I. Background

Primary airframe components are designed to static and dynamic loading, deformation, and other functional criteria. Operating service loading criteria for design and verification of durability and damage tolerance, both critical elements of airworthiness, are equally important. However, origination and growth of fatigue cracks have perpetually challenged airframe engineers.[1-9] Yet, service lives of commercial and military airplanes are being extended due to the increasing costs of fleet replacement. As a result, the aerospace industry has increased its focus on reducing both acquisition costs and total cost of aircraft ownership. Exploitation of aluminum alloys with superior fatigue and durability performance capabilities provides one means to address both the ownership cost and life extension objectives. To obtain the full benefit potential of these actions, an appropriate accounting of the aluminum interaction with airframe design criteria is a necessary prerequisite. This step is also important to planning and execution of cost-effective prevention and control strategies to mitigate potential safety risks associated with airframe aging (e.g., the widespread damage threat).[5, 9, 27]

From the airworthiness perspective, durability and damage tolerance methodologies have three critical elements:

- Residual strength, a measure of the maximum damage permissible without impairment to safety or function.
- Crack growth, the interval of damage from non-detection to allowable size determined by static strength safety margins for damaged structure.
- Damage detection, the sequence of and frequency of inspections.

Critical components must be evaluated for these characteristics, the outcome of which can affect airframe weight, cost and maintenance. Translation of raw material and product form characteristics to finished part performance according to these metrics is a key element of the design and material selection process.[1-9]

Growing size of airframes and pressures to reduce airframe build costs have resulted in a trend toward replacement of built-up assemblies with thick, monolithic components. Hand and closed-die forgings and thick plate product forms in high strength aluminum alloys (e.g., 7050 and others) compete for these applications.[11] Some airframe manufacturers are converting parts traditionally made from forgings to thick plate "hogouts." Historical technical reasons for the original preference for forged products in critical components are being compromised in product selection deliberations to realize a possible manufacturing cost reduction through avoidance of machining distortion problems sometimes encountered with forged parts.[11]

Structural durability and damage tolerance assessments based upon lab-scale test results and limited full component tests typically project superior fatigue performance for components manufactured as forged parts versus those machined from thick plate.[13, 17] Although these evaluations are limited in scope relative to the broad range of components for which plate and forgings compete, they represent trends which should be considered in the material and product form selection process. That is, the potential for acquisition cost saving advantage of thick plate should be weighed against the higher safety margin and/or weight and maintenance cost saving opportunities provided by forgings.[13, 18-22]

Many structural airframe components, such as bulkheads, spars, landing gear support, etc., manufactured from thick 7050-T74XX forged and plate products are internal to the aircraft. These components are subject to less traffic damage than external parts, so that in-service damage nucleation is often controlled by intrinsic material or product features rather than extrinsic events (e.g., traffic nicks and dings) as is the case of external structure. Since these thick product components are internal, it is difficult to inspect for fatigue damage (structural tear down is the only reliable method) and repairs can be costly. Because cracks are less tolerable in such internal components, it follows that almost any improvement in the host (raw) material product's durability and damage tolerance capabilities would be embraced by the user, provided said improvement is shown to be affordable.[24, 27]

Considerable research has been devoted to defining the role of microstructure on fatigue crack initiation and growth processes in high strength aluminum alloys.[14-17, 25-40] Much of this work has focused on evaluation of thick 7050 alloy product forms commonly specified for heavy sectioned internal aircraft components. Extensive fatigue testing has been completed using smooth, open-hole and fracture mechanics specimen test methods to obtain insight into the linkages between processing, microstructure, and performance for the purpose of guiding alloy development, raw material product processing development and component material and product form selections.

Resulting fatigue data have been organized for input into fracture mechanics based models developed to quantify the benefit potential of durability-improved materials and to discern the respective roles of metal pedigree, fabricating history, and configuration detail on end-component fatigue performance.[25-40] High resolution fractography and other evaluation techniques performed on failed fatigue specimens have yielded extensive statistical data on fatigue life-limiting microfeature populations for several commercial plate and forged product form variants. This work identified a hierarchy of fatigue crack initiating material microfeatures ranked below in descending order of severity for thick 7050-T74XX product applications:[25-40]

(1) Microporosity.
(2) Constituent particles.
(3) Persistent slip boundaries or other grain structure features.

Forged products may be under scrutiny with respect to the aerospace industry's drive to reduce manufacturing costs. However, an understanding of the forged products' process-microstructure-performance attributes suggests that forgings in some applications provide the opportunity for performance and maintenance cost saving enhancements. The excellent durability and damage tolerance capabilities of high strength, 7050-T74XX hand and die-forging emerge directly from the product's microstructure and fabrication (working) history.[16, 17] This observation is aligned with classical fatigue improvement scenarios, Figure 1.

In this report, forging durability and damage tolerance performance attributes are described phenomenologically and analytically, using models and coupon vs. part fatigue performance data. Forged products' durability performance is shown to be typically superior to other candidate products. Thus, forgings are expected to be especially exploitable when fatigue and durability are the limiting design criteria. These characteristics are necessary for the safety, reliability and affordability assurances demanded of long-lived, net-shape structural airframe parts.

II. Historical Advantages and Performance Capabilities of The Forging Process and Hand and Closed-die Forging Products

Forgings have historically been the preferred high strength, heavy-section, e.g. ≥ 4 in. thick, aluminum product for manufacture of aircraft components because of advantages provided by the forging deformation process. Well designed and executed forging and thermomechanical processes (TMP) for alloys such as 7050 impart high levels of multi-directional mechanical work (strain) and microporosity-healing compressive stress throughout the raw forging shape and the finished component cross-section. By so doing, the microstructure in all grain orientations of the forged product is homogeneous and thoroughly wrought. The multi-axis forging processes employed develop superior microstructures and properties in the short transverse (ST) grain orientation and in heavy section thicknesses.

In contrast to other conventional mill working processes (e.g., rolling, extrusion, etc.), the forging process, in general, is more robust in its ability to manipulate microstructural features controlling key mechanical properties. The higher levels of mechanical work typical of forgings better accommodate healing and/or break-up of deleterious remnants of the original cast structure. This deformation reduces both the size and frequency of weakening microfeatures important to ductility and fatigue strength.

Additionally, closed-die forgings provide contour-following, or controlled, grain flows, thereby enabling optimal tailoring of directional mechanical properties with principal load paths in the end-part. Controlled grain flow with respect to the finished component reduces end-grain and general corrosion and stress corrosion cracking concerns. Forged parts with contour-following grain flows will also exhibit superior resistance to growth of surface nucleated fatigue cracks, such as those initiated from corrosion or mechanical damage.

Moreover, it is well recognized that forgings offer a superior combination of damage tolerance and short transverse ductility capabilities in very heavy sections, e.g. ≥ 6 in. thick, without excessive strength property compromise. Finally, to properly compare forging vs. machined hogout property capabilities, the comparisons should be made on the basis of pre-machined product dimensions. That is, the properties of a reduced forged cross-section and design are more appropriately compared to those of the thicker host plate required to provide the same machined component.

The historical property advantages of forged products in airframe structure are being challenged by other thick aluminum alloy products. However, analytical and modeling technologies developed from current research permit **quantification of the durability and damage tolerance performance advantages of forgings.** With these data on durability and damage tolerance, **quantification of weight savings, life enhancement and total cost savings from forgings** can be accomplished.

The following subjects are considered in the balance of this report to define the Property and Performance Advantages of Forgings, with Focus on Durability and Damage Tolerance Attributes:

- Microstructural Basis For Fatigue Performance of 7050-T74XX and Other High Strength Aluminum Alloys (Section III).
- Microstructurally Based Life Prediction Tools (Section IV).
- Forged Product Process-Performance Relationships (Section V).
- Thick Component Life Prediction; Forgings vs. Machined Plate (Section VI).
- Full-Scale Fatigue Evaluation of Prototypical Parts (Section VII).
- Other Property/Performance Attributes for Aerospace Forgings (Section VIII).

III. Microstructural Basis for Fatigue Performance of 7050-T74XX and Other High Strength Aluminum Alloys

End-component performance is related to the properties of the component's starting raw material, which in turn is related to the material's microstructure. Microstructure is defined by the raw material product form's manufacturing process (i.e., forging, rolling, machining, etc.). Hence, if the effect of process on microstructure is known, then material properties and ultimately component performance are predictable from the governing microstructure-property relationships. The availability of performance data to compare forgings with other product forms on an equal component basis is limited. However, evaluation of the relative merits of forgings can be supplemented by first principles logic and understanding of process-microstructure-performance relationships derived from the extensive work done on other product forms.[25-43]

Fundamental knowledge applicable to assessment of 7050-T74XX forgings and other thick product durability and damage tolerance attributes was acquired from these activities:

- Quantification of metal pedigree effects on fatigue performance.
- Statistical characterization of life-governing microfeatures and their hierarchy of importance for various products and specimen types.
- Confirmation of fracture mechanics applicability down to the scale of life-limiting microfeatures.
- Corrective protocols to remove residual stress bias from coupon fatigue crack growth rate data.
- Analytical models to define:
  - Equivalent Initial Flaw Size (EIFS) from life data and random plane microstructures.
  - Structural life and crack growth probabilities from EIFS distributions.
  - Effects of microfeature type, size, shape and location distributions.

Critical microstructure-fatigue property relationships and hierarchy of life-limiting features for superior fatigue performance are independent of product form.[14-17, 23, 25-43] However, as demonstrated from parallel investigations, optimization of critical microstructures and microfeatures for superior fatigue performance is dependent upon product form, and particularly a product's processing and working history.[14-17, 26, 28, 33, 37, 40, 44] It is in this latter aspect that forged products demonstrate their value. For purposes of the balance of this discussion, a "life-limiting microfeature" is defined from Section I above as the microstructural feature(s), microporosity, constituent particles, persistent slip bands or other Stage I grain structure, identified by high resolution fractography as the initiation site for fatigue failure in smooth or notched specimen fatigue tests.

Historical fatigue data from thick 7050-T7451 plate, Figure 2, established a relationship between smooth specimen fatigue life and sizes of the life-limiting microfeature, in this instance microporosity.[25-28, 33-38, 43, 44, 56] Metal quality effects on fatigue have also been confirmed in U.S. Air Force tests on specimens prepared with production machining practices and representative part loadings, Figure 3.[39] In these tests, internal metal quality controlled fatigue performance even in the presence of surface-related features from machining.

Initial test programs were focused on 7050-T7451 thick (5.7 in.) plate improvement[33] and identified microporosity as the predominant fatigue crack-initiating microfeature, Figure 4. The product quality, in this instance, was directly related to the size and distribution of centerline microporosity. Microporosity characteristics, in turn, directly relate to fatigue performance in smooth and notched specimens.[34-37, 39] These observations led to the definition of the hierarchy of life-limiting microfeatures.[25-31, 37] Life limiting microfeature evaluations have subsequently been executed on several 7050-T74XX plates and extruded thicknesses from 1 to 6 in.[25-31, 40, 43, 44, 56]; on thick (6.25 in.) rectangular hand forging;[12] and on several heavy section, large closed-die forgings, with rib heights and/or cross-section thicknesses of up to 6 to 9 in.[16, 17]

To mathematically analyze and model fatigue behavior as a function of product quality or form, fatigue data were statistically treated through cumulative probability of failure plots. Figure 5 presents such a plot and represents a decade of 7050 thick plate process evolution to elevate fatigue performance.[25-28, 33] The figure also illustrates that substantial fatigue benefit is derived from the added mechanical work of rolling plate to a thin gage. While fatigue design allowables are seldom based on smooth specimen testing alone, the smooth specimen test is an excellent quality indicator tool (seeks out the weakest material link) as well as a valid tool for point design. Smooth specimen fatigue testing of 7050-T74XX, et.al. is required by some material procurement specifications as a means of controlling microporosity levels in thick aluminum plate for fatigue critical parts.[33-38]

Generation of allowable cyclic operating stresses for design generally entails notched specimen testing. Introduction of engineering notches into the fatigue test reduces the response to material or product internal quality.[45, 46] However, as illustrated in Figure 6, the impact of intrinsic microfeature characteristics on 7050-T7451 thick plate performance is not erased by these extrinsic open-hole features. Internal quality measurably influences performance of open-hole coupons and components they emulate.[26-28, 34, 37, 39] The example of Figure 6 also illustrates that improving open-hole quality, in this case by hole deburring, dramatically enhanced performance of the process-enhanced material (mid 1980's through early 1990's commercial practice), while deburring produced little or no improvement in the material of lesser pedigree (1970's through early 1980's commercial practice).

The above examples illustrate the potential for competition among life-limiting microfeatures, and how quality-improved material must be accompanied by manufacturing improvements to achieve the optimal component performance benefits. In the case of the lower quality thick plate material (1980 commercial pedigree), the specimens with deburred holes yielded the same S-N fatigue response as specimens with the as-machined holes. That is, coarse microporosity remained the life-controlling feature for the 1980 pedigree plate material regardless of whether the hole was deburred or not. In contrast, the more refined microporosity material (from 1990 commercial practice) exhibited fatigue crack initiation from edge-burrs of the as-machined holes. Upon subsequent testing with deburred holes, the life-limiting microfeature(s) of the enhanced pedigree plate reverted to either fine microporosity and/or material constituent particles.

Thus, analysis of microfeatures and their hierarchical effect on performance is a necessary component of understanding for material (alloy) and/or product form selections and the design and manufacture of fatigue resisting structures. Henceforth, the results of Alcoa open-hole testing presented in this report is for deburred holes unless otherwise specified.

The developing understanding of crack initiating microfeatures in high strength aluminum has fostered an evolution in thick product quality over the past decade.[33-39, 40, 44] Additionally, testing techniques and analytical approaches, both of which have served to better define the nature and hierarchy of microfeatures critical to fatigue performance, were expanded.[25-31, 41] For example, smooth specimen fractographs in Figure 7 reveal that the size of typical failure initiating micropores found in a low porosity 7050-T7451 thick plate variant is greatly diminished from that found in products produced with the commercial fabricating practices employed from the late 1980's to the early 1990's. Parallel fractographic analyses of failed open-hole and other notched fatigue specimens suggest that as material quality is enhanced in terms of microporosity refinement, other microfeatures (e.g., constituent particles) compete and evolve as the dominant failure initiators.

In general, it has been found that fatigue failures originating from constituent particles result in longer lifetimes than failures originating from micropores. However, it can not be unequivocally stated that life-limiting feature changes from microporosity to smaller constituent particles will guarantee fatigue improvement. As illustration of this point, Figure 8 shows fatigue crack initiating features revealed from failure examinations of deburred, open-hole specimen tests from two variants of 7050-T7451 thick (5.7 in.) plate possessing differentiated microporosity refinement. The life-limiting feature in the 1990 pedigree product (Figure 8, left) is microporosity just below the surface wall of the drilled hole. In contrast, the life-limiting feature of the lower porosity plate variant (Figure 8, right) is a hard constituent particle located at the hole corner. The life-limiting particle in the specimen on the right is about half the size of the life-limiting micropore in the specimen on the left; however, both specimens failed at comparable lifetimes.

Probabilistic fracture mechanics concepts have aided in understanding this observation.[30, 31] The explanation is based on the interaction of the stress concentrating notch with competing life-limiting microfeature (e.g., microporosity vs. constituent particle) distributions in the most highly stressed material volume (i.e., the metal sampling effect).[47] Because of high volume fractions, constituent particles almost always can be found in the vicinity of hole corners. If large enough, fatigue failure is most likely to originate at the particle-hole corner interface where stress concentration is 10-15% higher than in the hole bore. By comparison, microporosity is sparse. Even though life-limiting micropores are larger than constituent particles, encountering a critical micropore at a hole corner is a more rare event. Thus, micropore initiated fatigue failure is more likely to be associated with the surface region in the bore of the hole where the probability of a large pore encounter is greater.

The broader implication of these observations is that while smooth specimen fatigue response is more likely to be controlled by microporosity concentration, notched specimen test response is more sensitive to distributional differences among competing life-limiting features and their interaction within the highest stressed material volume.[47] Moreover, it is entirely conceivable that fatigue ratings derived from various types of notched specimen tests could be affected depending upon whether the volume of highly stressed material associated with the notch is large or small.[47]

The level of thick product microporosity may be refined, for example the low porosity 7050 thick plate variant in Figure 8 and/or by higher deformation levels typical of closed-die and hand forged products. In these examples, constituent particles, not microporosity, are more likely to become the life-limiting material microfeatures, particularly so in configurations where point stress concentrations exist (e.g., at hole corners and sharp notches). Figure 9 illustrates that the size and distribution of constituent particles within the bore of an open hole specimen are comparable for the two pedigrees of 7050 thick plate in Figure 8. It follows from Figures 8 and 9, that enhancement in open-hole specimen fatigue strength may not be attained by microporosity refinement alone. Process modification, via working history, composition or both, to reduce both size and frequency of constituent particles must accompany microporosity refinement to achieve further open-hole cyclic life enhancement.

In contrast, many finished airframe parts contain low-stress concentration cutouts, fillets, lands, etc. for which the volume of highly stressed surface material can be large. In this instance, the fatigue benefit potential of microporosity refinement, achieved primarily from working history, can be appreciably greater, because a larger volume of material is being sampled than that observed from the open-hole specimen result, where fatigue originates at the hole corners.

Figure 5 presents a comparison of lives of three pedigrees of thick (5.7 in.) and one pedigree of thin (1 in.) 7050-T7451 plate. All pedigrees are compositionally similar. The deformation history of the thin plate product is different from the three thicker product gauges. Figure 10 illustrates fractographs of typical microfeature initiation sites in the more highly worked thin (1 in.) plate. Note in the thin product, working was sufficient to result in exclusively constituent particles as the life-limiting microfeature.

Comparing size of the failure originating particles from Figure 8, right, for the low porosity thick (5.7 in.) plate variant to Figure 10 for the 1 in. thin plate variant, it is clear that the processing (working) history of the thin (1 in.) plate provided a more refined life-limiting particle, in this case a particle 50% smaller than that of the thick (5.7 in.) plate. Accordingly, the vastly superior smooth specimen fatigue resistance of thin plate shown in Figure 5 is evidence that the higher working received by the thin plate is effective as a microporosity suppressant. The superior performance of the thin (1 in.), more highly worked plate is a reasonable surrogate for and predictor of the performance of forged products, particularly close-die forgings. Similar working history effects on life-limiting features (constituents) hold for forged products. As discussed below, this is due to the high levels of compressive stress and mechanical work (strain) imparted by the forging process.

The final hierarchical level of fatigue life-limiting material microfeature is illustrated in Figure 11. As material and part manufacturing quality is enhanced by processing to reduce size and frequency of micropores, particles and/or manufacturing imperfections (e.g., scratches and tool marks), the default mechanism becomes the more classical Stage I slip induced initiation behavior. This mechanism has been the subject of much classical research on the subject of fatigue[48, 49] and is in part explained by the development and stabilization of persistent slip boundaries (PSB)[50] and other phenomena beyond the scope of this report. Post-test fractography of literally hundreds of failed smooth and open-hole coupons from various thick commercial aluminum product forms, however, has revealed that it is far more common for fatigue cracks to initiate from pore or particle type irregularities, acting singly or interactively, than it is to have classical Stage I initiated fatigue. That is, the Stage I initiation mode represents the ultimate upper performance bound for commercial thick aluminum product.

In summary, the quantification of microstructural influence on laboratory investigations of thick aluminum product fatigue performance leads to the generalized hierarchy of life-limiting microfeatures listed below in order of decreasing importance.[27] Available research work has confirmed that the hierarchy of microfeatures is independent of product form.[15-17, 26-31, 33, 37, 40, 41, 44] The microstructurally based knowledge form a set of first principles that can be exploited for analysis and quantification of the part performance of competitive products, including forgings, and the related effects of microstructure, processing and part making histories characteristic of the uses of these competitive products.

The essential points to be taken from the discussion of this section are that

(1) In absence of full component fatigue test results, the technical concepts of life-limiting microfeatures and various analytical approaches to fatigue, durability and damage tolerance evaluations can be used to understand advantages of forgings. Forged products derive their superior fatigue strength and durability characteristics from working and process histories that enable alteration in size and frequency life-limiting microfeatures in ways unavailable to other wrought product forms.

(2) Optimal transfer of laboratory data to fatigue design is possible when the role of life-limiting microfeatures is understood. The accuracy of projected outcomes can be affected depending upon the degree of control of said feature(s) in manufacturing and the quality in the detail of the planned evaluation.

IV. Microstructurally Based Life Prediction Tools

Substantial recent progress has been made in developing fracture mechanics based tools to relate microstructure and fatigue performance.[23, 26-31, 34-37, 41, 51] A number of salient conclusions from these works is listed below:

- Features of microstructure which govern fatigue life have been identified and statistically characterized for a number of product variants and laboratory specimen types.
- Links between life-governing microfeature populations and fatigue performance have been defined, modeled and validated (Section III).
- Size distributions of crack initiating microstructural features measured directly from the fracture surfaces agree well with equivalent flaw representations back-calculated from lifetime data.
- Guidelines have been established for estimation of life-limiting feature size distributions via scaling size distributions of like features measured by random plane metallography.
- The effects of the life-limiting in homogeneity size, shape, and location distributions of specimen fatigue life distributions have been demonstrated and analytically predicted.
- Characteristic microstructural feature distributions, derived from basic laboratory coupon tests, have been applied to predict structural element performance.

Though the above findings were largely derived from investigations involving various 7050-T74XX plate product forms, the findings are applicable to all high strength aluminum alloy product forms, including forgings.

Figures 12 and 13 illustrate the flow and translation of microstructural understanding from basic coupon testing to analytical model development and then to design data for component performance appraisal.[27] A key input into the component model is an "equivalent" initial flaw size (EIFS) distribution, that is a characteristic of a given raw material product or product pedigree.[7, 8, 33, 35, 36] One means to acquire this information is to correlate EIFS distribution with failure-initiating microfeatures directly measured from failed specimen fractures. A second, and perhaps more affordable, alternative is to invoke fracture mechanics models to back-calculate EIFS population data from distributional lifetime data obtained from fatigue tests used for quality screening. The path employed for this calculation is presented in Figure 12 and good agreement of the model with experimental observations has been demonstrated.[36]

Flaw populations from different life-limiting feature distributions, Figure 14, may then be used to assess the effect of material manufacturing processes, composition and other process variables on structural component performance. In Figure 14, the three flaw size populations represent the evolution of product quality in a selected thick product, or alternatively, the input EIFS distributions of three competitive product forms. The performance models developed in References 7, 8, 35, and 36 enable the frequency of flaw size excedance(s) to be predicted for prototypical structural components.

The prediction of flaw size excedances is accomplished by computing the distributional crack growth accrued from simulated in-service loadings and presumed to originate from the starting EIFS population. The EIFS population is in turn linked to raw material microstructure. The hypothetical calculation of Figure 14 was undertaken to illustrate how three representative input material "qualities" or "pedigrees," based upon identifiable initial flaw populations linked to material microstructure, might affect the potential for multi-site fatigue damage (MSD) in the lower wing of a military fighter.

Detailed discussion of this model, and parallel models utilized in analyses of other service performance criteria, is beyond the scope of this document. References 7, 8, 23, 30, 31, 35, 36, 50 and 56 are recommended to provide more detail on modeling techniques correlating flaw population predictions with component or system performance through durability and damage tolerance methodologies.

The basic conclusion to be drawn from this discussion is that **reasonable estimates of durability and damage tolerance capabilities of actual components can be linked with and modeled from life-limiting microfeature populations derived from laboratory coupon tests. The models provide a set of analytical tools to translate understanding of life-limiting features of material microstructure, known to emanate from the compositional and processing history of any given aluminum alloy product, into useful design guidance for airframe manufacturers.** Such models can be and have been successfully used to assist in component designs, evaluations of aluminum raw material product options and raw material product quality enhancement efforts.[36-38, 40, 41]

V. Forged Product Process-Performance Relationships

In Section III, a microstructural basis and hierarchy of life-limiting microfeatures controlling smooth and open-hole (notched) fatigue performance in 7050-T74XX (or other aluminum alloys) was established. Descriptions of equivalent initial flaw size (EIFS) populations linked to life-limiting microstructural features are then utilized as input into fracture mechanics models to predict crack origination and growth in end-components (Section IV). Calculated results from these technologies have been shown to agree favorably with results of actual structural element tests. Thus, an expanded number of material, product-form and manufacturing options can be evaluated analytically, at much earlier stages of design, without having to resort solely to prohibitively large and expensive test programs. In this section, the capabilities of candidate aluminum raw material products for the manufacture of components are quantified to facilitate selection on the basis of performance, costs or a combination of both.

In selecting among material and product form options for manufacture of fatigue critical components, from the above analyses, it is entirely conceivable that working history differences among competing products will have a bearing on acceptable end-component performance. For example, consider a typical large, web-rib component, whose finished cross-section is shown as ghost outlines in Figure 15. This part may be produced either as a hogout from the thick plate or as a finished machined part from the closed-die forging depicted in the figure.

Figure 15 delineates the significant differences in deformation imparted to the two candidate host raw material product form options: (1) a thick plate 7 in. x 37.25 in. (cross-sectional area 260 sq.in.) and (2) a large closed-die forging with webs thickness at 0.75 in. and rib heights of 4.75 to 6.75 in. (cross-sectional area 70 sq.in.). Plate 7.0 in. thick is necessary to assure part coverage by allowing for all adverse tolerances. From the contoured shape of the die forging, maximum rib height is reduced to 6.75 in. for machined part coverage due to reduced adverse tolerance build-up. While comparison plate thickness versus die forging web thickness is not a wholly accurate measure of the working differences between the two products because of the multiple axis working utilized in forgings, it is a reasonable general indicator. On the basis of plate thickness vs. die forging web thickness, the deformation (e.g. reduction or level of strain) of metal into the webs of the die forging is at least nine (9) times greater than thick plate. However, comparison of plate thickness vs. die forging web thickness is not a reasonable gauge of differences in microporosity-healing compressive stress introduced. The forging process has been shown[15, 16, 17, 27] to impart very high levels of compressive stresses to the work piece that are not imparted by the rolling process.

From the preceding discussion (Sections III and IV), it is quite reasonable to expect that fatigue testing would reveal differences in raw material intrinsic life-limiting microfeature populations traceable to the differentiated metal working experience of the two host products in Figure 15. Specifically, webs and rib fatigue performance in the end-component is expected to be controlled by constituents or PSB's and grain structure in the more heavily worked forging, while constituents or microporosity are the life-limiting features anticipated for the thick plate hogout. Such expectations are confirmed by actual observations, as discussed below.

Plate fatigue performance is known to be affected by product thickness, as illustrated in Figure 16 for smooth specimen tests at maximum cyclic stress of 40 ksi. For thick plate, deformation during rolling may be insufficient to heal centerline microporosity present in the starting ingot. However, plate produced with an optimal microstructure, low porosity 6 in. plate in Figure 16, has clearly superior fatigue performance. Increasing the amount of mechanical work in rolling to thinner plate gages decreases both the amount and size of microporosity, with a commensurate smooth specimen fatigue improvement. The plate gage dependency persists to gages less than 3 in., Figure 17. In the latter cases, however, it is necessary to increase the test stress level to 45 ksi (about 65% of yield strength) to differentiate smooth fatigue performance among the different plate thicknesses.

Process and working histories of hand forgings, closed-die forgings and plate are uniquely different. Because these histories impact pore and particle populations and grain morphology in different ways, it follows that relative fatigue performance ratings among plate, hand forgings and closed-die forged products will be affected when these features are the life-controlling factors, Figure 18. Note that the most recent quality evolution of optimally produced, low porosity thick plate compares favorably in performance with thick hand forgings, whose pedigree dates to the early 1990's. The early 1990's pedigree closed-die forgings remain superior to the optimal plate product. Capture of the same improvements employed in the most recently produced (1995) optimal, low porosity plate product can be anticipated to improve performance of hand and die forgings as well.

Heavy-section forged products exhibit the same types of life-limiting microfeatures as thick plate, Figure 19. However, the forging process appears to modify (reduce) the size and frequency of micropores, reduce the size of constituents and drive the life-limiting microfeature to PSB's. For example, compare the very fine microporosity observed in Figure 19, pore lengths of 0.0006 to 0.0009 in., for specimens taken from a heavy section 7050 die-forging with maximum thickness of 6.3 in. vs. the life-limiting microporosity sizes observed in Figure 4 (0.002 to 0.004 in.) and Figure 7 (0.005 to 0.0015 in.) that illustrate evolving quality of 7050 thick plate.

Fractographic examination of numerous failed smooth and notched fatigue specimens extracted from various type forgings (thick and thin)[16, 17] reveals that constituent particles and Stage I PSB's (comparable to Figures 10 and 11, respectively) compete as the most frequently encountered type of material-intrinsic crack initiating microfeature in forgings. In contrast to thick plate where microporosity initiated fatigue cracking is a more common occurrence, the more effective microporosity healing achieved by the forging deformation history drives the fatigue process to seek a lower ranking member of the life-limiting microfeature chain, Table 1.

These microstructural observations for forgings confirm that the working history of forged products is the overpowering feature of this raw material form in terms of its fatigue performance advantage over plate, where the rolling process does not introduce high levels of compressive stress. The fatigue lifetimes of specimens from heavily worked die forgings even exceed those of specimens removed from thin plate, Figure 20.[17] In these tests, all specimens excised from the web section of a die forging with a rib height of 6 in. (comparable plate would be at least 6 in. thick) were runouts at stresses of at least 60% of the yield strength of 7050-T74XX, demonstrating the superior fatigue strength of forgings.

A forger has several options available in design of the forging process for any given forged part, but particularly for large, heavy section closed-die forgings. These options include (1) selection of input material, e.g. as-cast ingot vs. wrought stock forms of rolled, drawn or extruded bar or plate; (2) selection of preform or open die forging processes and preform geometry; and (3) selection of single or multiple closed-die working process histories. From the analyses and evaluations presented above, starting stock, pre-working and final deformation process(es) selections may have marked influence on the final forged (and machined) part's fatigue performance. This observation is illustrated in Figure 21, where Process Route B produces clearly superior smooth specimen fatigue performance over Process Route A.[16,17] The improvement of performance through Process B is attributed to a multiple-axis working history, with higher levels of total forging reduction than Process A parts, which have a single axis deformation history.

Finally, the performance advantage of forgings, in particular die forgings, is retained even in the presence of notches, as illustrated in Figure 22. Plotted are open-hole fatigue results from the same plate and forged products (Process B) presented in Figures 20 and 21.

In summary, **the forging process itself affords a means to further differentiate the fatigue performance advantage of forged parts from that of comparable thickness plate hogouts.**

Table 1: Hierarchy of fatigue crack initiating microfeatures commonly observed in coupon specimen evaluations of commercial 7050-T74XX thick products.

	Predominant life-limiting microstructural feature		
Rank	Smooth (round bars)	Open-hole (as-machined)	Open-hole (deburred)
(1)	Coarse microporosity	Coarse microporosity	Coarse microporosity
(2)	Microporosity	Microporosity & hole quality	Microporosity
(3)	Constituent particles	Hole quality	Constituent particles
(4)	Grain structure		Constituent particles & grain structure

VI. Thick Component Life Prediction; Forgings vs. Machined Plate

Full component test appraisals of the performance of competitive high strength aluminum product forms are costly. Thus, few have been undertaken and reported, other than those discussed in Section VII below for precision forgings. Because it is necessary for the airframe manufacturer to make quantifiably sound component design and material product selection judgments, predictive models facilitate an expanded range of options, in shorter times, and at lower costs.

The majority of high strength aluminum alloy component durability and damage tolerance predictive modeling has been based upon 7050 alloy plate fatigue crack growth rate (FCGR) performance.[25-31, 34-36] In this section, justification for using plate fracture mechanics data and models for forgings, with appropriate treatment of possible residual stress bias in forging FCGR data generation, is presented. It is shown that forged product capability can be reasonably estimated from available plate FCGR property data as a function of grain orientation in order to demonstrate the benefit potential of forging's contour-following grain flow and refined life-limiting microfeature population. These model results are then reviewed in terms of the potential life extension, weight and cost reduction advantages of forgings.

Life prediction models begin with fracture mechanics analyses based upon the material FCGR relationship expected for the end-component. Insertion of forging data into plate models and utilization of plate data to analyze forging product performance requires justification. Previous published work has addressed the fracture mechanics performance issues of this conversion.[12, 14, 15, 17]

Plate FCGR properties for 7050-T7451 have been shown to be independent of product thickness, Figure 23, and the FCGR properties of 7050-T74XX in forgings and plate are comparable, compare Figure 23 to Figure 24. However, the industry's FCGR database for 7050 forgings is tainted by test method induced biases, e.g., Figure 25, that produce spurious FCGR measurements from coupons isolated from partially stress relieved parts.[12, 15, 16, 52] A method has been developed[52] to remove the residual stress bias from FCGR data generated by standard fracture mechanics test methods, Figure 26.

The correction practice employs a factor, derived from crack closure-type measurement techniques, to remove internal residual stresses from computation of the specimen cyclic crack drive (ΔK) solution.[52] Without this correction, the residual stress bias introduced in the coupon has been shown in some cases (dependent on specimen and part geometry) to produce an effect on crack driving force that is greatly exaggerated beyond that observed for naturally originating cracks in actual parts.[52]

A comparison of Figures 26 and 27 shows that when the same crack closure-based correction practice is applied to coupon generated data from stretched 7050 plate and non-stress relieved 7050 forgings, the FCGR relationships are similar. Hence, the intrinsic FCGR performance of forgings can be reasonably estimated from plate data of comparable grain flow.[15, 16] Thus, when forging FCGR data are either not available or of suspect quality, reasonable first estimates of forging FCGR performance can be judged from plate FCGR performance.

An optimally designed web-rib die-forging requires minimal finish machining so as not to disrupt the contour-following grain flow in the final part.[17] Consider the engineering component of Figure 28, which contains attachment holes and can be manufactured either as a plate hogout or a near-net-shape die forging. In the die-forging, the predominant grain orientation in the rib changes with part contour in comparison to a part machined from plate, where grain flow cannot be tailored. The die-forging grain flow may be controlled to be favorably oriented with the part load path, compared to that in a plate component where machining may interrupt the predominantly longitudinal plate grain flow. FCGR performance of plate, which will be utilized as an indicator of FCGR in forgings, varies with grain orientation (Figure 28 inset), even when corrected for crack closure, Figure 29. If one considers crack Location A in Figure 28, the plate grain orientation to establish FCGR performance is S-L, whereas in the forging it is L-T, due to conformance of the grain flow to the component shape.

The potentially substantial fatigue benefit of forgings is demonstrated by the results portrayed in Figure 30. The figure presents the predicted open-hole S-N fatigue response of a hypothetical part (like that in Figure 28) machined from plate versus the same part designed as an optimal die forging. The calculation employed a generalized probabilistic crack growth model with power law FCGR relationship (extended to the short crack regime). Cracks were assumed to initiate from the respective product life-limiting microfeature populations (inset Figure 30), and the model considered the possibility that cracks could occur anywhere along the bore of the hole. The input FCGR behavior for the model was derived from plate test results. Crack growth was presumed to be in the L-T and S-L orientations for forging and plate, respectively (i.e., analogous to location A in Figure 28). The upper and lower S-N bounds for the two competitive products illustrate the maximum possible difference in closed-die forging vs. plate hogout S-N response for the modeling assumptions used.

The hypothetical examples of Figures 31 and 32 further illustrate the potentially substantial weight and/or operator cost saving opportunities afforded by the forging process. Figure 31, again contrasts the calculated fatigue performance of a part machined from plate against that of the same part designed as an optimal die forging. The calculation employs a deterministic crack growth model, assuming the same FCGR relationship assumed for the calculated results of Figure 30. Cracking is presumed to grow from an open hole starting as a corner crack equal to a representative mean life-limiting feature size of the respective raw material product form (0.003 in. for forging and 0.004 in. for plate).

Under the above set of assumptions, the forged part accommodates 31% higher maximum cyclic stress (from 10 ksi to 13.1 ksi) at equivalent fatigue life for plate, or the die forging can accommodate about a five times life increase over plate for the same 10 ksi maximum cyclic operating stress. A companion example to Figure 31 is presented in Figure 32. In this latter example, crack growth is presumed to start from a mechanical 0.010 in. flaw located at the corner of an open hole. Under the best possible scenario, where crack growth is in the L-T vs. S-L orientation for forging and plate respectively, the die forging accommodates a 27% higher cyclic stress (from 10 ksi to 12.7 ksi) at equivalent fatigue life for plate, or almost a four times life increase in life for the die forging over plate for the same 10 ksi maximum cyclic operating stress.

In summary, as the preceding examples illustrate:

(1) The fatigue advantage of forgings can be more than incremental, provided the positive attributes of forgings are tailored to the final part objectives.

(2) The preceding hypothetical calculations show that when forgings are tailored to final part objective, near-net-shape die forgings, in particular, can translate into opportunities for substantial safety margin increase, weight reduction and/or inspection interval increase.

(3) These advantages for forgings can best be realized when planned for at the outset of the design process and entail a concurrent engineering approach, teaming the forging supplier and the user.

Premature specification of an oversized forging to accommodate uncertainties in design and production machining scheduling may entail heavier metal removal than necessary, negating the potential advantage of forged products' working history and contour following grain flow. Fabrication of an optimized forged part, particularly closed-die forgings, with superior fatigue performance can best be accomplished when the final machined part's geometry requirements, and therefrom the forged part's final geometry, have been fully resolved in design. If not fully resolved in design, before fabrication respective final part and forging designs must be as close as possible to this point in the component's manufacturing history. Concurrent engineering is the technology which facilitates this objective.

VII. Full-Scale Fatigue Evaluation of Prototypical Parts

Ideally, manufacturers would like to have data from full component tests of critically selected structural elements to appraise the competitive and airworthiness aspects of various material product form options. With actual part results, durability and damage tolerance models for the various manufactured part options could be validated directly, and the data would be useful for extending the selection criteria to other component scenarios. However, side-by-side full component tests of candidate raw material products fabricated into the same finished components are both costly and rare.

One such study was undertaken to determine the relative resistance to fatigue resulting from aluminum 7XXX alloy net-shape precision forging and hogout technologies.[13] Excerpts from this study are presented in Figures 33 to 35. The program tested fatigue performance of finished components instead of specimens "cut" from the parts themselves, Figure 33. The precision forgings were manufactured and heat-treated to blueprint specifications. The hogout parts were machined to final dimensions from certified heat-treated plate or extruded bar. A number of the components were also tested with and without surface shot peening. A typical result for one of the configurations evaluated is shown in the cumulative failure probability plot, Figure 34, while Figure 35 summarizes data from all configurations tested. Both figures clearly display the superior fatigue resisting capability of the precision forged parts evaluated, which on average doubled the lifetime of their equivalently tested hogout counterparts.

Similar full component fatigue tests of parts machined from heavy section hand and closed-die forgings and parts machined from thick ($\geq$ 4 in.) plate have been recommended[18-22] but have not yet been conducted. In the absence of such full scale test data from thick products, critical appraisal and acceptance of the hand and closed-die forging products' fundamental durability performance advantages rest upon the following train of logic:

- The forging product has inherently smaller and lower ranking life-limiting microfeatures due to the product's fabrication and working history.
- Hand and closed-die forging products' superior microstructure translates directly, through durability and damage tolerance models, to weight savings from higher allowable operating stresses for equivalent lives and/or life cycle cost savings from longer inspection and maintenance intervals.
- Airworthiness of components manufactured from forgings are superior in terms of higher residual strength at comparable lives, longer intervals between inspections and improved manageability of multiple-site fatigue damage (MSD).

VIII. Other Property/Performance Attributes for Aerospace Forgings

A. Static Strength Properties: Static strength remains an important design characteristic and measures the load carrying capability of undamaged structures. Generally, static properties are the subject of "allowables" handbooks, either industry-wide or customer-specific. A number of points regarding the static strength properties of forgings should be noted:

- Forgings have superior short transverse ductility (Figure 36) at strength levels comparable to other thick products of equivalent gages.
- To properly compare properties of shaped die-forgings against those of machined plate hogouts, the properties of the latter should be based on products having adequate gage thickness to machine the end-part.
- Handbook design mechanical properties tend to be unintentionally biased against forgings because of a number of reasons associated with data collection, data reduction, statistical manipulation and subtle differences in the presentation format. For example:
  - Handbook property values for forgings are typically obtained from pooled data that consolidates widely variant shapes and fabrication histories. The resulting statistical scatter unduly penalizes design property values attached to certain forgings. A more level playing field for forgings is created when specification and allowable property determinations are based on product(s) with well defined fabrication history and fewer shapes.
  - Die-forging transverse (not-parallel) handbook values integrate the analog of LT, ST and 45° grain orientations for other products (e.g., plate and extrusion) and are therefore very conservative due to scatter increase in forging data. For improved comparison, forging allowables would be better based on specifications and orientation(s) representative of actual grain flow(s) in the end-part.
  - In Mil-Handbook-5, bearing strength properties of forgings may be penalized by up to 15% vs. other products (plate) due to differences in specimen orientation. Rectification of this difference, including conversion factors, is being sought.

B. Corrosion Performance: Aging aircraft issues and longer service lives have increased the emphasis on enhanced long term corrosion performance of structural components and the materials from which they are manufactured. The following points concern corrosion of thick forged products:

- Hundreds of tests on 7050-T74XX (and other 7XXX-T7X type alloy) forgings performed over many years have shown no difference in corrosion performance for forgings vs. other products in equivalent grain orientations.[53]
- Closed-die forging processes and properly designed closed-die forging shapes have part conforming grain flow that results in less exposed end grain than components made from other products which can:
  - Prevent or delay stress corrosion cracking and other forms of intergranular attack.
  - Impede corrosion damage penetration and reduce size, severity and spread of potentially fatigue life-limiting microfeature[s], such as intergranular fissures and pits.
  - Delay or retard fatigue crack growth originating from corrosion-caused microfeatures.

C. Other Forging Design and Evaluation Issues: Some development is needed to capture the full potential of forgings in this era of focus on affordability, life extension, and supportability:

- Forgings become more attractive when point design approaches are considered instead of "allowables" and empirical factor-based approaches.
- Generic data and efficient analytical procedures are needed to reduce the expense of part design and certification on a case-by-case basis.
- The role of microstructure and its relationship to design and final part certification must be understood and integrated into the design and certification process.
- Good test practices must be followed to minimize the scatter effect.
- Enhanced controls are needed in forging manufacture to assure consistent, high quality, and reproducible end products.
- Component technical demonstrations must be developed to serve as validation of the building blocks and models.
- Optimum forging utilization requires customer and supplier relationships that integrate forging attributes into the design and manufacturing cycle, through techniques such as concurrent engineering.

D. Manufacturing Issues Being Addressed in Forged Products: The aerospace industry's emphasis on acquisition cost, lead-time and flow-time reductions have brought into focus several issues in the manufacturing stream of forgings that affect the hand and closed-die forged products' "user friendliness." The issues being addressed are:

- Machining performance enhancement through capture of advanced immersion quench technology[54, 55]; quench path, stress relieval and machining modeling and process optimization; and optimal metal removal planning.
- Cost, lead-time and flow-time reductions on both tooling and forged products through electronic data interchange; computer aided engineering, artificial intelligence and expert systems; finite element method process modeling; and Concurrent Engineering.
- Product consistency through statistical process control and statistical quality control.
- Product and process change management.

IX. Conclusions

From data and results presented on: (1) microstructural basis for fatigue performance of 7050-T74XX and other high strength aluminum alloy forgings; (2) microstructurally based life prediction tools; (3) forged product-process performance relationships; (4) thick component life prediction of forgings vs. machined plate; and (5) full-scale fatigue evaluation of prototypical parts, the following conclusions can be reached:

A. **Aluminum hand and die-forgings for aerospace applications can be differentiated as a high quality product with performance benefits that can create user preference.**

B. **The fatigue and durability performance advantages of 7050-T74XX and other high strength aluminum alloy forged products are directly correlatable to the reduced size and population (or frequency) of characteristic life-limiting microfeatures.**

C. **The reduced size and population of life-limiting microfeatures in forgings are fundamentally linked with the working histories employed in forging fabrication. Forged product consistency in durability and fatigue performance, and possibly other properties, is linked with selection and execution of optimum working histories and starting stock.**

D. **Microstructurally based durability and damage tolerance models enable the merits of forgings to be conveyed to final airframe components in terms of: weight saving potential from higher operating stress allowables at equivalent lifetime; maintenance cost savings from longer inspection and maintenance intervals at comparable operating stress levels; and/or allowable increase in service lifetime beyond existing design envelopes.**

E. **Parts manufactured as optimally designed forgings offer superior airworthiness capabilities in terms of higher structural residual strength capability at comparable lifetimes, longer intervals between inspections, and improved prevention/control management of widespread damage and its consequences.**

REFERENCES

1. "Airworthiness Standards: Transport Category Airplanes" 14 CFR part 25 of the Federal Aviation Regulations (FAR), Department of Transportation, Federal Aviation Administration.

2. Department of the Air Force, "Aircraft Structural Integrity Program Requirements," Military Standard MIL-STD-1530A, 1975.

3. U. G. Goranson and J. F. McGuire, "Airworthiness," Aerospace Engineering, March 1994, pp. 28-34.

4. U. G. Goranson, "Elements of Structural Integrity Assurance," Fatigue of Aircraft Materials, Proceedings of the Specialists' Conference dedicated to the 65th Birthday of J. Schijve, Delft University Press, the Netherlands, 1992 pp. 275-320.

5. U. G. Goranson, "Damage Tolerance Fact and Fiction," 14th Plantema Memorial Lecture, 17th Symposium of the International Committee on Aeronautical Fatigue, Stockholm, Sweden, June 9, 1993.

6. A. P. Berens, D. S. Morcock, K. E. Brown, J. C. Davis, R. L. Johnson, C. E. Larson and D. J. White, "Handbook of Force Management Methods," AFWAL-TR-81-3079, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, OH, April 1981.

7. J. L. Rudd, J. N. Yang, S. D. Manning, B. G. W. Yee, "Probabilistic Fracture Mechanics Analysis Methods for Structural Durability," in Behavior of Short Cracks in Airframe Components, AGARD Conference Proceedings No. 328, NATO Advisory Group on Aerospace Research and Development, April 1983, pp. 10-1 - 10-23.

8. S. D. Manning and J. N. Yang, "USAF Durability Design Handbook: Guidelines for the Analysis and Design of Durable Aircraft Structures," AFWAL-TR-83-3027, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, OH, August 1988.

9. T. Swift, "Widespread Fatigue Damage Monitoring - Issues and Concerns," 5th International Conference on Structural Airworthiness of New and Aging Aircraft, Hamburg, Germany, June 16-18, 1993.

10. W. Schutz, "Design of Heavy Sections," Fracture Mechanics Design Methodology, AGARD Lecture Series No. 97, AGARD-LS-97, Advisory Group for Aerospace Research and Development, North Atlantic Treaty Organization, 1979, pp. 7-1 - 7-11.

11. "Ultra-Thick Plate Used in 767 AWACS Supports," Aviation Week and Space Technology, March 20, 1995, pg. 34.

12. R.J. Bucci, "Evaluation of Aluminum Plate and Forging Fatigue and Fatigue Crack Growth Behaviors," WESTEC 1992, Society of Manufacturing Engineers, Los Angeles, California, 1992 March.

13. Weight and Cost Benefits of Precision Forgings, Precision Forging Association of Southern California, November 1992.

14. R.W. Bush, R.J. Bucci, P.E. Magnusen and G.W. Kuhlman, Fracture Mechanics Characteristics of High Strength Aluminum Alloy Forgings, Alcoa Forged Products, April 26, 1993.

15. R. W. Bush, R. J. Bucci, P. E. Magnusen, and G. W. Kuhlman, "Fatigue Crack Growth Rate Measurements in Aluminum Alloy Forgings: Effects of Residual Stress and Grain Flow," Fracture Mechanics: Twenty Third Symposium, ASTM STP 1189, American Society for Testing and Materials, Philadelphia, 1993, pp. 568-589.

16. R.W. Bush, "Effects of Starting Stock on Fatigue Quality of 7050-T74 Closed-Die Forgings As Compared to 7050-T745X Hand Forgings, Plate and HFL Plate," Alcoa Laboratories, Report 57-93-20, 1993 July 9.

17. R. J. Bucci, R. W. Bush, A. J. Hinkle, H. J. Konish, M. Kulak, R. H. Wygonik, and G. W. Kuhlman, "High Strength Aluminum Forged Product Durability and Damage Tolerance Capabilities for Weight and Total Life Cycle Cost Saving," Proceedings of the 1995 USAF Structural Integrity Program Conference, Volume II, WL-TR-96-4094, Wright Laboratory, WPAFB, Ohio, August 1996, pp. 681-702.

18. Private Communications, Northrop - Grumman Corporation, 1992 March.

19. Private Communications, Martin - Lockheed Corporation, 1993 June.

20. Private Communications, Boeing Company, 1994 October.

21. Private Communications, McDonnell-Douglas West, 1994 November.

22. Private Communications, McDonnell-Douglas East, 1994 December.

23. J. C. Newman, Jr., E. P. Phillips, M. H. Swain and R. H. Everett, Jr., "Fatigue Mechanics: An Assessment of a Unified Approach to Life Prediction," Advances in Fatigue Lifetime Predictive Techniques, ASTM STP 1122, American Society for Testing and Materials, 1992, pp. 5-27.

24. A. J. Hinkle, P. E. Magnusen, R. J. Bucci and J. L. Rudd, "Fatigue Durability Improvement in Thick-Section Metallic Airframe Parts," White Paper, Appendix, Advanced Metallic Structures Technology Development Plan, Aerospace Industries Association, 1993 March 31.

25. R. J. Bucci, J. R. Brockenbrough, A. J. Hinkle, P. E. Magnusen, and S. M. Miyasato, "The Role of Microstructure on Fatigue Performance of Metallic Alloys," Office of Naval Research, Structural Reliability Progress Report Meeting, Reston, VA, December 13, 1993.

26. P. E. Magnusen, R. J. Bucci, A. J. Hinkle, J. R. Brockenbrough, S. M. Miyasato and H. J. Konish,

"The Role of Microstructure on Fatigue Performance of Aluminum Aerospace Alloys," Annual Contract Briefing: ONR Contract No. N00014-91-C-0128, Office of Naval Research, Arlington VA, January 20, 1995.

27. P. E. Magnusen, R. J. Bucci, A. J. Hinkle, J. R. Brockenbrough, H. J. Konish, and S. M. Miyasato, "The Role of Microstructure on the Fatigue Durability of Aluminum Aircraft Alloys," Final Report, Office of Naval Research Contract N00014-91-C-0128, November 1995.

28. P. E. Magnusen, R. J. Bucci, A. J. Hinkle, J. R. Brockenbrough, and H.J. Konish, "Analysis and Prediction of Microstructural Effects on Long-Term Fatigue Performance of an Aluminum Aerospace Alloy," First International Conference on Fatigue Damage in Structural Materials, Hyannis, MA, September 22-27, 1996 (*accepted, International Journal of Fatigue*).

29. A. F. Grandt, T. D. Scheumann, R. E. Todd and A. J. Hinkle, "Modelling the Influence of Initial Material Inhomogeneities on the Fatigue Life of Notched Components," Fatigue and Fracture of Engineering Materials and Structures, Vol. 16, No. 2, 1993, pp. 199-213.

30. A. J. Hinkle and A. F. Grandt, "Predicting the Influence of Initial Material Quality on Fatigue Life," ICAF'93, International Committee on Aeronautical Fatigue, Stockholm, Sweden, June 7-11, 1993.

31. J. R. Brockenbrough, A. J. Hinkle, P. E. Magnusen and R. J. Bucci, "Microstructurally Based Model of Fatigue Initiation and Growth," FAA/NASA International Symposium on Advanced Structural Integrity Methods for Airframe Durability and Damage Tolerance, NASA Conference Publication 3274, Part 1, September 1994, pp. 71-84.

32. T. H. Sanders, Jr. and J. T. Staley, "Review of Fatigue and Fracture Research on High Strength Aluminum Alloys," Fatigue and Microstructure, American Society for Metals, Metals Park, OH, 1979,
p. 467.

33. C. R. Owen, R. J. Bucci and R. J. Kegarise, "An Aluminum Quality Breakthrough for Aircraft Structural Reliability," Journal of Aircraft, Vol. 26, No. 2, Feb. 1989, pp. 178-184.

34. A. J. Hinkle, P. E. Magnusen, R. L. Rolf, R. L. and R. J. Bucci, "Effect of Microporosity on Notched Specimen Fatigue Life," Structural Safety and Reliability, Vol. 2, Proceedings ICOSSAR'89, Fifth International Conference on Structural Safety and Reliability, American Society of Civil Engineers, New York, NY, 1989, pp. 1467-1474.

35. P. E. Magnusen, R. J. Bucci, A. J. Hinkle, M. E. Artley and R. L. Rolf, "The Influence of Material Quality on Airframe Structural Durability", Advances in Fracture Research, Vol. 2, Proc. Seventh International Conference on Fracture (ICF 7), 1989 March 20-24, pp. 999-1006.

36. P. E. Magnusen, A. J. Hinkle, W. Kaiser, R. J. Bucci and R. L. Rolf, "Durability Assessment Based on Initial Material Quality", Journal of Testing and Evaluation, Vol. 18, No. 6, Nov. 1990, pp. 439-445.

37. P. E. Magnusen, A. J. Hinkle, R. L. Rolf, R. J. Bucci and D. A. Lukasak, "Methodology for the Assessment of Material Quality Effects on Airframe Fatigue Durability", in Fatigue 90, Vol. II, Proc. Fourth International Conf. on Fatigue and Fatigue Thresholds, Materials and Components Engineering Publications Ltd., 1990, pp. 2239-2244.

38. A. J. Hinkle and M. R. Emptage, "Analysis of Fatigue Life Data Using the Box-Cox Transformation," Fatigue and Fracture of Engineering Materials and Structures, Vol. 14, No. 5, 1991, pp. 591-600.

39. P. E. Magnusen, R. J. Bucci, A. J. Hinkle, J. G. Burns, J. L. and Rudd, "Effect of Microporosity on Fatigue Durability of Thick 7050 Aluminum Plate," Proceedings of the 1992 USAF Structural Integrity Program Conference, WL-TR-93-4080, Materials Directorate, Wright Laboratory, Air Force Materiel Command, Wright Patterson AFB, OH, September 1993, pp. 379-410.

40. D. A. Lukasak, B. J. Sova and R. L. Lash, "Thick Product 7050-T74511 Extrusions," AeroMat'94, ASM International's Advanced Aerospace Materials/Processes Conference, Anaheim, CA, June 6-9, 1994.

41. A. J. Hinkle, J. R. Brockenbrough, J. T. Burg, and R. J. Bucci, "Microstructurally Based Performance Models Relevant to Performance of Net-Shaped Parts," AeroMat'95, ASM International's 6th Advanced Aerospace Materials & Processes Conference, Anaheim, CA, May 8-11, 1995.

42. C. Y. Kung and M. E. Fine, "Fatigue-Crack Initiation and Microcrack Growth in 2024-T4 Aluminum Alloys," Metallurgical. Transactions A, Vol. 10A, 1977, pp. 603-610.

43. M. A. Przystupa, "Development of the Microstructure Based Stochastic Life Prediction Models," Final Report, Office of Naval Research Contract N00014-91-J-0199, July 1997.

44. A. Heinz and W. Schelb, "Improvement of Fatigue Strength of AA 7050-T7451," Proceedings of the 4th International Conference on Aluminum Alloys, 1994, pp. 733-740.

45. Templin, R. L., "Fatigue of Aluminum," H. W. Gillette Memorial Lecture, Fifty-Seventh Annual Meeting of the American Society for Testing Materials, 1954.

46. Butz, G. A. and Nordmark, G. E., "Fatigue Resistance of Aluminum and its Products," National Farm, Construction and Industrial Machining Meeting, Milwaukee, WI, September 14-17, 1964.

47. J. N. Yang, S. D. Manning, J. L. Rudd and R. M. Bader, "Investigation of Mechanistic-Based Equivalent Initial Flaw Size Approach," ICAF'95,

International Committee on Aeronautical Fatigue, Melbourne, Australia, May 3-5, 1995.

48. P. J. E. Forsyth, Acta Met., Vol. 11, 1963, p. 703.

49. C. A. Stubbington and P. J. E. Forsyth, J. Institute of Metals, Vol. 90, 1961 to 1962, p. 347.

50. F. D. S. Marquis, "Mechanisms of Formation of Hydrogen Porosity in 7X50 and 2X24 Aluminum Alloys." Effects on Mechanical Behavior, Gas Interactions in Nonferrous Metals Processing TMS Annual Meeting 1996, Minerals, Metals & Materials Society (TMS), Warrendale, PA, USA, 1996, pp. 43-62.

51. A. J. Hinkle, R. Skjong and G. Sigurdsson, "Probability Methods for Durability and Damage Tolerance Analysis," Proceedings of the 1992 USAF Structural Integrity Program Conference, WL-TR-93-4080, Materials Directorate, Wright Laboratory, Air Force Materiel Command, Wright Patterson AFB, OH, September 1993, pp. 302-340.

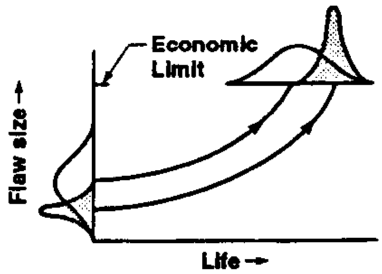
52. R. J. Bucci, "Effect of Residual Stress on Fatigue Crack Growth Rate Measurement," Fracture Mechanics: Thirteenth Conference, ASTM STP 743, American Society for Testing and Materials, 1981, pp. 28-47.

53. Metals Handbook, Volume 13, Corrosion, ASM International, Metals Park, Ohio, USA, 1987.

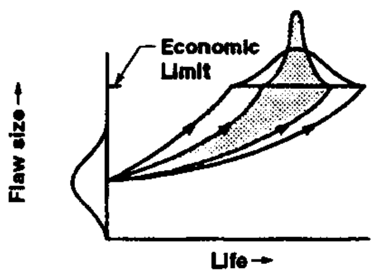
54. J. A. Nicol, E. D. Seaton, G. W. Kuhlman, H. Yu, and R. Pishko, "New Quenchant for Aluminum," Advanced Materials & Processes, Vol. 149, no. 4, April 1996, pp. 40S-40V.

55. G. W. Kuhlman and E. D. Seaton, "Enhancing Machining Performance of Aluminum Forged Products," Metal Heat Treating, Penton Publishing, Inc., Cleveland, OH, USA, January/February 1996.

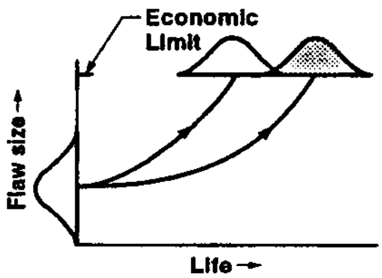
56. J. H. Elsner, E. P. Kvam and A. F. Grandt, "Modeling and Microstructure Analysis of Fatigue Initiation Life Extension by Reductions in Microporosity," Metallurgical and Materials Transactions A, Vol. 28A, May 1197, pp. 1157-1167.



(a) Reduce initial flaw size population.
(Quality increase)



(b) Reduce crack growth variability.
(Product/test consistency)



(c) Increase crack growth resistance.
(Alloy/part design)

Figure 1: The forging process is consistent with a classical durability improvement scenario.

- In the above figure, durability is defined as the ability to prevent and control origination and growth of cracks to dimensions of unfavorable economic consequence.

- The Figure portrays three routes to durability performance enhancement:
  (a) Decrease both the size and number of potentially fatigue crack initiating microfeatures (e.g., reduced microporosity/better corrosion resistance).
  (b) Reduce variability of crack growth processes (product consistency).
  (c) Select an alloy and/or part design to retard corrosion and growth of cracks.

- Aspects of forging microstructure and process history are well aligned with the above durability improvement scenarios.
  - Forging's high degree of mechanical work can effectively heal microporosity, and/or break up deleterious remnants of the original cast structure.
  - Forging's contour-following grain flow capability enables placement of the optimal corrosion and fatigue resisting microstructure at the part surface (i.e., where it is needed the most).
  - The mechanical working benefits of the forging process can be imparted in more than one direction.

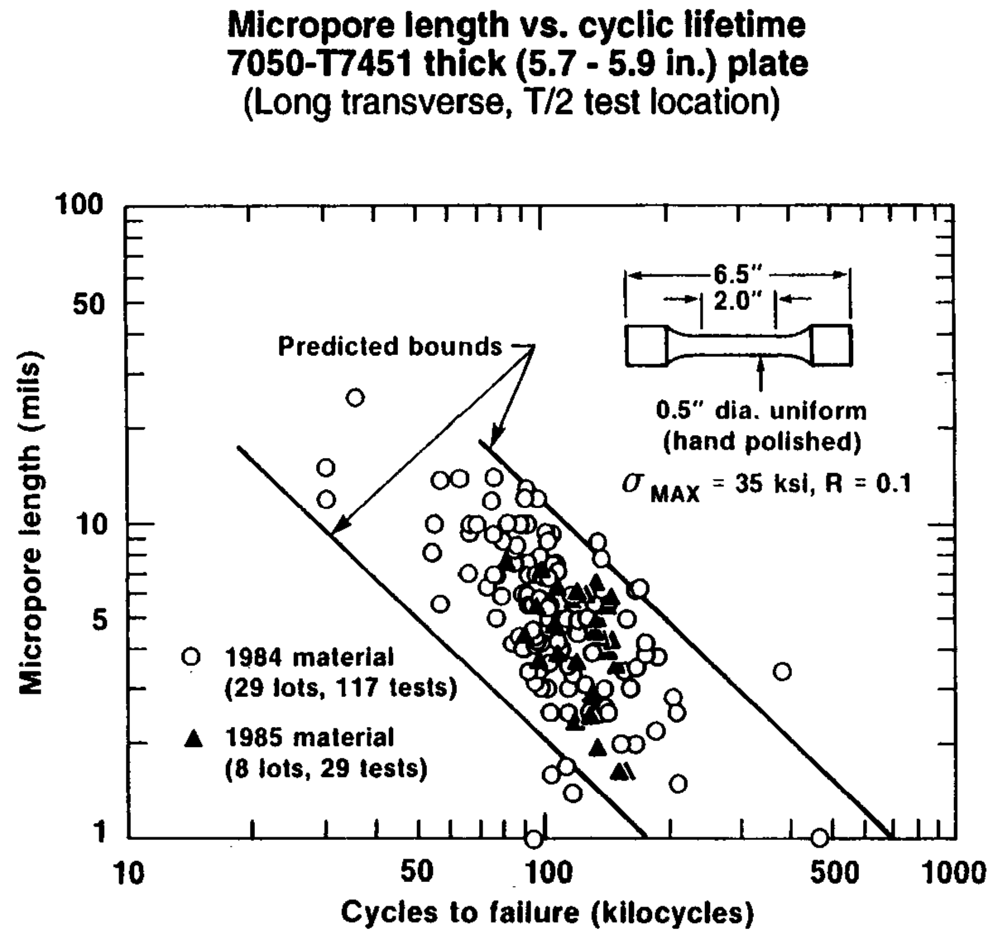
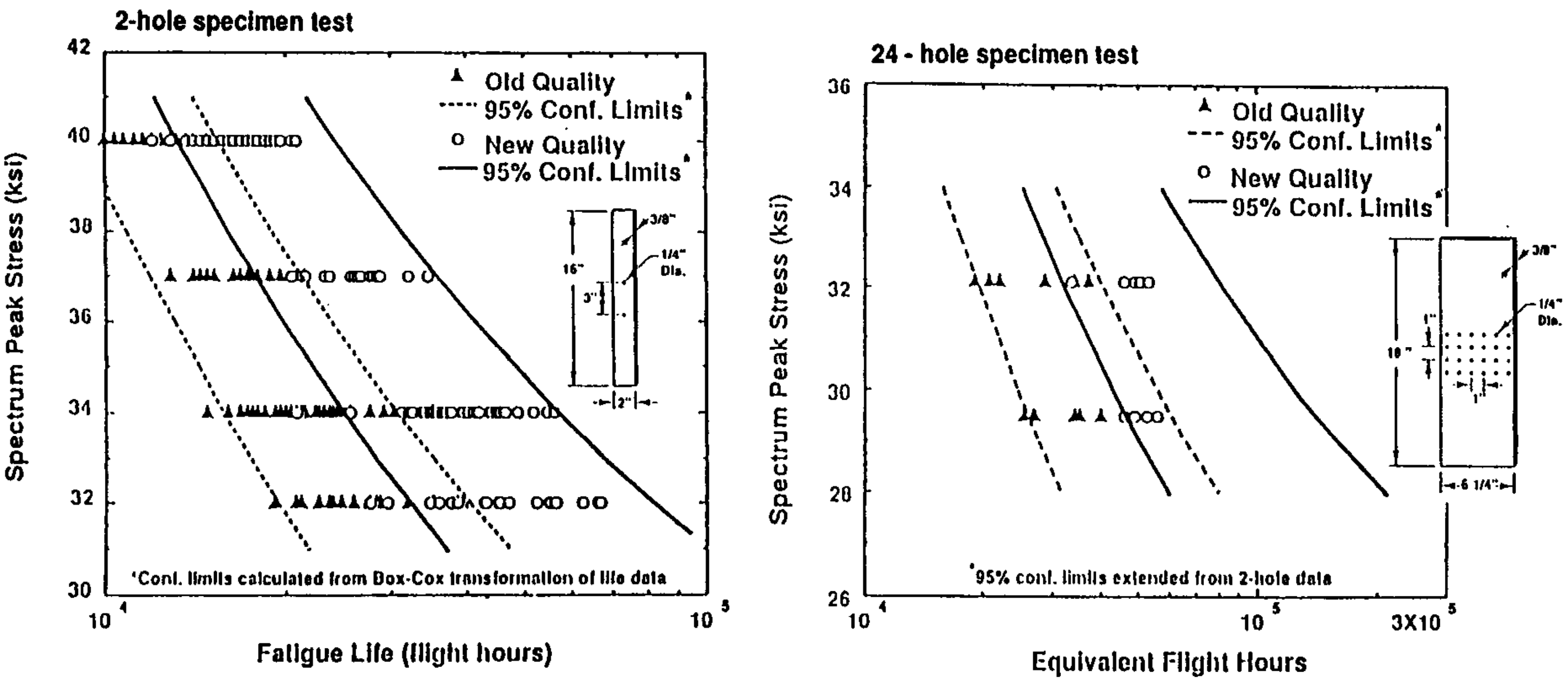
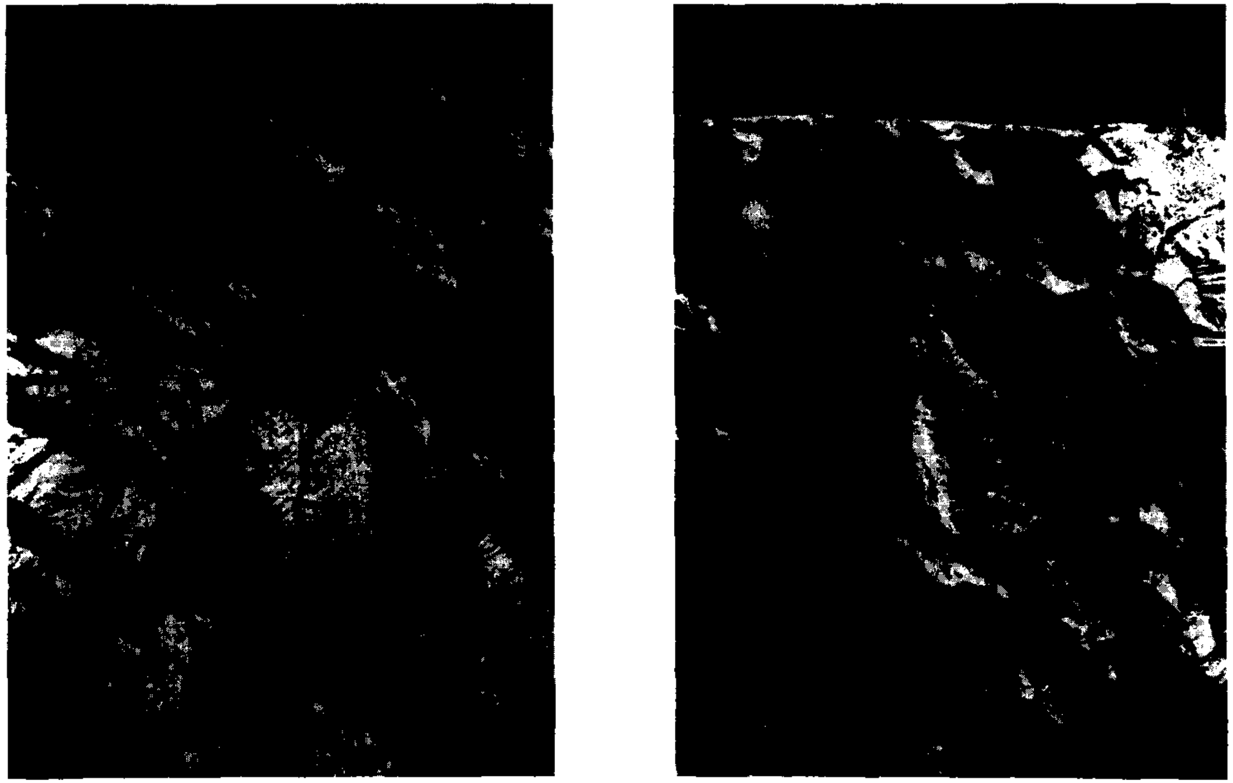


Figure 2: Alcoa historical data shows that smooth specimen cyclic lifetime depends on scale of the fatigue life-limiting microfeatures.



Effect of metal quality on open hole specimen fatigue performance
7050-T7451 thick plate (5.7 in.), long transverse, T/2 test location
F-16 400 hr. lower wing spectrum (8000 hrs. = 1 service lifetime)

Figure 3: The metal quality effect was confirmed in USAF tests employing production machining practices and representative loadings.



0.002 in.

0.002 in.

1980 pedigree plate
Max. pore length = 0.013 in.

1990 pedigree plate
Max. pore length = 0.006 in.

The figures show typical crack-initiating micropores linked to failure of smooth fatigue specimens taken from the T/2 location of 7050-T7451 thick (5.7 in.) plate representative of 1980 and 1990 commercial pedigrees. During this timeframe virtually all aluminum manufacturers had some effort in place to control porosity content in thick aerospace plate. Note that the material of lesser pedigree (left) had the larger failure initiating pore, and a correspondingly lower fatigue strength capability.

Figure 4: Microporosity has been consistently linked to fatigue limitations of thick 7050-T7451 plate.

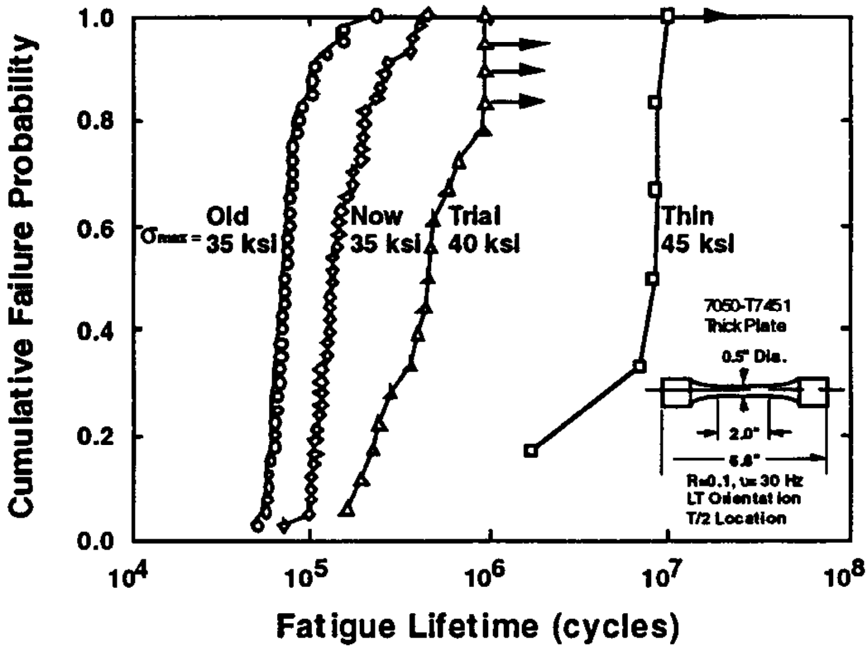
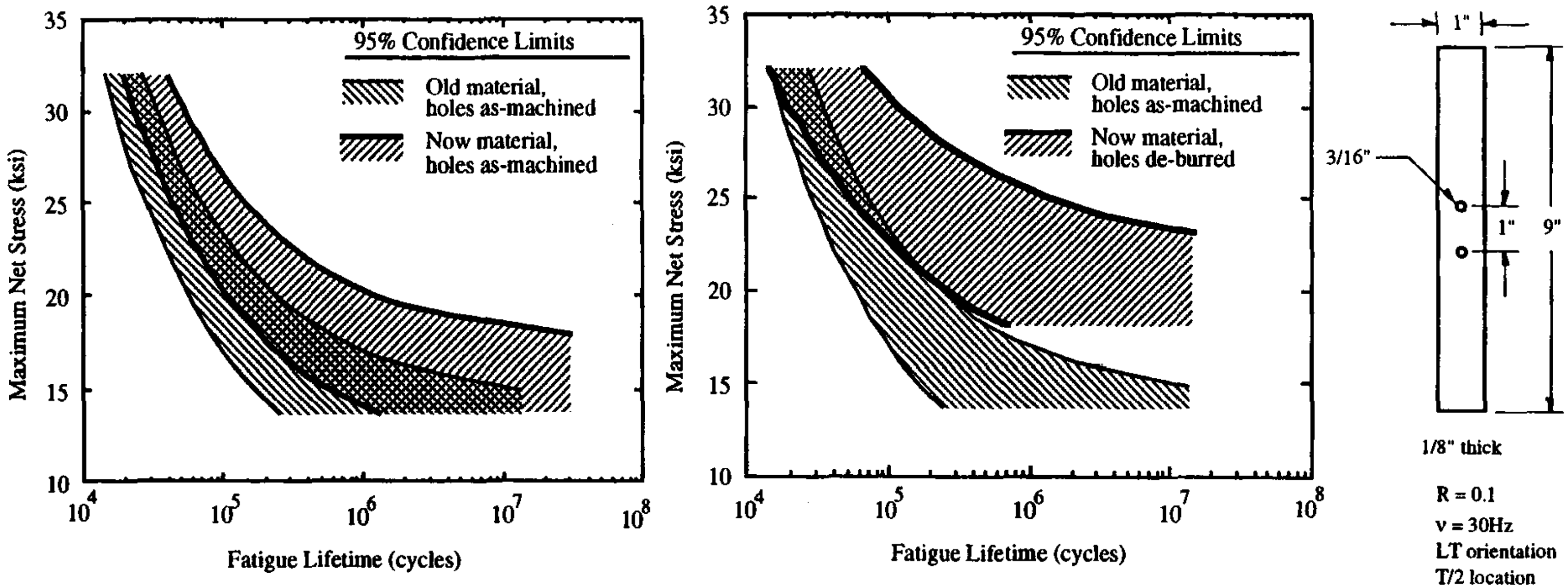


Figure 5: Fatigue reliability can be improved through microstructure refinement

- The Figure shows cumulative fatigue failure probability plots for four variants of 7050-T7451 plate processed to contain progressively lower amounts of microporosity:
  - Old: 1980 pedigree thick (5.7 in.) plate
  - Now: 1990 pedigree thick (5.7 in.) plate
  - Trial: special process, low porosity thick (5.7 in.) plate
  - Thin: 1990 pedigree thin (1 in.) plate
- All four plate variants above were fabricated on a commercial plant scale.
- The fatigue enhancement potential of quality-improved materials is more than incremental.
- Use of fatigue screening tests has reached specification status; thereby enabling airframers to capture the value of higher quality products.



Open hole fatigue performance of 7050-T7451 thick plate increases with metal pedigree; hole deburring doubles the improvement.

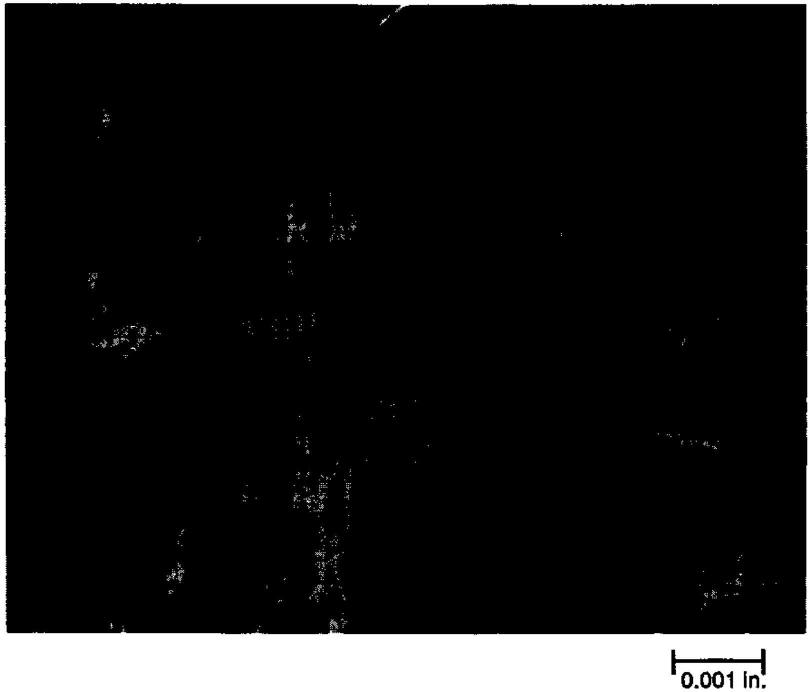
old material: 1980 commercial production practice
now material: 1990 commercial production practice

Figure 6: Microstructural effects on the fatigue performance of thick product are not masked by those of geometric features or machining.

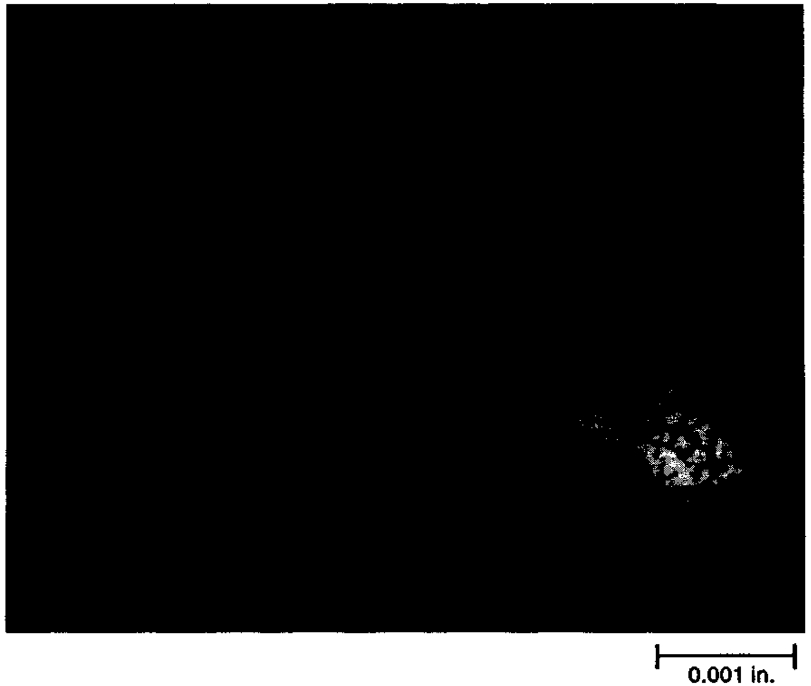
1990 pedigree plate
Pore size = 0.005 in.

Low porosity plate
Pore size = 0.0015 in.

Figure 7: Typical smooth specimen fatigue fractures of 1990 and low porosity thick 7050-T7451 plate variants showing microporosity at the failure origin.

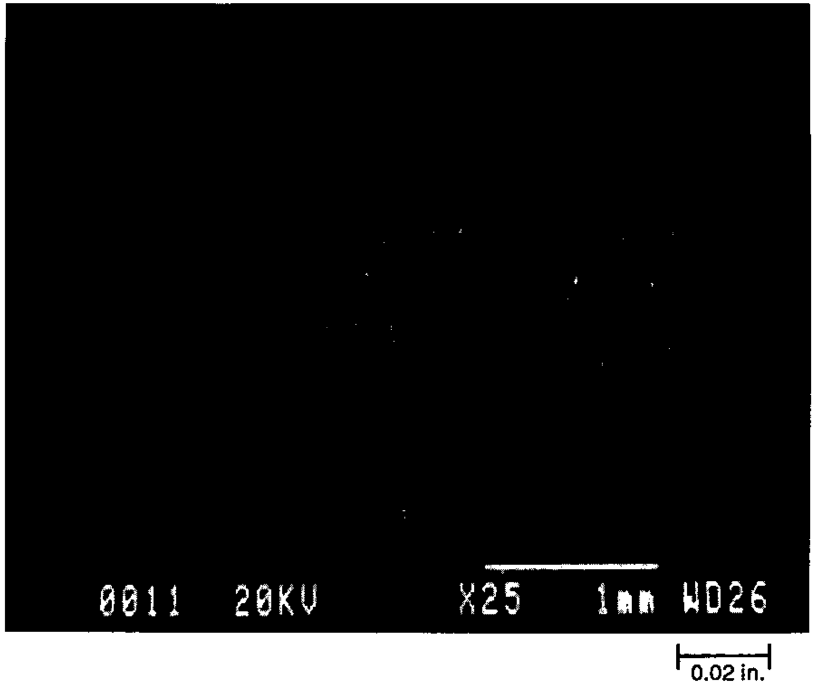


1990 pedigree plate
Pore size = 0.0044 in.

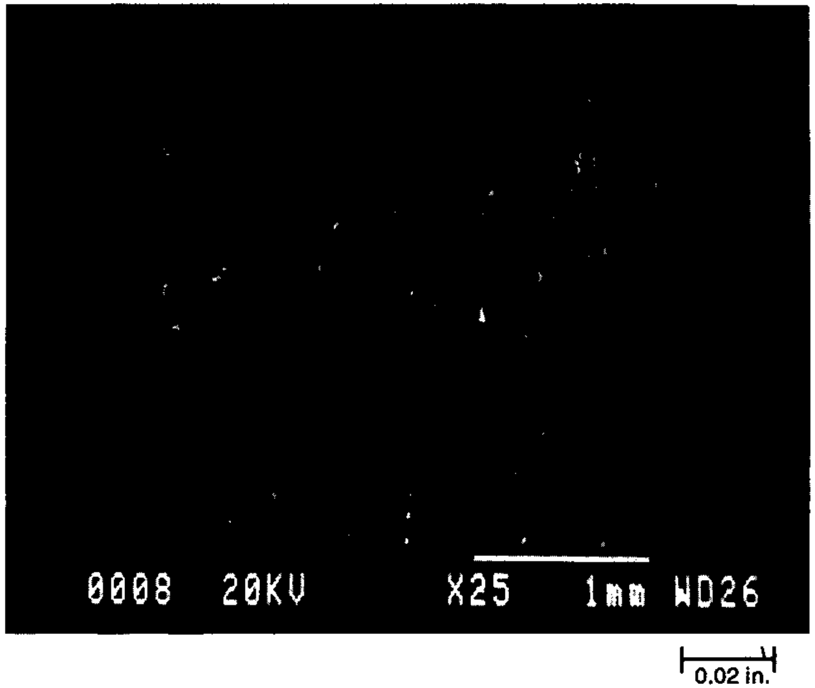


Low porosity plate
Const. part. size = 0.0019 in.

Figure 8: Typical open-hole specimen fatigue fractures of 7050-T7451 thick plate showing microporosity at the failure origin of the 1990 plate variant and a constituent particle at the origin of the low porosity variant.

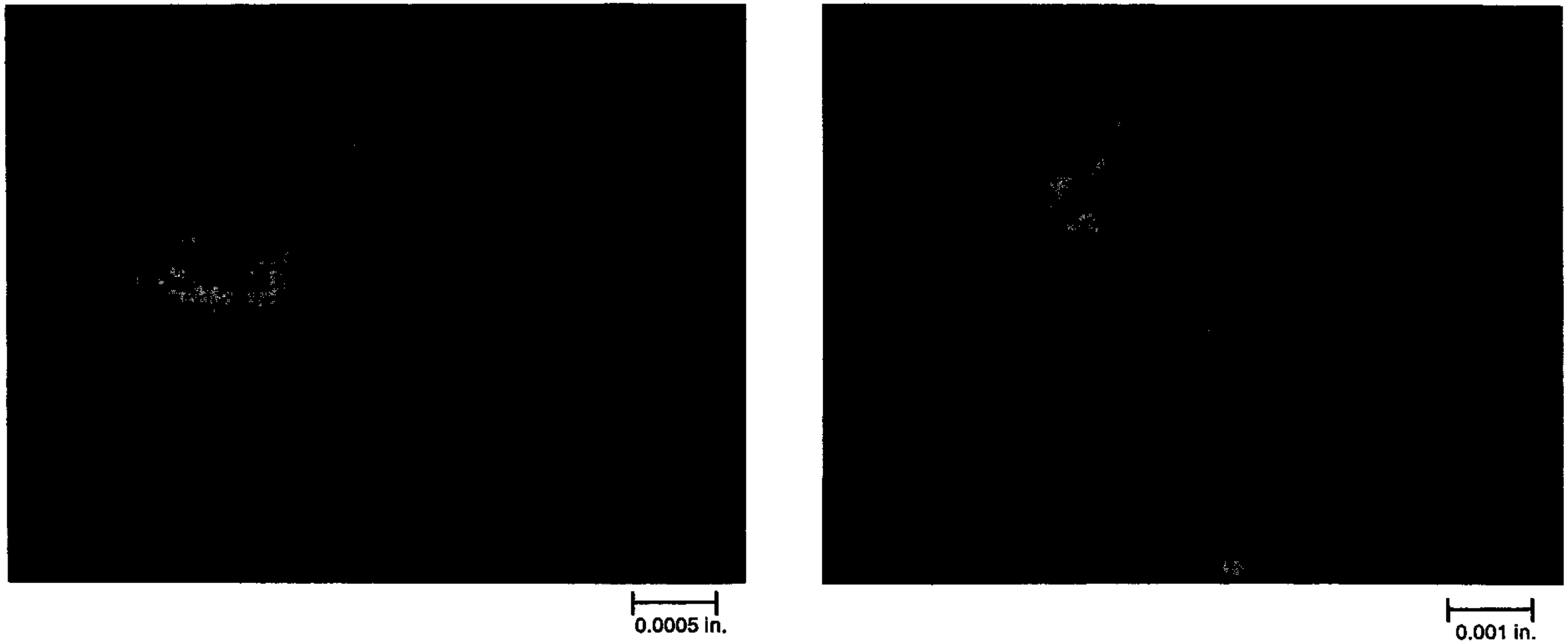


1990 pedigree plate



Low porosity plate

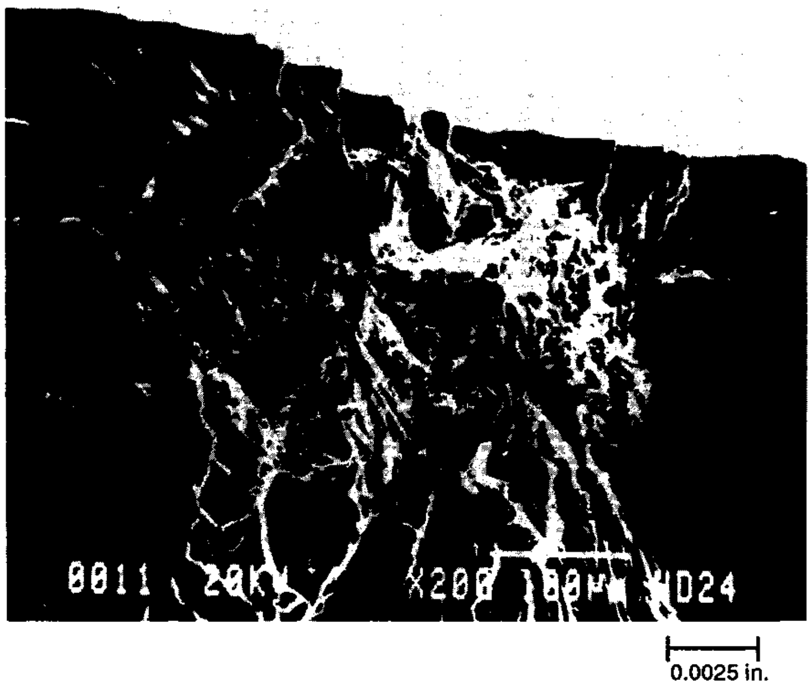
Figure 9: Backscattered SEM images of constituent particles located in the hole bore of open hole fatigue specimens from the 1990 and low porosity 7050-T7451 thick plate variants.



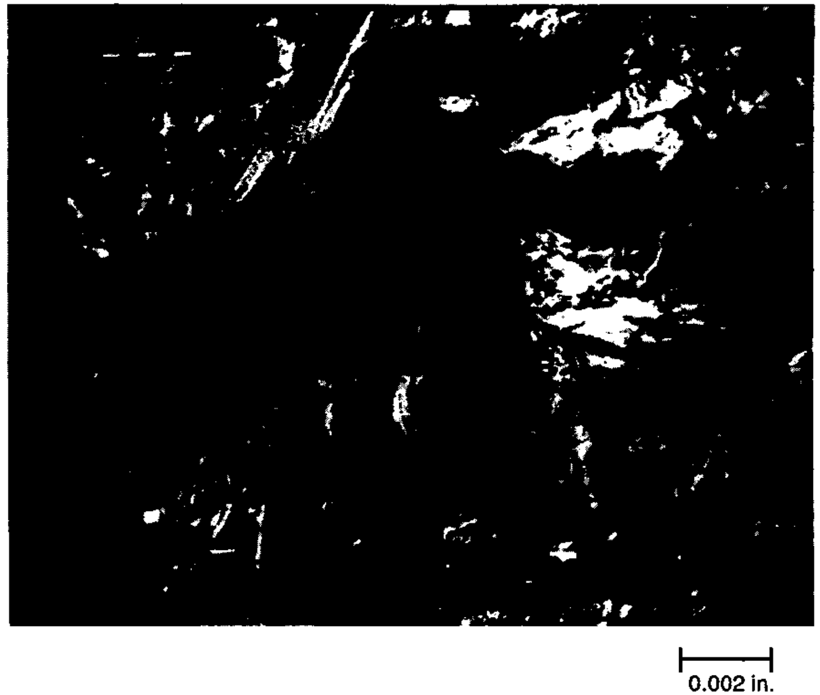
Const. particle size = 0.0010 in.

Const. particle size = 0.0009 in.

Figure 10: Open-hole specimen fractures from the thin (1 in.) 7050-T7451 plate variant showing constituent particles as the failure origin.



Low particle plate, T/4



1 in. plate, T/2

Figure 11: Open-hole specimen fractures showing Stage I type initiation at the origin of fatigue failure in high purity (low particle) plate and thin (1 in.) 7050-T7451 plate.

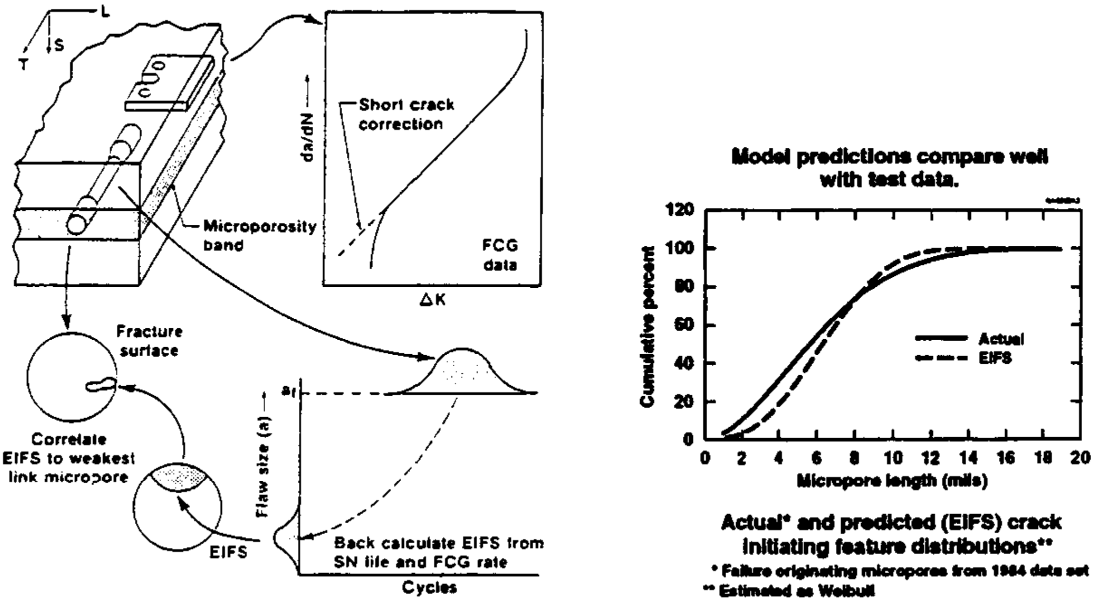


Figure 12: Predictive models are available that accurately link fatigue life to crack-originating microfeatures and vice-versa.

- Recent Alcoa modeling efforts* to relate microstructure and fatigue performance have produced significant results.
  - Features of microstructure which govern fatigue life have been identified and statistically characterized for several material variants and specimen types.
  - Links between life-governing microfeature populations and fatigue performance have been defined, modeled and validated.
  - Size distributions of crack initiating microstructural features can be measured directly from fracture surface examinations, back-calculated from lifetime data, or scaled from random plane microstructure.
  - The effects of the initial inhomogeneity size, shape, and location distributions on specimen fatigue life distributions have been demonstrated and analytically predicted.
  - Characteristic microstructural feature distributions derived from basic coupon tests has been applied to predict structural element performance.

- Penetration of corrosive attack found in moderate to severely corroded metallic aircraft structure is comparable to, and often exceeds, the dimensions of fatigue life-limiting microfeatures commonly associated with failure in pristine element tests. (typically, 0.5 to 20 mils in the latter).

* Support of these modeling efforts by the Office of Naval Research (ONR Contract N00014-91-C-0128) is gratefully acknowledged.

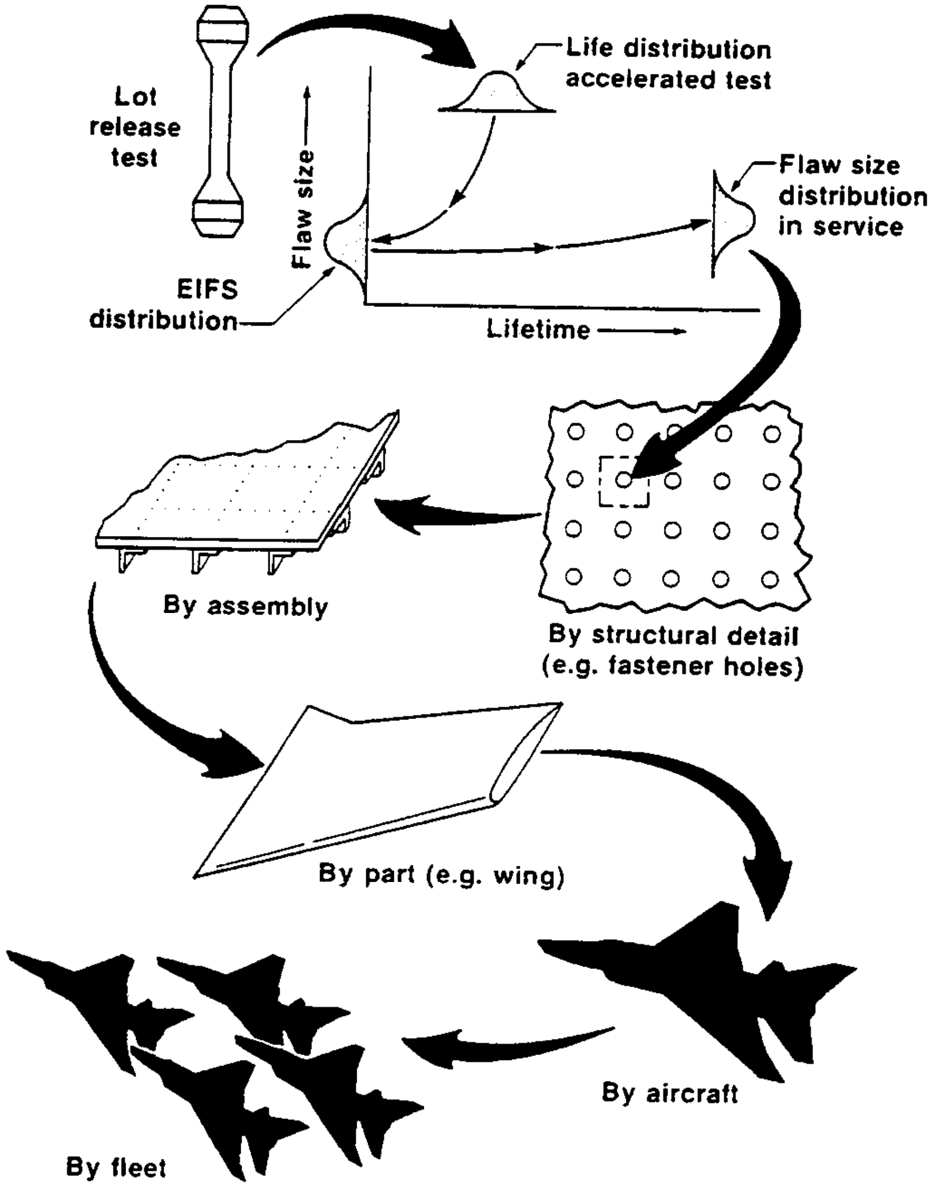
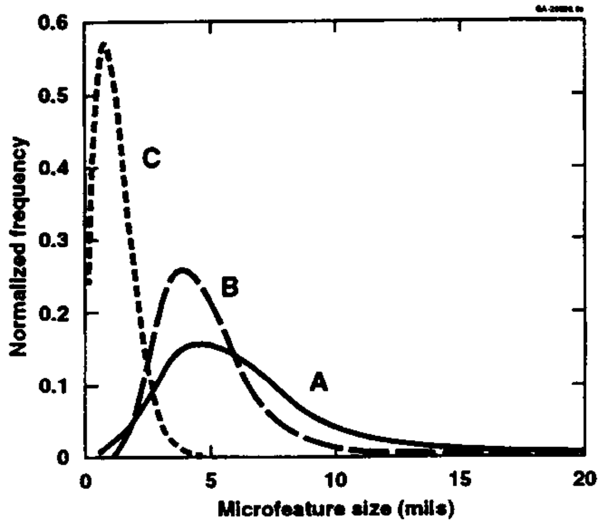


Figure 13: A coupon to component transfer model has been devised based on life-limiting feature population.

Life-limiting microfeature distributions in three material variants.



Microfeature distribution can be related to potential for multi-site damage.

	Calculated no. flaw exceedances per 1000 fastener holes*					
Flaw size (in.)	one lifetime**			two lifetimes**		
	A	B	C	A	B	C
0.03	196	3	0	850	850	44
0.05	2	0	0	633	499	1
0.1	0	0	0	195	3	0
0.2	0	0	0	3	0	0

* Calculated after Manning and Yang
** Fighter lower wing spectrum

Figure 14: Probabilistic fracture mechanics models can be used to study the effect of microfeature distribution on structural performance.

- Consider the example above from 7050 plate. Three different equivalent initial flaw size (EIFS) distributions (linked to microstructure of three 7050 process variants) are shown in the figure on the left. For each of these crack starting feature distributions, the expected number of cracks exceeding a given size per 1000 fastener holes was calculated for one and two lifetimes of anticipated service loadings. It can be seen that the distribution linked to process variant C has the lowest probability of developing multi-site fatigue damage.

- The lack of EIFS distribution data for representative materials and structures presently constitutes a major hurdle to broader application of these tools in design and risk assessment processes.

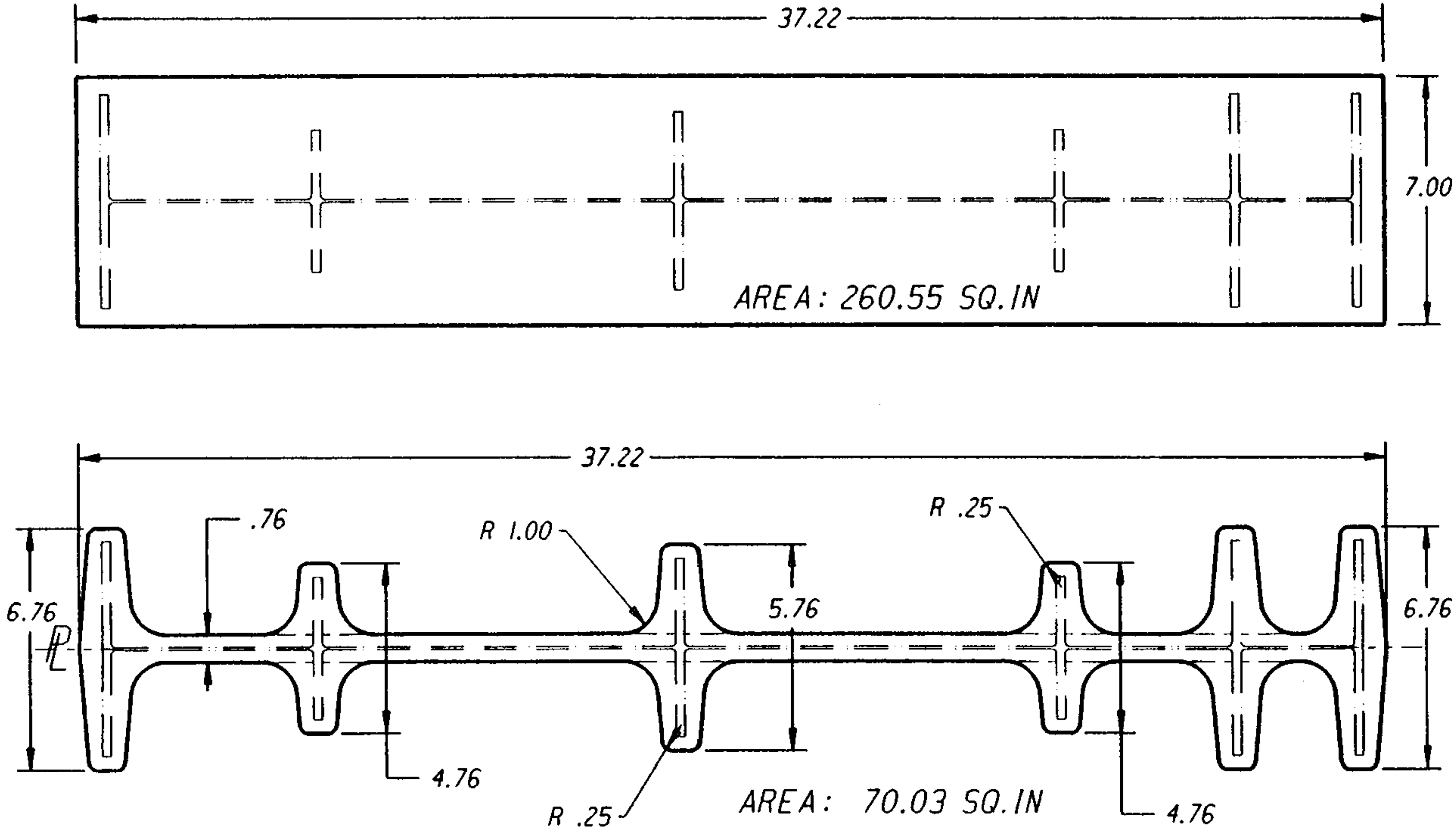
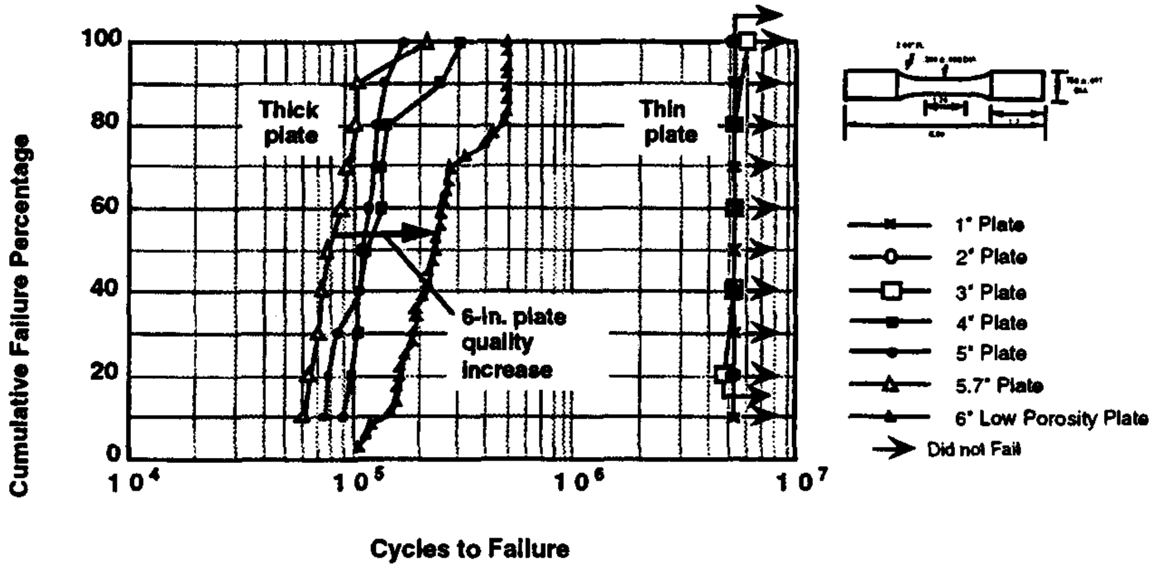


Figure 15: Closed Die Forging vs. Thick Plate Raw Material Product Comparison for a Typical Machined Web-Rib Airframe Component.



Cumulative Fatigue Failure Distributions
7050-T7451 Plate (1 - 6 in. thk.)
(Max. stress = 40 ksi, R = 0.1, kt = 1, long-transverse, T/2 test location)

Figure 16: Plate fatigue performance is affected by product thickness and manufacturing pedigree.

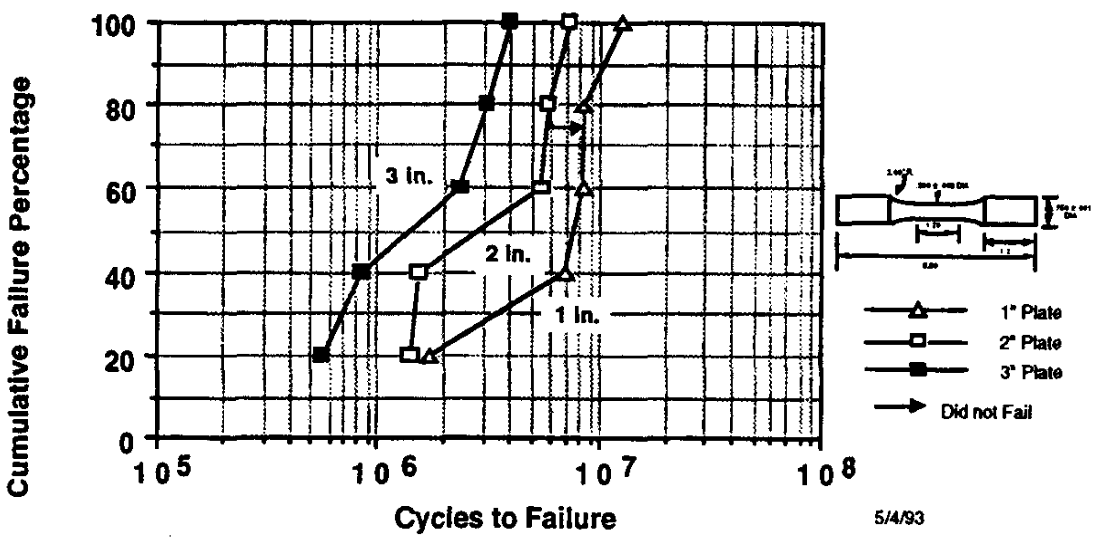
- Engineers have known for some time that microporosity can shorten life of cyclically loaded components by accelerating the initiation of fatigue cracks.

- In thick plate, microporosity persists through to the final product where deformation during rolling is often insufficient to effectively break-up and/or heal porosity present in the starting ingot.

- Increased mechanical work in rolling to thinner plate gages decreases both the microporosity size and volume fraction, and hence fatigue resistance is improved over that of thick plate.

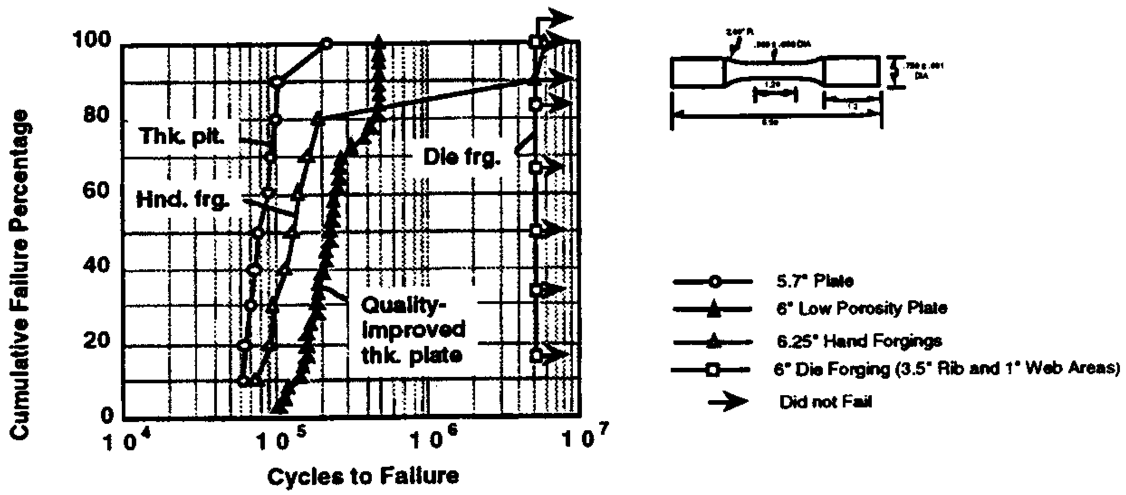
- Thick plate fatigue improvement potential has been demonstrated through control of manufacturing processes to curb microporosity.

- Because of the loss of inherent crack stoppers in consolidated parts, new cost reduction initiatives seeking to replace conventional assemblies with fewer, thick parts must consider control of microporosity as a fatigue crack preventive measure.



Cumulative Fatigue Failure Distributions
7050-T7451 Plate (1 - 3 in. thk.)
(Max. stress = 45 ksi, R = 0.1, kt = 1, long-transverse, T/2 test location)

Figure 17: Fatigue strength dependency on plate thickness extends to thin (≤ 3 in.) gages.



Cumulative Fatigue Failure Distributions
7050-T74XX Thick Products
(Max. stress = 40 ksi, R = 0.1, kt = 1, long-transverse, T/2 test location)

Figure 18: Product form (forging or plate) affects material fatigue performance.

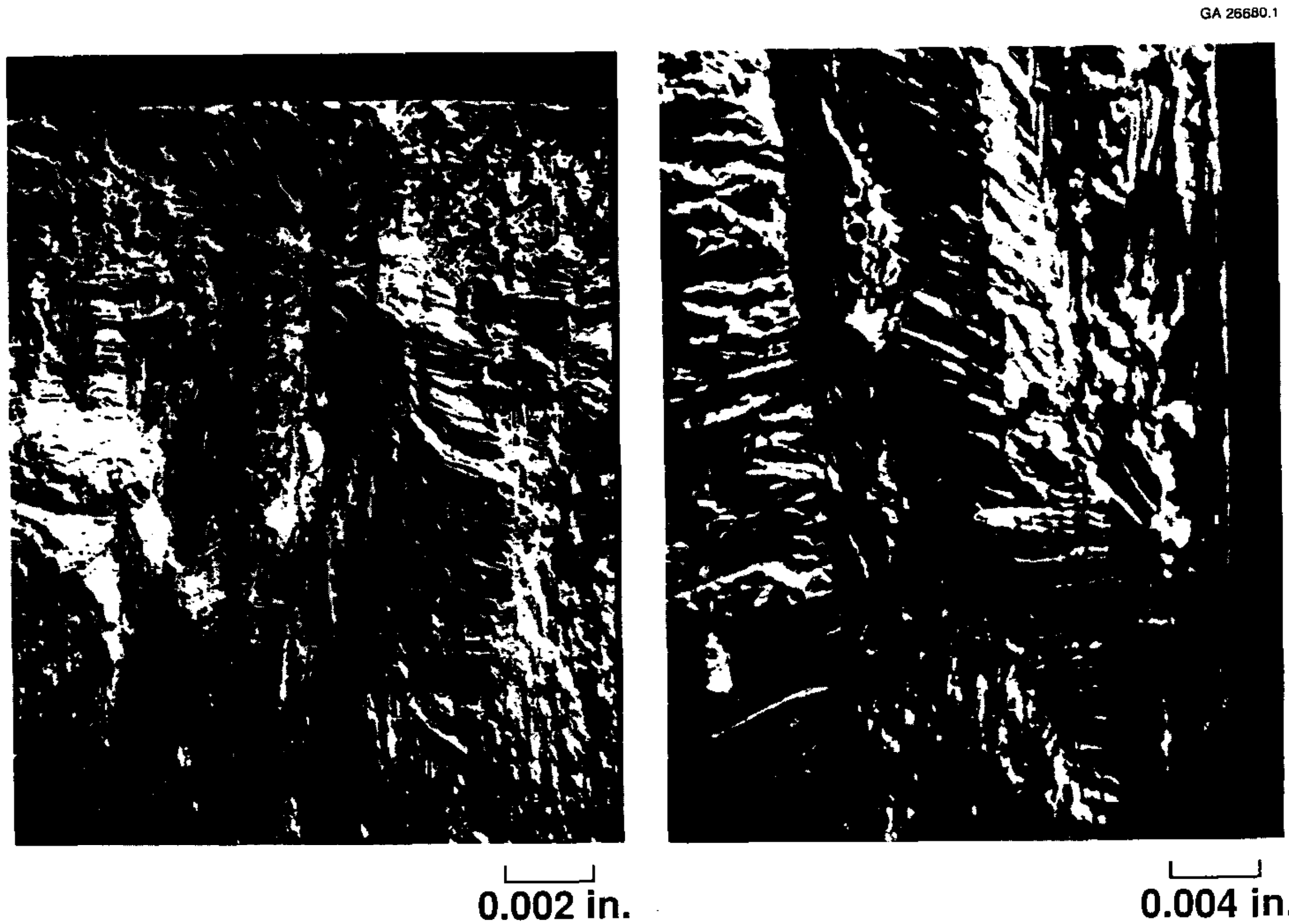
Die forging fatigue resistance is superior to that of thick plate product needed to machine the same part.

- The fatigue resistance of heavy section die-forgings is typically much greater than that of thick plate product needed to machine the same part.

- Hand forging fatigue resistance is generally equal to or better than that of standard (1990 pedigree) thick plate, but somewhat inferior to that of the process improved low porosity plate.

- Hand forging fatigue performance is also limited by microporosity, and like plate, enhancement should also be possible through implementation of improved processing methods for control of microporosity.

- In the > 6" product thickness range hand forging fatigue resistance generally remains stable, whereas plate fatigue resistance generally degrades with thickness increase.



The figures show partially healed micropores found on fracture faces of short-lived specimens taken from a 6 in. thick 7050-T7452 hand forging.

Figure 19: Microporosity is sometimes found to be the failure-initiating microfeature in tests of smooth fatigue specimens taken from thick hand forgings.

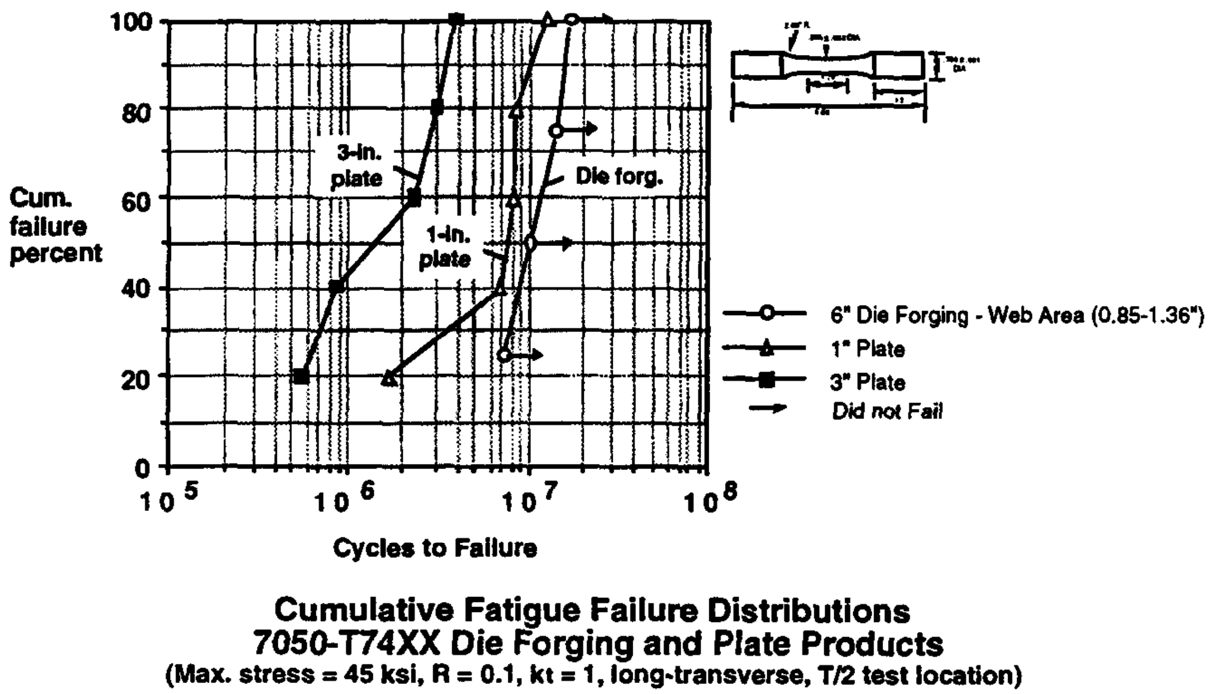


Figure 20: Cyclic lifetimes of specimens from heavy-worked die-forgings exceed those of specimens from thin plate.

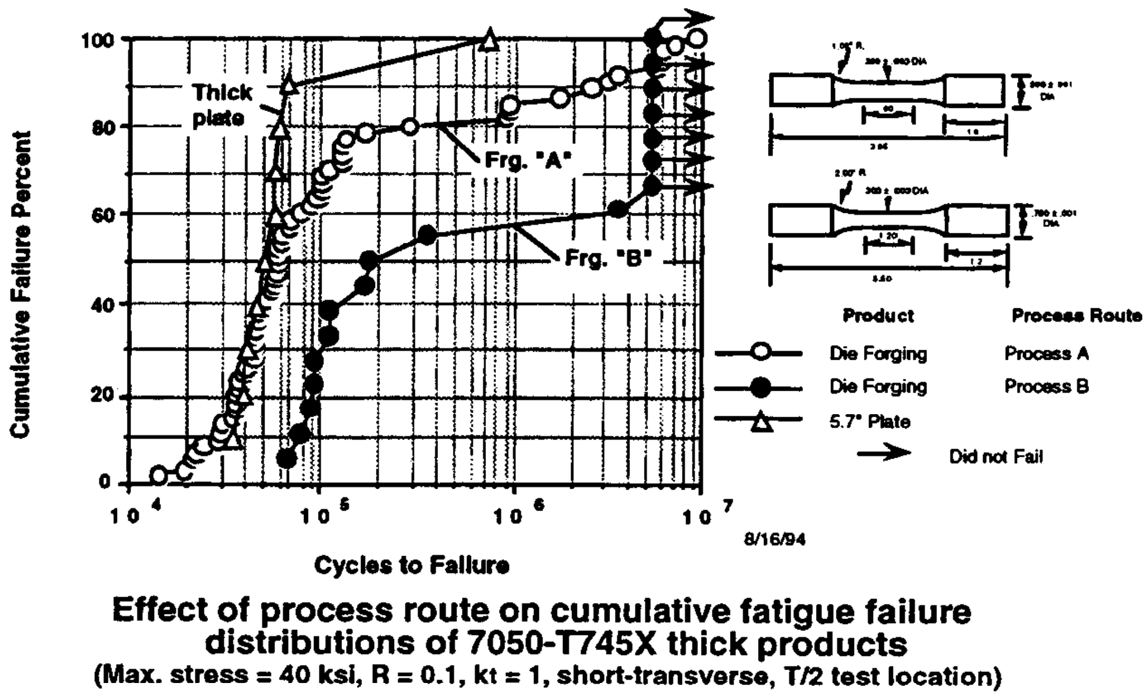


Figure 21: Process route affects forged part performance.
More sophisticated process route B increases fatigue performance.

- Forging process "B" employs a greater number of manufacturing steps to control microstructure (viz., microporosity), and thereby allow higher fatigue resistance to be attained.
- Die-forgings, and to lesser degree hand forgings, offer a variety of alternative paths to arrive at the same shape part shape. Optimal use of the forgings will result when user and vendor blend expertise and tune their respective manufacturing processes to requirements of the end-part. Such relationships may be necessary to offset the negative implications of forgings higher initial cost.
- Much recent progress has been made in developing modeling linkages among processing, microstructure and performance. These models are being used to challenge conventional airframer material selection processes to consider the benefit potential of quality-improved materials to gain an overall end component cost/performance advantage.

Comparison of 7050-T74XX products open hole fatigue performance for thick plate (5.7 in.) and die forging (6.0 in.) and thin (1.0 in.) plate

(LT orientation, T/2 test location, R = 0.1)

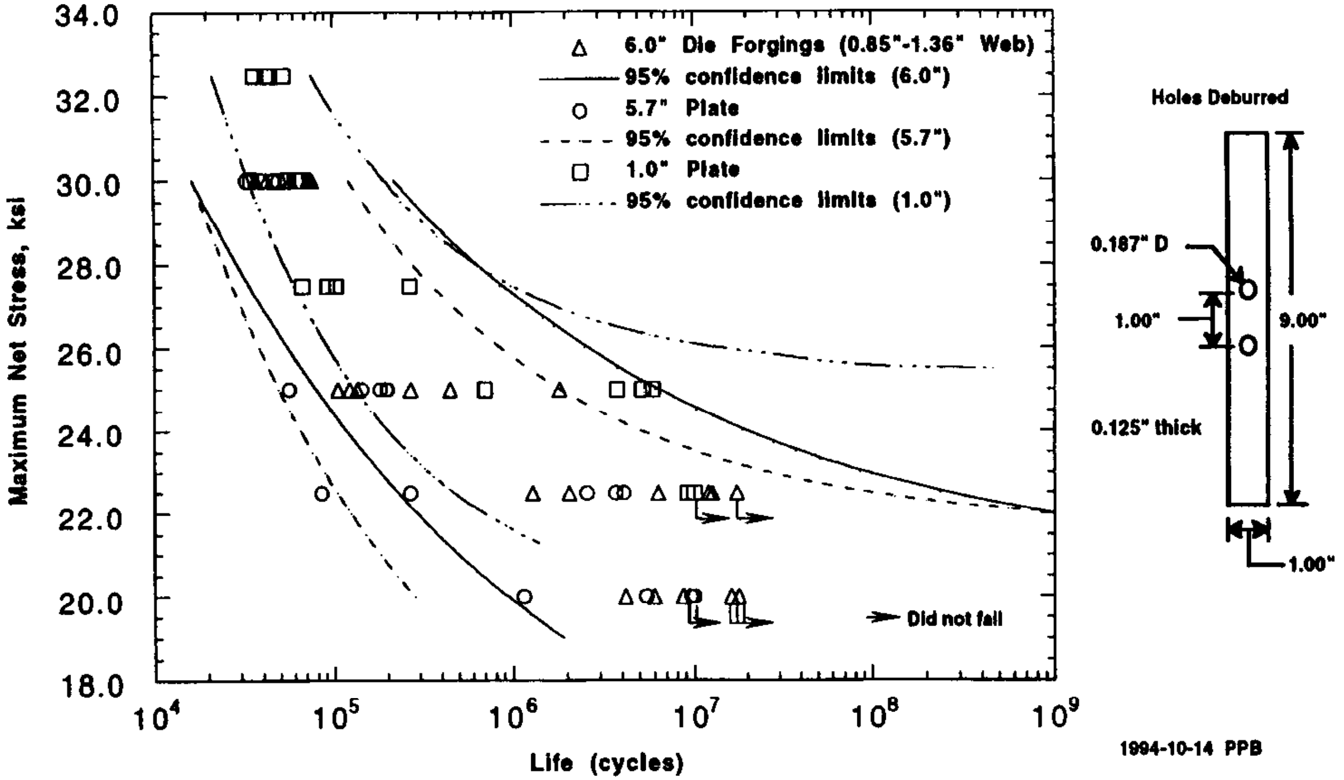


Figure 22: Smooth fatigue rankings prevail in the presence of a design detail.

Open hole fatigue performance of 1 in. plate and die forgings are superior to that of thick plate.

Const.-load-amplitude FCG data for various thicknesses of 7050-T7451 plate
(L-T orientation, R = 0.33, high humidity air)

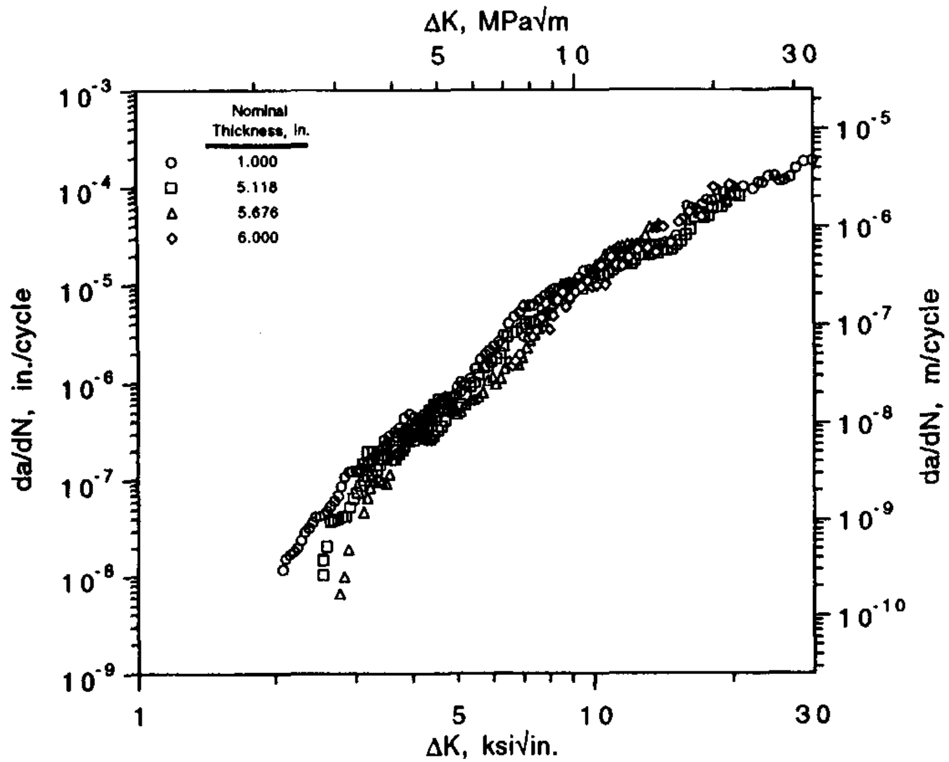


Figure 23: Plate fatigue crack growth rate properties are independent of product thickness.

No effect of product thickness holds in all three major test orientations (L-T, T-L & S-T).

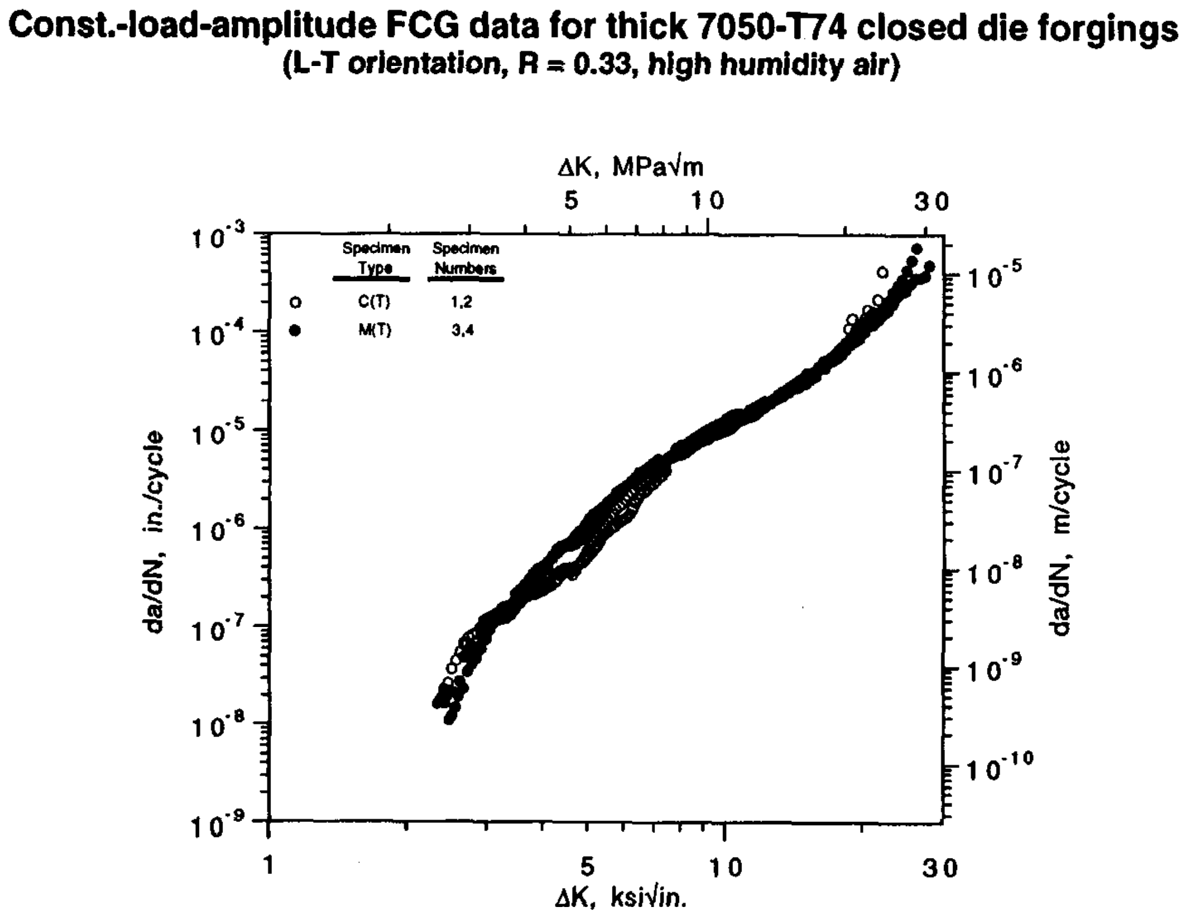


Figure 24: Fatigue crack growth rate properties of 7050 forging and plate are similar.

FCGR data from thick, incompletely stress relieved 7050-T74X hand forgings
(S-L orientation, R = 0.33, high humidity air)

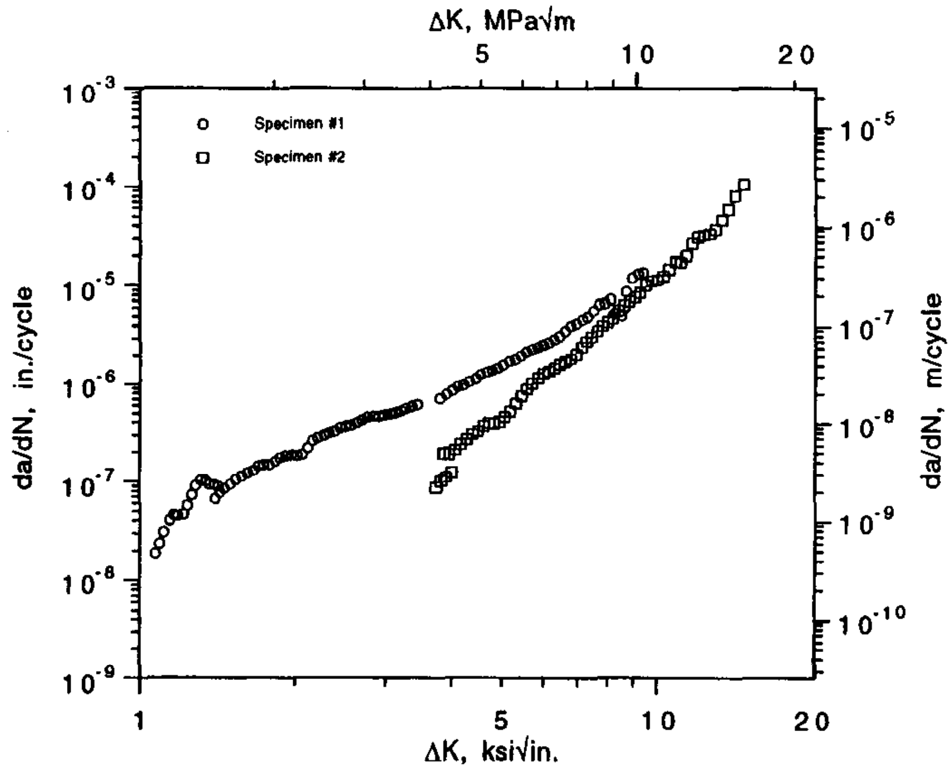


Figure 25: The industry's forging FCGR data base is tainted by residual stress induced artifacts.

The forging residual stress effect is magnified in coupon tests.

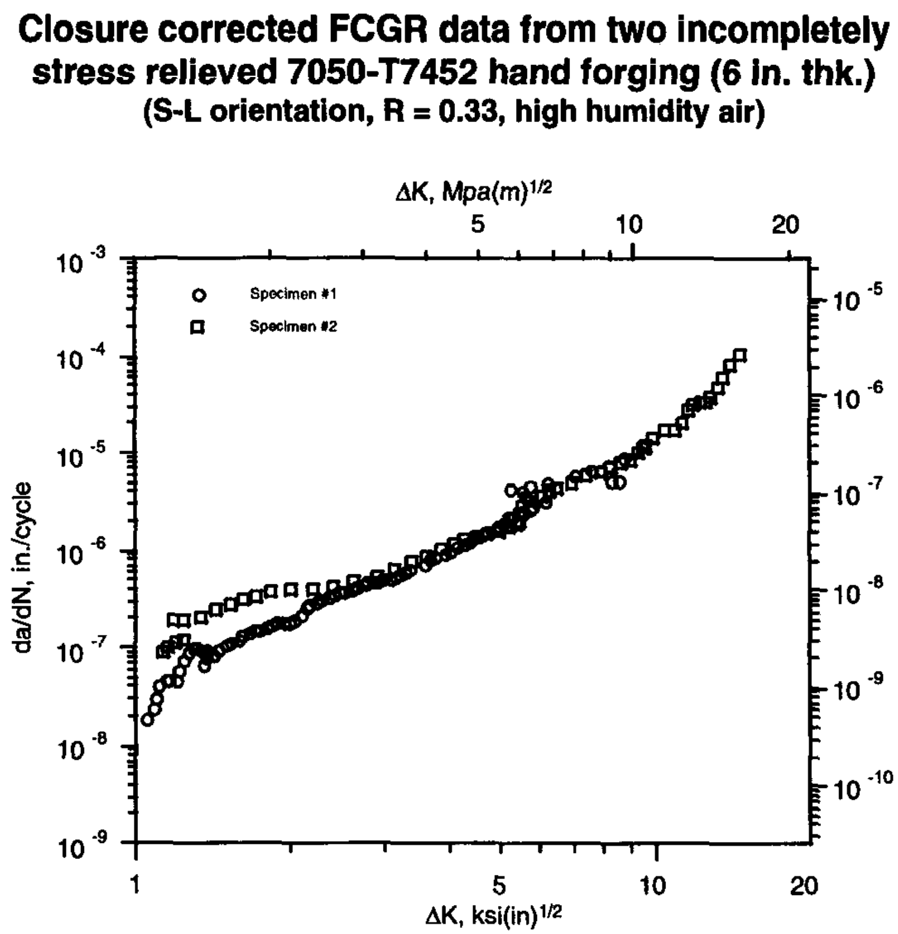


Figure 26: A corrective practice has been devised to remove residual stress bias from FCGR data.

FCGR data from residual stress containing specimens are collapsed into a single curve when the crack closure based corrective practice is applied.

Closure based FCGR data for various thicknesses of 7050-T7451 plate
(S-L orientation, R = 0.33, high humidity air)

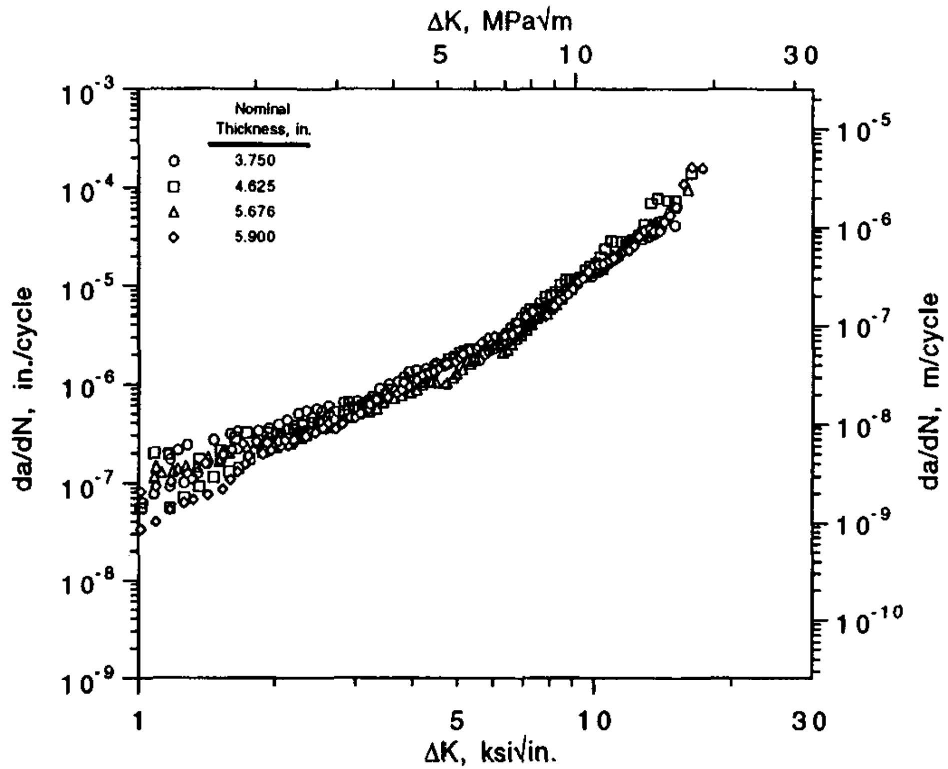
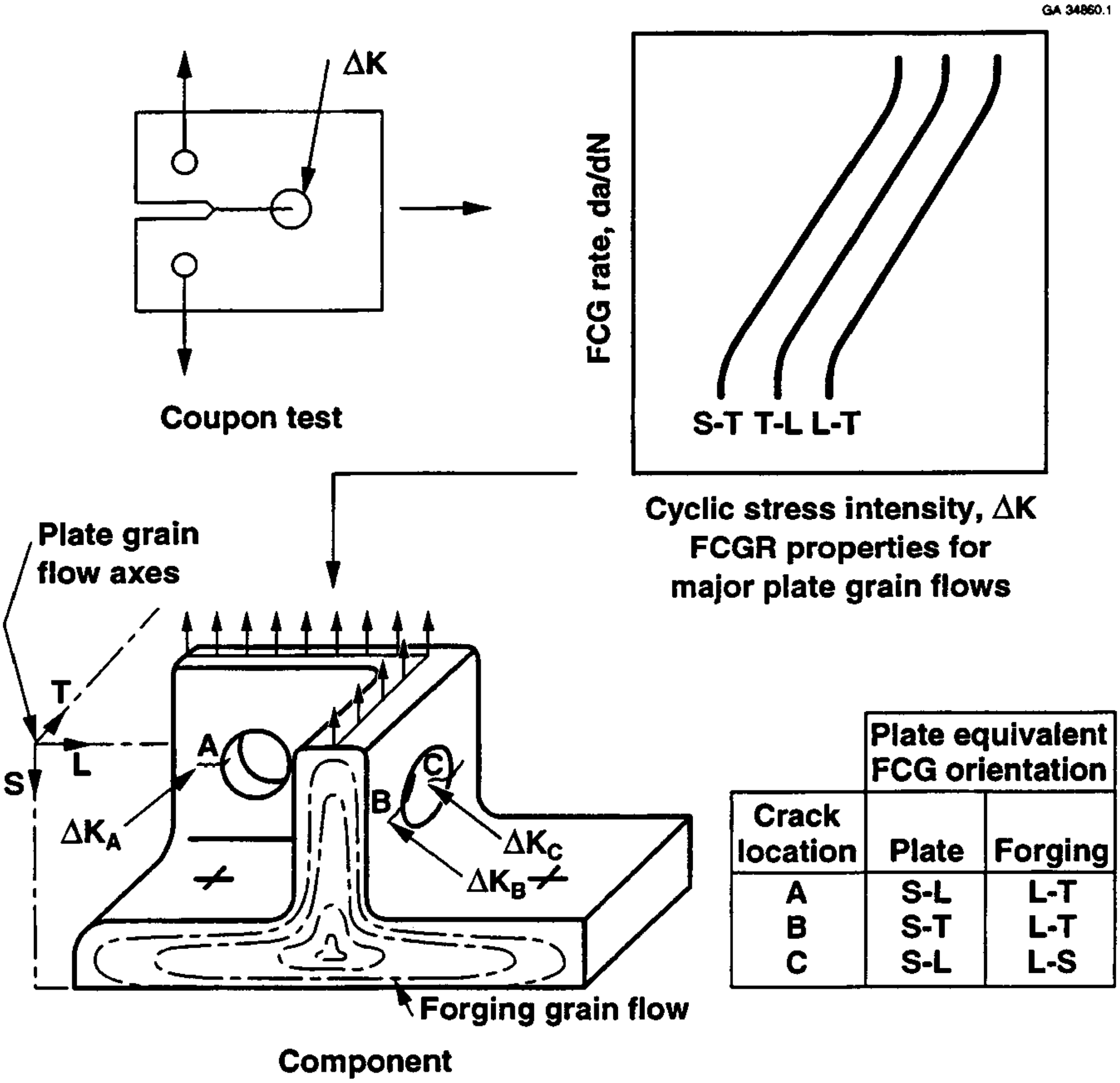


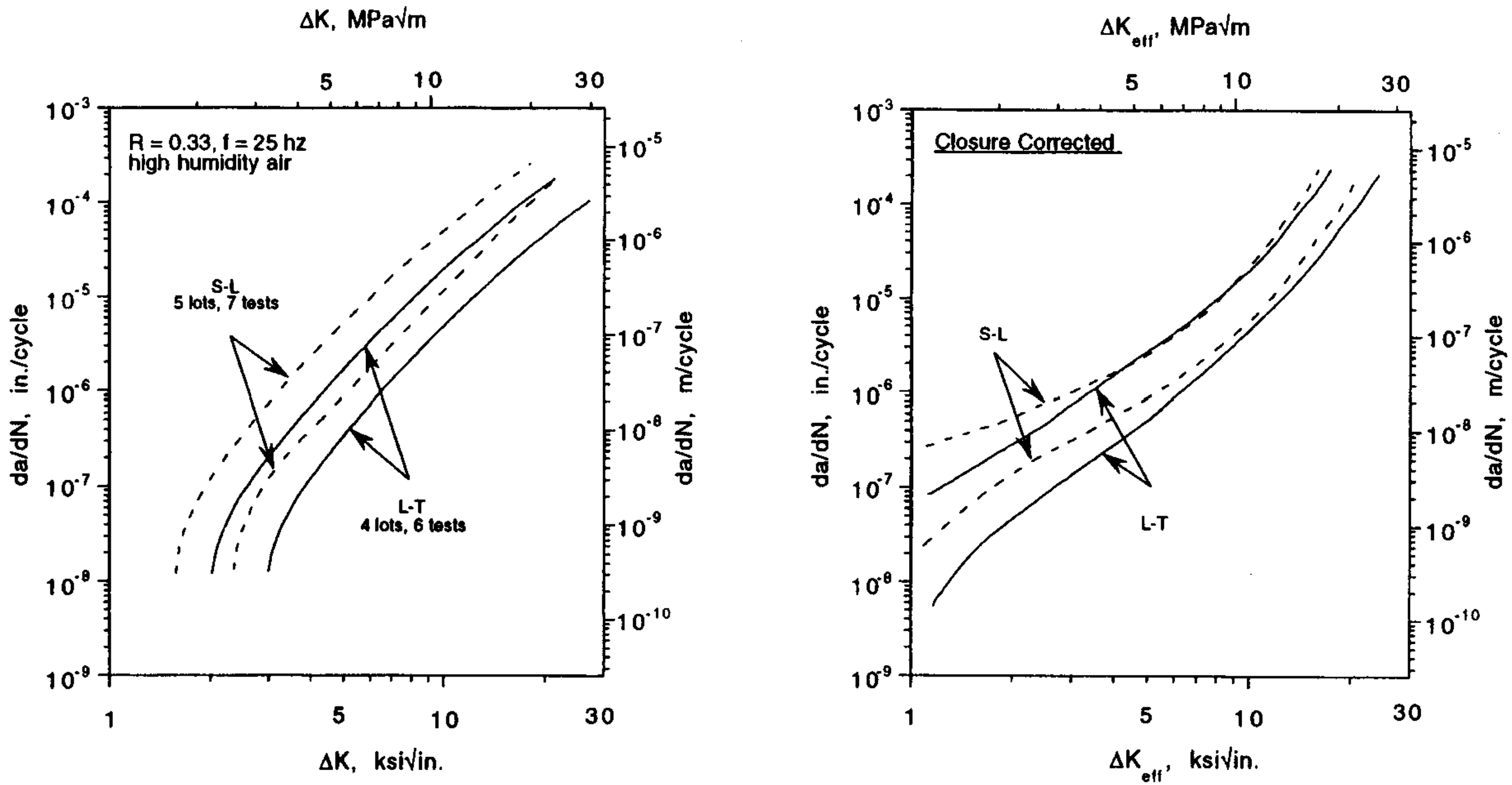
Figure 27: Closure corrected FCGR data from 7050 plate and non-stress relieved forging are similar.

Thus, intrinsic FCG resistances of plate and forgings can be considered equivalent, and plate and forging data can be used interchangeably for purpose of FCG life estimation.



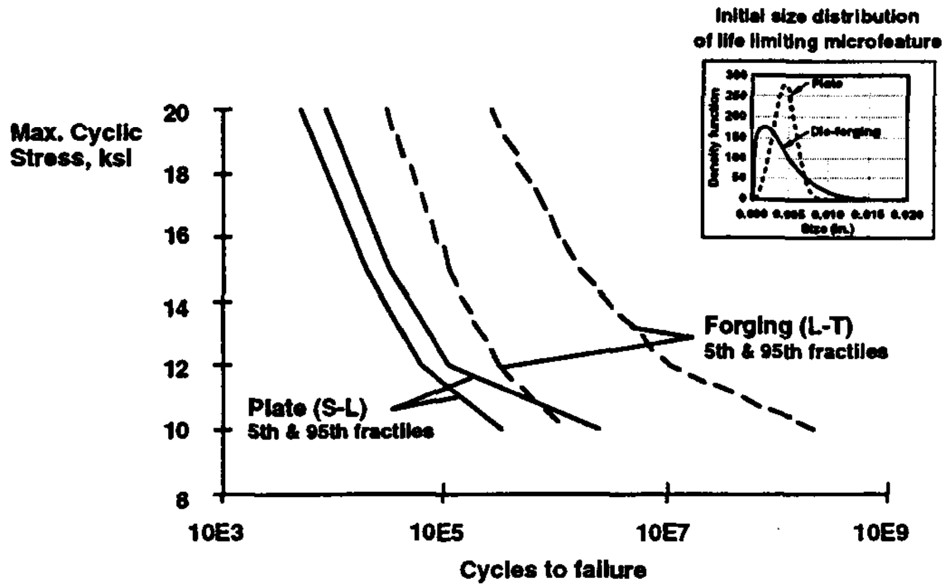
Crack location	Plate equivalent FCG orientation: Plate	Plate equivalent FCG orientation: Forging
A	S-L	L-T
B	S-T	L-T
C	S-L	L-S

Figure 28: The benefit of contour-following grain flow on forged part life can be estimated from plate data.



7050-T7451 plate L-T and S-L FCG performance bands
da/dN vs. ΔKapplied (left), da/d/N vs. ΔKeff (right)

Figure 29: Plate L-T and S-L FCGR properties were used to estimate the benefit potential of favorable forging grain flow.

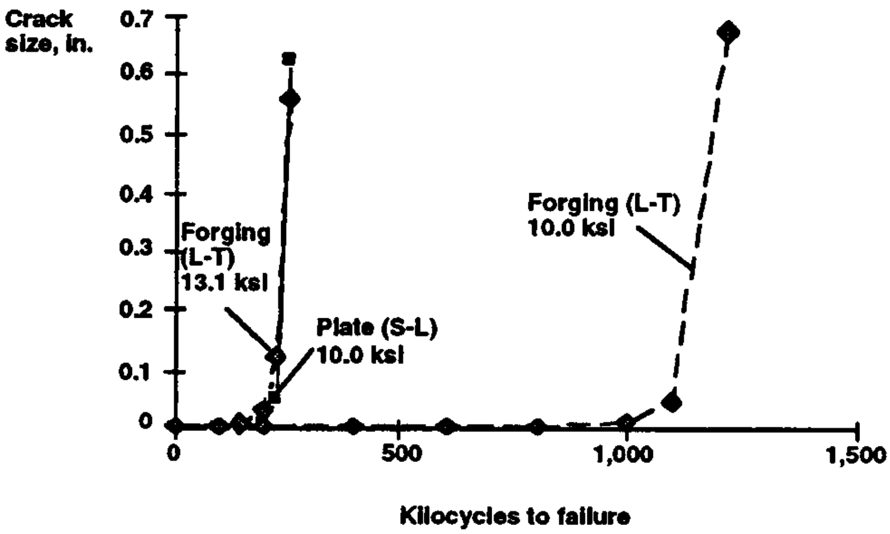


Predicted open hole S-N response of forging vs. plate

Figure 30: The fatigue benefit potential of optimum design die-forgings can be substantial.

- The above plot contrasts the hypothetical open hole S-N fatigue response of a part machined from plate versus the same part designed as an optimal die-forging. The calculated result portrays the maximum possible difference between a forging and plate hogout for the modeling inputs used.

- The calculation employed a generalized probabilistic crack growth model with power law FCGR relationship *(extended to the short crack regime)*. Cracks were assumed to initiate from the respective product life-limiting microfeature populations (inset), and the possibility that cracks could occur anywhere along the bore of the hole was considered by the model. The input FCGR behavior for the model was derived from plate da/dN-ΔK data, and crack growth presumed to be in the L-T and S-L orientation for forging and plate, respectively.

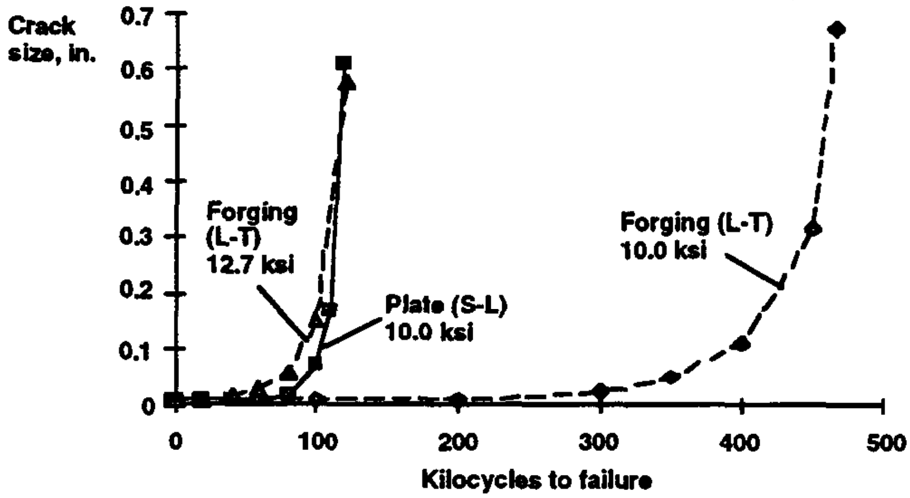


Projected plate and die-forging crack growth lifetimes for open hole specimen with an initial corner crack of size equal to the mean life-limiting microfeature (0.003 in. for forging, 0.004 in. for plate).

Figure 31: Die-forgings offer opportunity to save weight and/or increase inspection interval.

- The above hypothetical example contrasts fatigue performance of a part machined from plate against that of the same part designed as an optimal forging. The calculation employs a deterministic crack growth model assuming a power law FCGR relationship (extended to the short crack regime). Cracking is presumed to grow from an open hole, starting as a corner crack of size equal to the mean life-limiting microfeature of the respective product form (0.003 in. for forging, 0.004 in. for plate).

- Under the above best possible scenario, the forging accommodates 31% higher max. cyclic stress (from 10 to 13.1 ksi) at equivalent plate life, or about a 5 times life increase over plate for the same 10 ksi max. cyclic operating stress.

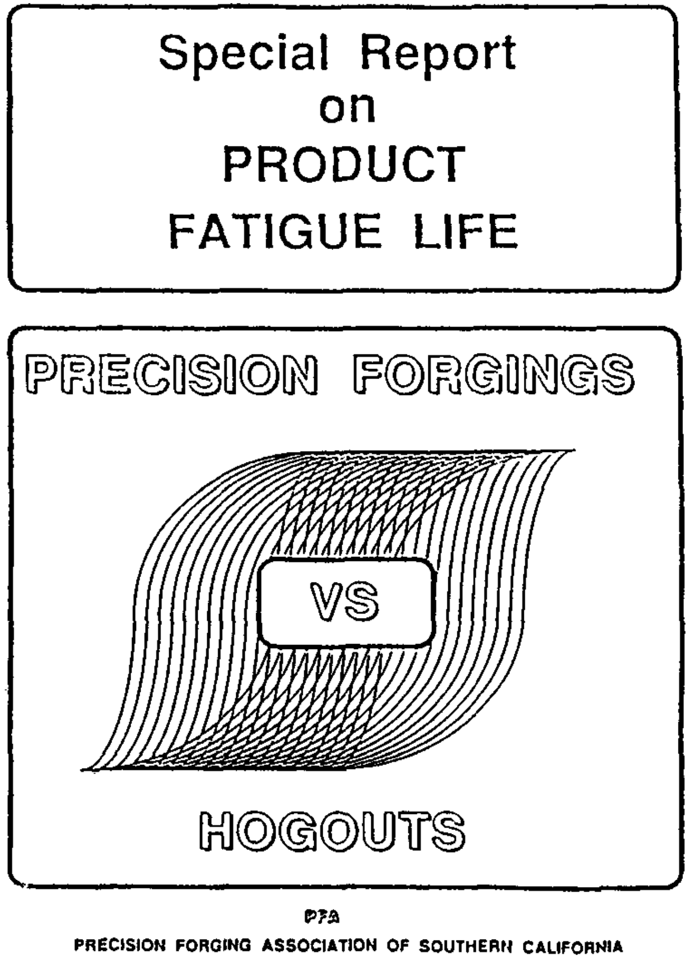


Projected plate and die-forging crack growth lifetimes, initial 0.010 in. corner crack from open hole

Figure 32: Die-forgings offer opportunity to save weight and/or increase inspection interval.

- The above hypothetical example contrasts fatigue performance of a part machined from plate against that of the same part designed as an optimal forging. The calculation employs a deterministic crack growth model assuming a power law FCGR relationship (extended to the short crack regime). Crack growth is presumed to start from a mechanical, 0.010 inch corner flaw located at the corner of an open hole.

- Under the above best possible scenario, the forging accommodates 27% higher max. cyclic stress (from 10 to 12.7 ksi) at equivalent plate life, or an almost 4 times life increase over plate for the same 10 ksi max. cyclic operating stress.



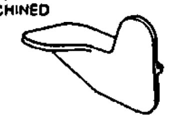
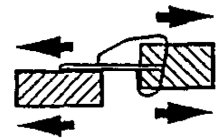
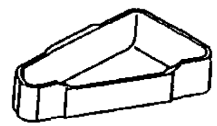
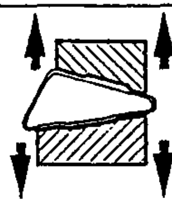
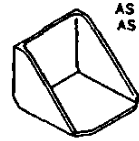
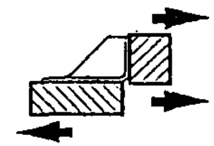
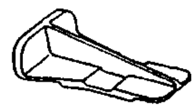
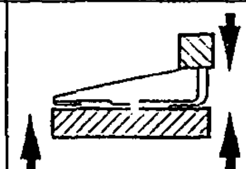
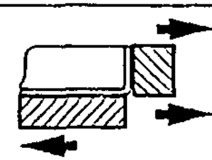
PRODUCT FATIGUE LIFE TEST PROGRAM		
PART	TEST SKETCH	TEST
AS FORGED AS MACHINED 		Test Type: Hight Cycle Fatigue Maximum Load: 4,000 lbs Minimum Load: 400 lbs Frequency: 30 Hz
AS FORGED AS MACHINED 		Test Type: Low Cycle Fatigue Maximum Load: 2500 lbs Minimum Load: 250 lbs Frequency: 20 Hz
AS FORGED AS MACHINED 		Test Type: Low Cycle Fatigue Maximum Load: 500 lbs Minimum Load: 250 lbs Frequency: 20 Hz
AS FORGED AS MACHINED 		Test Type: High Cycle Fatigue Maximum Load: -3000 lbs Minimum Load: -300 lbs Frequency: 40 Hz
AS FORGED AS MACHINED 		Test Type: Low Cycle Fatigue Maximum Load: 1000 lbs Minimum Load: 100 lbs Frequency: 25 Hz

Figure 33: Plate vs. forged part performance was the subject of an independent laboratory study.

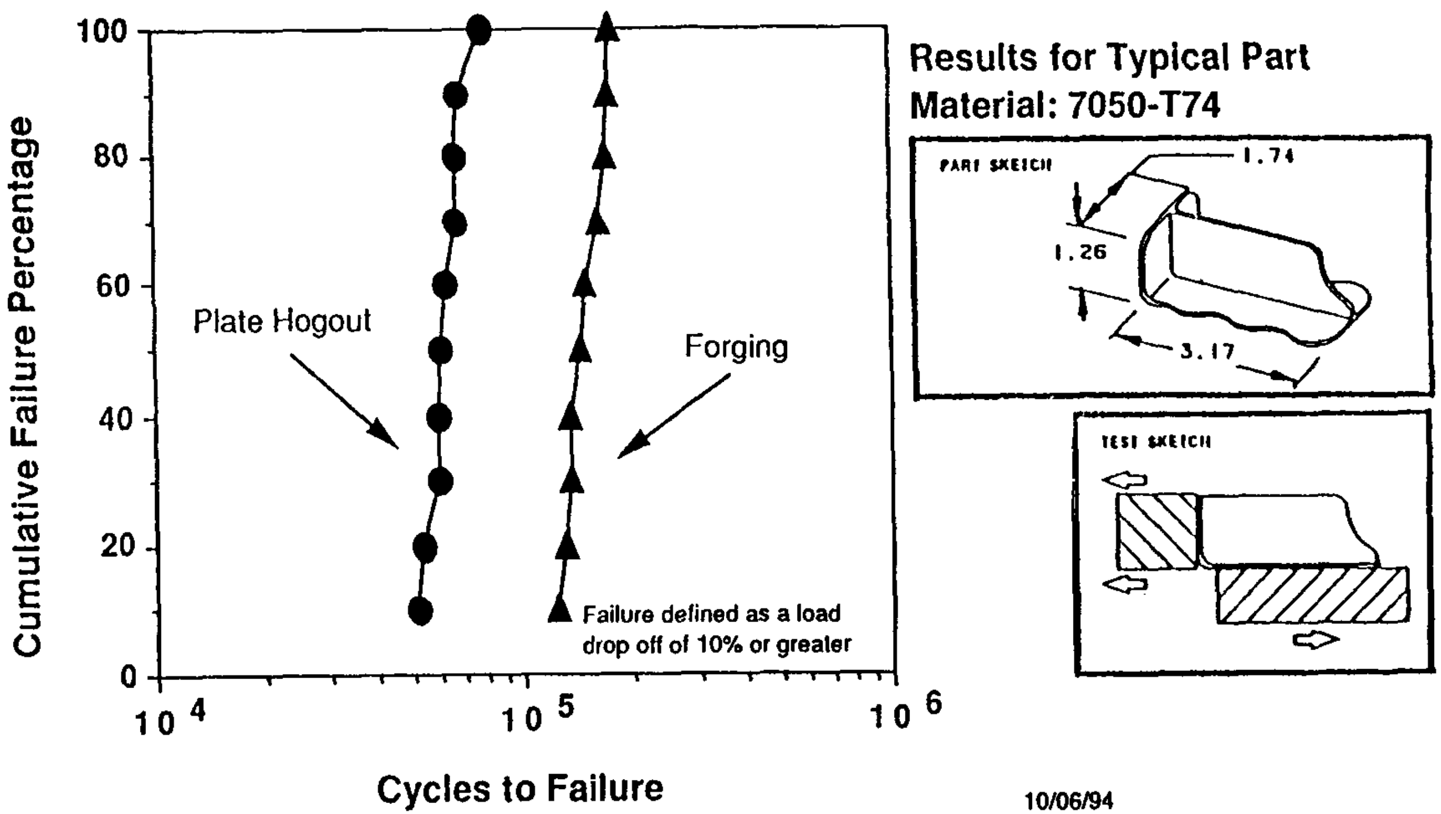


Figure 34: The study affirmed forging's fatigue advantage over plate in representative part tests.

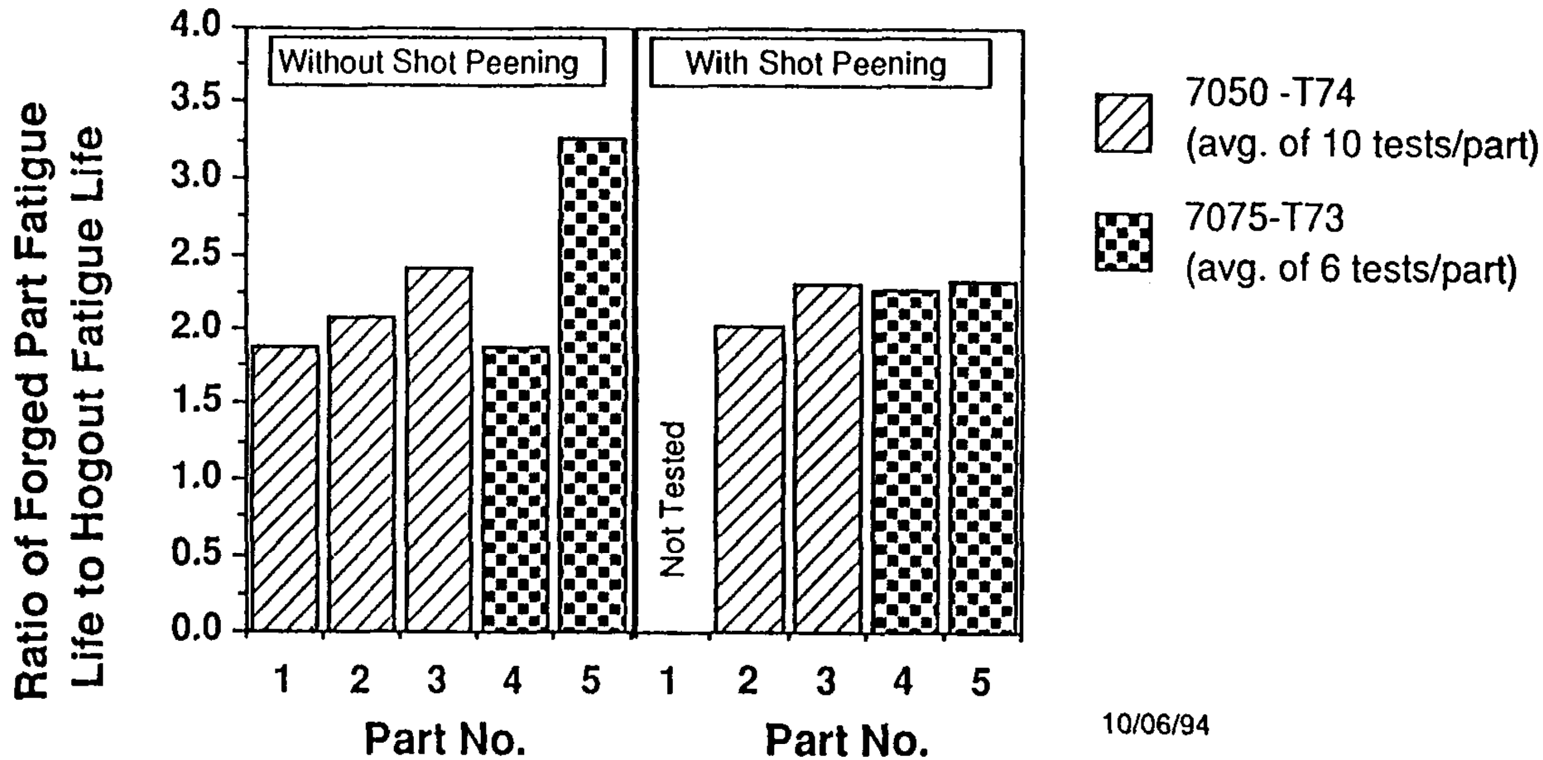
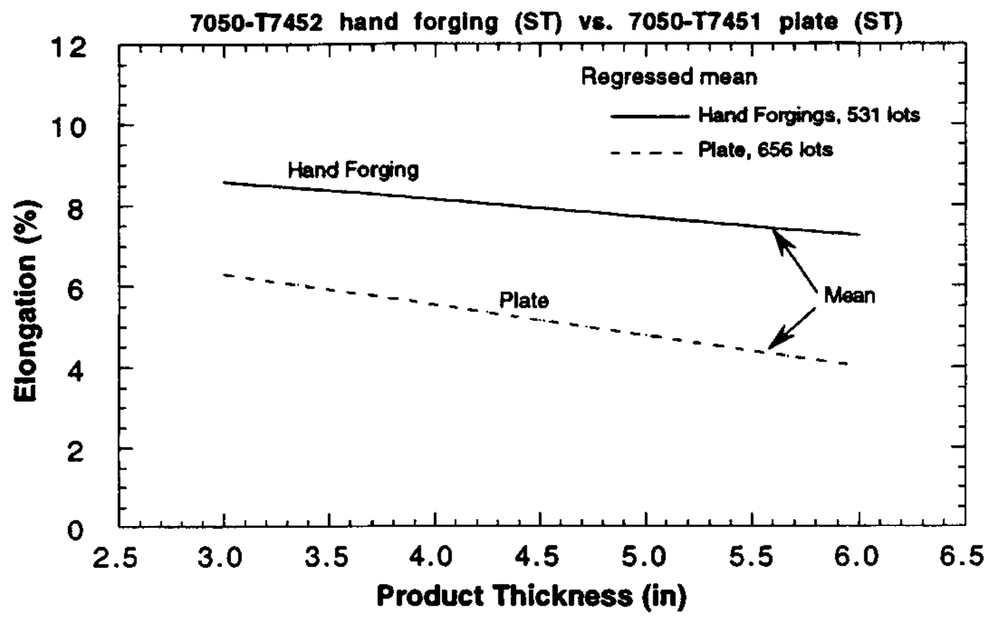
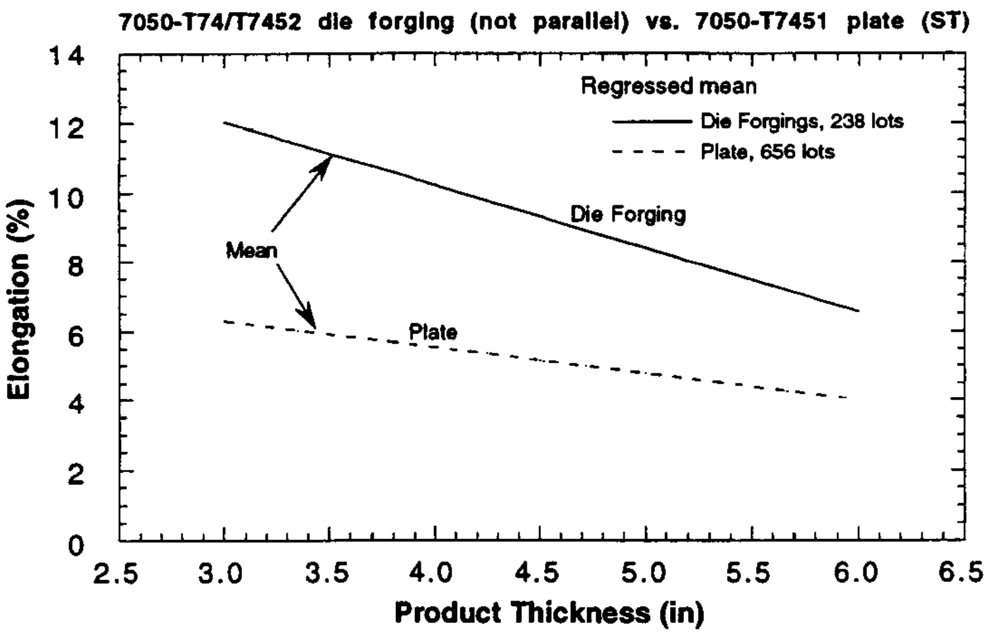


Figure 35: Precision forgings averaged twice the life of plate hogouts in tests of five prototypical parts.





7050 plate and forging ST elongation vs. product thickness

Figure 36: Forging elongations are generally superior to those of plate.