinski Jr., R. L. Brazill, W. T. Kaiser, and P. E. Magnusen, Alcoa Laboratories, for assistance in the fatigue experimentation and data analysis, and to P. L. Mehr, Aerospace Applications Engineer, for technical consultation.

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