Design of Fabricated Static Structures for Long Cyclic Life

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High-performance, lightweight jet engines, which are designed for relatively low cost production and long life requirements, place stringent restrictions on material utilization. Static structure design criteria require that tensile, creep, and cyclic life limits be met. However, the long operational lifetimes require increased accuracy and reliability of material data and analysis methods. In addition, the widespread use of welded sheet fabricated structures has emphasized the need for quality control of manufacturing processes and for a viable defect-tolerance approach to cyclic life prediction. A design method which is based on the fracture mechanics approach is presented. Both material and geometric imperfections are considered, and guidelines are presented to achieve safe lifetimes for lightweight welded structures.

I. Introduction

THE demand for higher performance and lighter weight aerospace structures combined with high reliability and long life requirements has reinforced the need for efficient materials utilization. With these increased demands, the stringent requirements placed on rotating structure design (discussed in other papers in this issue of the *Journal of Aircraft*) in relation to life capability, defect tolerance, etc., must be extended to static structures as well. Here, the confounding problems of fabrication add complication. Turbine or fan disk designs, albeit dependent on state-of-the-art materials and processing, are usually integral members. When subject to melting and forging, and machining close process control, they exhibit consistent cyclic life behavior. Static structures, by virtue of the complications introduced by joints, have traditionally suffered from limitations of available analyses as evidenced by major static structure failures of welded ships, bridges, pressure vessels, etc. Recent aerospace incidents have provided clear warnings to engine designers.

The philosophy of designing fabricated structures to use increasingly higher percentages of parent material properties has been stemmed by an awareness of factors which influence local stress and, consequently, cyclic life. The consequences of premature failures have led to extensive refinements in structural analyses to the extent that today, static structures are subjected to scrutiny and detailed analysis equaling or exceeding that of other structures.

Considerations of weld quality have led to several weldment classification specifications in the industry, stipulating allowable anomalies for specific quality levels. Shop-floor welding specifications must be integrated with appropriate design practices which, in turn, define allowable stress levels which embrace "practically" obtainable weld quality. The traditional suspicion concerning weld structural integrity has to a large extent been allayed by the characterization and understanding of the roles of weld parameters, metallurgical structures and anomalies. Of particular interest in the latter category is the sharp, cracklike inherent flaw which can invalidate detailed fatigue analyses and lead to premature failures. The assumption that inherent flaws, albeit small, are inevitably present in long weld lengths has led to more reliable structures, since defect tolerance considerations "built-in" additional margins in conventional LCF analyses. Methods are now available to describe stable crack growth from initial defects which can be utilized to calculate cyclic lifetimes. Analytical procedures used in life prediction will be discussed later in the paper.

On the other hand, applications of these sophisticated models to certain structural situations can lead to difficulties in measuring the parameters needed in the life prediction analysis. Misalignment of joint members and detailed measurement of geometric features needed to calculate stress amplification factors may not be possible, with the desired accuracy, and a more general approach needs to be adopted, i.e., specific stress concentration factors associated with the various weld categories based on typical observations. Even this approach needs material considerations, since weldment flow ("wettability") effects may result in essentially similar stress concentration factors for a wide range of weld configurations in one material and significantly differing concentration factors for other alloy systems. In addition, the constituent materials' "notch sensitivity" has to be recognized in evaluating geometric features.

The designer is faced with the problem of bringing order to the often puzzling array of weldment fatigue data to be found, to carefully evaluate the contributing factors, and to utilize design practices which ensure long-lifetime hardware. Conversely, he must not be excessively conservative because of accompanying weight penalties. The following sections discuss design factors, outline the basics of cyclic life calculation, and explore the utility of a simple engineering approach with particular emphasis on application to titanium sheet metal weldments.

The analyses presented in this paper are applicable to most weld configurations, providing a good stress description is available. Applications have typically been made to axial casing welds, circumferential flange welds and to casing pad or insert welds.

II. Factors Influencing Design Life

Structural weldments are designed to withstand steady-state and fatigue loading conditions. Steady-state loads, by definition, remain constant over a period of time and are a function of pressure, temperature, engine speed, normal part weight, etc. The steady loads are repeated during flight missions, and may also be fatigue limiting in themselves; critical maneuver load conditions, identified in engine technical requirements, and ultimate loads, defined in terms of crash loads, surge loads, abrupt stopping loads, etc. are designed according to static load materials data to maintain structural integrity. Dynamic load effects are considered under high cycle fatigue requirements

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Index category: Materials, Properties of.

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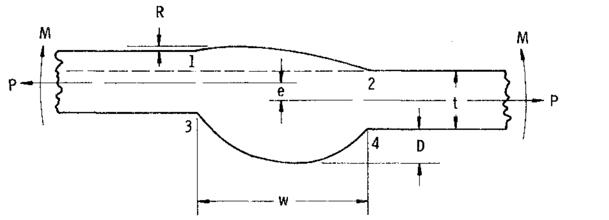

Fig. 1 Weld bead geometry schematic: e = offset; R = reinforcement; D = drop through; t = thickness; w = width; P = load; M = moment; 2, 3 = tension; 1, 4 = compression.

when induced by rotor imbalance, aeroelastic instabilities, blade passing frequencies, gear clash frequencies, etc. or as low cycle fatigue when ground-air-ground (flight) cycles are analyzed. Interactions of high cycle fatigue with steady state loads and high cycle and low cycle fatigue in combination form important categories which may also prove life-limiting.

For the purpose of sizing a component during initial design, stress calculations can be based on an assumed thickness and weld configuration in a similar manner to that used in unwelded structures. For steady-state loading, a design criteria based on minimum 0.2% yield strength (static parts), minimum 0.02% yield strength (rotating parts), or the minimum 0.2% plastic creep strength or, perhaps, 80% minimum rupture strength may be used. In the case of limit or ultimate load criteria, the assumption of the presence of a credible defect is usually made to provide additional safeguards. For most applications, defining allowable stresses for dynamic loading form the major considerations.

III. Low-Cycle Fatigue Considerations

The cyclic life response of welded structures is directly related to local stress amplitude and weld quality. Considering the elements separately, it can be shown by simple mechanics that weld misalignment significantly affects nominal stress distribution by introduction of an additional bending moment. The cross section shown in Fig. 1 represents a weldment subjected to combined axial and bending loading. The eccentricity of the constituent member center lines, effects a bending moment, $P\epsilon'$, which can be shown to be a maximum stress of $3P\epsilon'/t^2$, and is

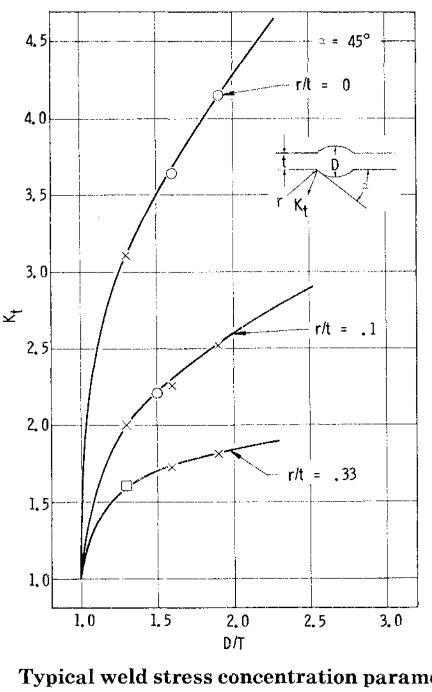

Fig. 2 Typical weld stress concentration parameters.

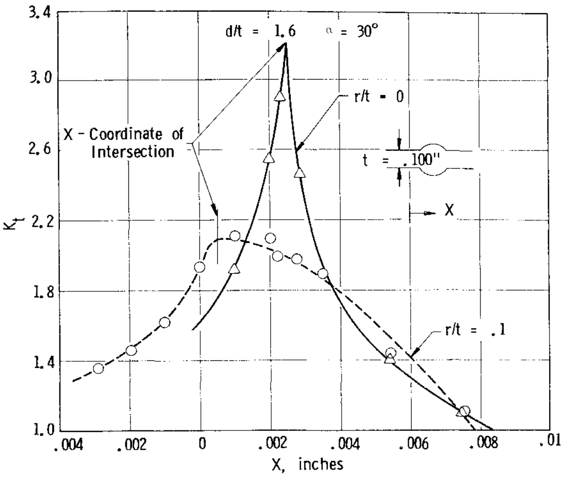

Fig. 3 Stress distribution from weld bead—d/t = 1.6.

additive to the direct applied bending stress, if any. The stress concentration of the weld profile shape (as shown in Figs. 1 and 2) operates on the combined stress and, assuming the bending and tension factors to be nearly equal, the maximum weld stress, σ_w, can be expressed as

$$\sigma_w = [\sigma_A(1 + Q\epsilon'/t) + \sigma_B]K_t$$

where σ_A, σ_B are the axial and bending stresses, respectively, and Q a proportionality constant related to geometry, with a numerical maximum of 3.

For specific weldments, ϵ', t, K_t, and Q can be accurately determined, recognizing that Q is a function of sheet thickness, width of weld, sheet flexibility (related to unsupported sheet length), and temperature. For given alloys, Q can be determined experimentally for each weld class and subsequently used in life predictions. The stress concentration factor is related to the weld thickness, the fillet radius at the intersection of the weld bead and parent metal and, to a lesser extent, on the weld tangency angle. The results of calculations for a tangency angle of 45° are shown plotted in Fig. 2, indicating stress concentrations in the range 1.5 to 4. Additional analysis has shown this concentration to be extremely local with a steep gradient, (Figs. 3 and 4), leading to conservatism when evaluating flaws located in the general heat affected zone. Fatigue data for weldments, judged defect-free by conventional x-ray and zyglo examination, revealed stratification in sensible agreement with geometric considerations. Figure 5 shows the fatigue strength of 17-4PH weldments at 500° F for three weld categories, identified as Classes A, B, and C. In the absence of actual part measurements, average values of K_t for the classes have been assigned as 1.6, 2.2, and 3.0, respectively, however, more severe strength reductions may be obtained when off-set values exceed the designated limit. From the experience

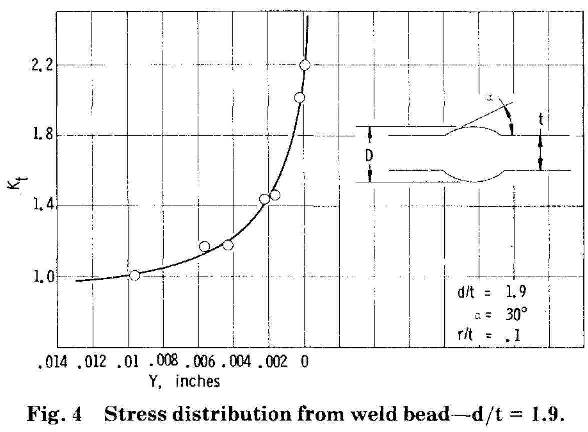

Fig. 4 Stress distribution from weld bead—d/t = 1.9.

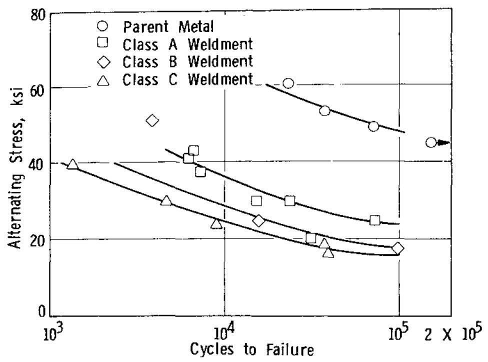

Fig. 5 17-4 PH LCF for 0.065-in.-thick sheet, 500° F, $A\ \sigma = 0.95$, heat number 8044393.

of testing weldments at room and elevated temperature in Inconel 718, René 41, 17-4PH, and Ti-6-2-4-2 alloys, it was shown that weldment lifetime can be meaningfully ranked in terms of weld category. The problem of actual parameter measurement must be emphasized, particularly for hardware configurations. Nonetheless, the utility of general, average values for weld classes is particularly attractive, and provides a means of evaluating weld anomalies. Fatigue data from standard laboratory weldments, i.e., essentially defect-free, are of limited value in actual design considerations since they represent upper rather than lower boundary properties. Thus, a realistic assessment of the nature and likelihood of weld anomalies reducing cyclic capability is required for a viable life-prediction method to evolve. Our approach to the formulation of such a method is discussed in Sec. IV.

IV. Effect of Weld Anomalies on Cyclic Life

The role of weld imperfections on cyclic life is governed by type of flaw and its location. At best, the imperfection may prove to be innocuous—of low-stress concentration in a low-local stress field; at worst, the flaw severity may completely circumvent the initial fatigue damage stage of the fracture process and the cyclic life is restricted to the propagation life of an equivalent sharp-crack. This latter case is well treated by fracture mechanics methods and will be discussed in more detail later. Other than crack-life defects, weld imperfections likely to reduce cyclic life include low welds, undercut weld beads, porosity, some types of weld "repairs," lack of weld fusion and lack of weld penetration. These features may be present singly or in combination and to varying degrees of severity, sometimes presenting problems of clear definition.

A limited program was recently completed within he Material and Process Technology Laboratories of General Electric to rank the effects of such anomalies on the fatigue strength of Inconel 718 GTA weldments at 1000° F. Axial load fatigue tests were conducted on nominally aligned weldments of 80 mil stock, with weld widths of 2½ in., cut from 12 to 18-in. long weld runs, which were fully heat-treated following the weld cycle. Specimens which contained porosity as a result of trapped gas in the welds exhibited spherical defects ranging from 2 mils to 48 mils in diameter, with up to 11 pores per specimen gage width. Specimens with undercut and low weld features were fabricated to standards associated with the lowest class of production welds, with 2 mils to 12 mils in "negative reinforcement." Samples exhibiting lack of fusion and lack of penetration were again restricted to low quality weld levels; i.e., 20 mils deep and ¼ in. length lack of fusion, and some 10% to 30% lack of penetration. Lack of penetration or fusion is not permitted by our specifications. The effect of weld repair was examined on specimens fabricated from two weld passes, the first including one or more of the aforementioned anomaly types and the second pass performed to repair the defect introduced earlier. The results of fatigue tests on these samples and referenced to baseline, nominally defect-free, welds can conveniently be summarized in Table 1.

Table 1 Fatigue test results

Anomaly	Fatigue strength reduction for failure in 10,000 cycles	Stress concentration factor
1) Defect-free	0%	1.36
2) Porosity	10%	1.36
3) Low weld and undercut	16%	1.5–1.23
4) Repair welds	16%	1.55
5) Lack of fusion	57%	5.0
6) Lack of penetration	81%	5.0

It is of interest that the data do not correlate with nominal stress concentration factors, except that lack of fusion and penetration exhibited high K_t and life degradation. The repair weld geometry effect (K_t increased to 1.55 from 1.36) was essentially reflected in the fatigue strength values assuming full notch sensitivity was exhibited. The strength reductions indicated for lack of fusion and penetration form clear warnings regarding the acceptance of such weldments. Variability in the data were frequently identified with nonuniform weld bead shape, particularly for manual wedments.

Similar studies have been completed on other welded alloys, particularly titanium, to support a more general philosophy. It should be mentioned that porosity, for instance, may prove to be more deleterious where weld beads are ground flush with the parent metal than in the "reinforced" weld bead shape, except for the case of a pore being randomly located at the weld bead to parent metal interface. Treatment of spherical pores as sharp equivalent cracks was found, not surprisingly, to be conservative; however, until flaw shapes, particularly buried flaws, can confidently be described analytically, such conservatism has to be accepted in the design philosophy. The mechanics of life prediction for weldments containing sharp, crack-like flaws is reviewed in the following section. It was also of interest to the authors that fracture mechanics approaches to the lack of penetration or fusion geometry would not fully account for the strength reduction observed, whereas fatigue notch theory was either acceptable or conservative.

V. Fracture Mechanics Approach

In view of the long weldment lengths present in modern jet engines, it is unrealistic to assume ideal, "defect-free" quality levels can be consistently maintained; the concept of inherent defects, just below, but approaching, inspection sensitivity levels, is generally accepted. Defects may result in reduced cyclic life by the mechanism of local notches sharpening into cracks and propagation to failure or, directly in the form of cracks which are extended under cyclic load, if not properly considered during design. The geometric (notch) approach was reviewed in Sec. IV, however, the basic concern of initial cracks located in the weld heat-affected zone, in a highly stressed area, has lead to the development of a simple fracture mechanics-based method to calculate residual life. The crack geometry is expressed in terms of the stress intensity factor, K, and referenced to the materials' crack growth rate curve which is described as the crack extension rate in inches of incremental growth per stress cycle ($\Delta a/\Delta N$) as a function of stress intensity range. Integration from the initial crack size, real or hypothesized, to the onset of unstable fracture results in the calculated residual cyclic life or cumulative cycles to failure.

Mathematically,

$$\hat{K} = M \cdot \hat{\sigma}(\pi a)^{1/2} \qquad (1)$$

where $\hat{\sigma}$ is the local stress, amplified by stress concentration and offset effects, ksi; a, the crack depth, or semi-length for through-cracks, ins.; and M, a proportionality constant related to a specific crack geometry. Also

$$\hat{K} \alpha \Delta a/\Delta N \qquad (2)$$

Hence, $\Delta a/\Delta N \alpha^{p} a$ for $\hat{\sigma}$ = constant and

$$\int_{a_i}^{a_f} \Delta N/\Delta a \times da = N_R \qquad (3)$$

Given the functional relationships implicit in Eqs. (1) and (2), computational integration of Eq. (3) becomes a relatively simple task. The problem areas are in the determination of stress concentration, the irregular nature of weld bead shapes, and analytical definition of actual defects. The fracture mechanics model has to recognize stress gradient, stress ratio, plasticity and free-surface effects, and must also combine bending and tension modes; however, these factors have been continually discussed and further developed in the literature though not necessarily applied to weldments. Previous work by the authors[1] remains applicable. Recent studies have increased precision in stress analysis, particularly stress concentration effects, and in experimental verification of the analytic prediction capability.

Extensive work[2] on defect-tolerance of rotor materials has substantiated that in the life-prediction method for configurations with surface flaws, the average ratio of predicted lives to observed lifetimes approaches unity.

An important aspect of weld defect characterization is the initial nondestructive inspection, particularly to establish the confidently detectable defect size. For the purpose of the work discussed in this paper, production inspection methods were used, namely radiographic and fluorescent penetrant examinations, to ensure initial weld integrity. It has been the routine practice to introduce artificial flaws at desired locations by Electro-discharge-machined slots and fatigue-cycling them to produce sharp cracks of pre-determined sizes. In this manner, cracks of 20 to 30 mils in length were introduced at weld-parent metal interfaces. Smaller cracks have been considered, but frequently were not the fatigue nucleation site. Presumably, local stress concentrations associated with weld bead contour at other locations were of equal or greater severity. However, since the crack detection sensitivity is of the order of 40 mils for overall hardware inspection, the residual life data were regarded as relevant for design use.

VI. Laboratory Data

As a basis for residual life calculations, crack growth rate data were obtained as a function of stress intensity factor for the materials of interest. Data were obtained for parent material and weldments using center-cracked sheet specimens, cycled from zero to tension at 20–30 cpm. Crack length observations as a function of load cycles were reduced to crack growth rates, inches per cycle, and plotted against stress intensity factors for the through-thickness cracks using the Forman and Kobayashi analysis.[3] Crack growth rate curves for Inconel 718 and Ti-6-2-4-2 are shown in Figs. 6–9. It is interesting to compare the weldment data with corresponding base material properties, noting that the stress intensities shown are nominal values and ignoring the weld offset and stress concentration previously discussed. Inconel 718 at RT (Fig. 6) exhibits increased crack propagation rates for weldments compared to parent metal for equivalent nominal stress intensity; at 1000° F, a reverse trend is indicated (Fig. 7), but in this case may be a consequence of material variability. Ti-6Al-2SN-4Zr-2Mo crack growth data seem influenced by the weld process (Figs. 8 and 9).

One approach to weldment life prediction is to assume basically similar crack growth resistance of weldments and parent material, previously suggested by the authors,[1]

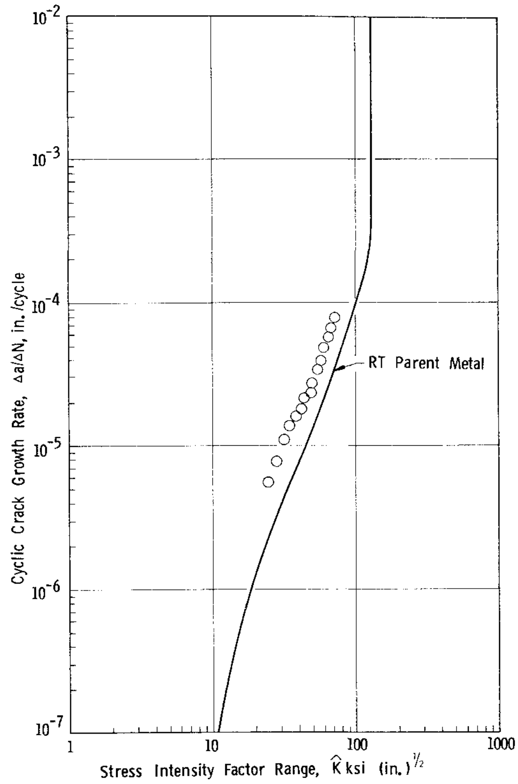

Fig. 6 Inconel 718 Class B sheet weldment crack propagation, RT, $A\ \sigma = 0.95$, $t_h = 0$.

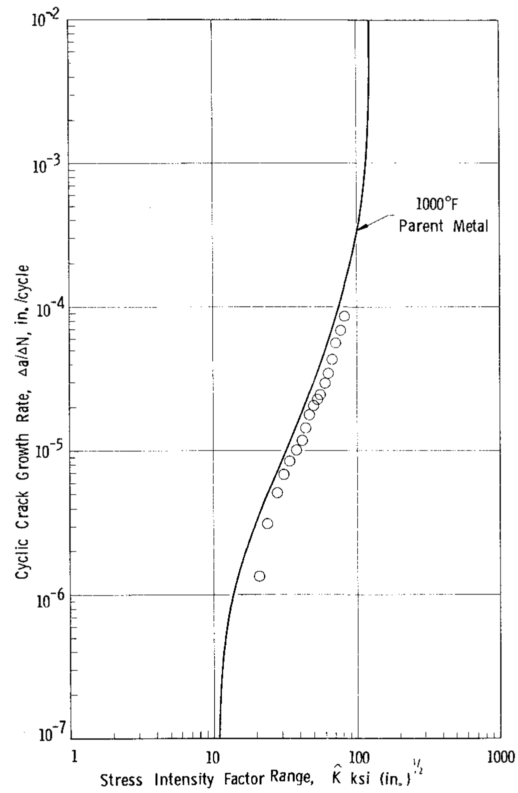

Fig. 7 Inconel 718 Class B sheet weldment crack propagation, 1000° F, $A\ \sigma = 0.95$, $t_h = 0$.

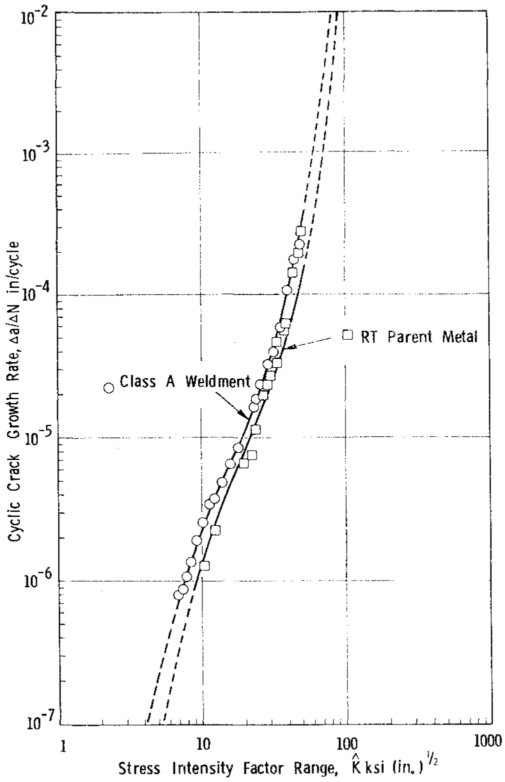

Fig. 8 **Ti-6Al-2Sn-4Zr-2Mo Class A sheet weldment crack propagation, RT, $A\ \sigma = 0.95$, $t_h = 0$.**

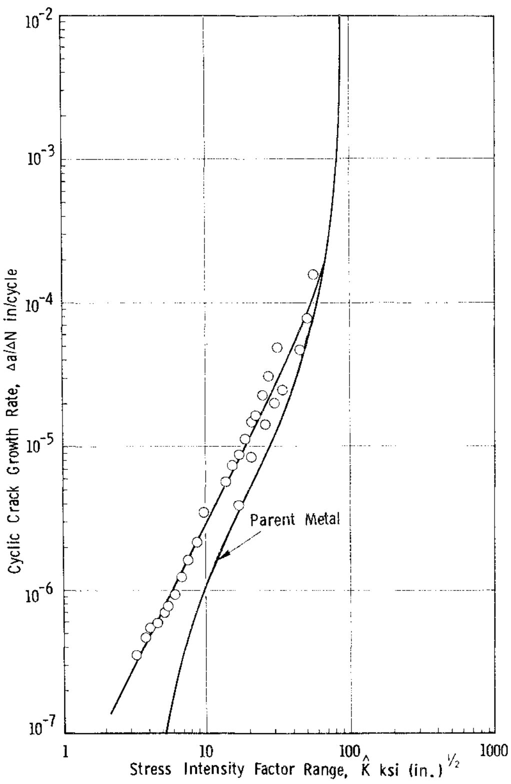

Fig. 9 **Ti-6Al-2Sn-4Zr-2Mo Class B sheet weldment crack propagation, 750° F, $A\ \sigma = 0.95$, $t_h = 0$.**

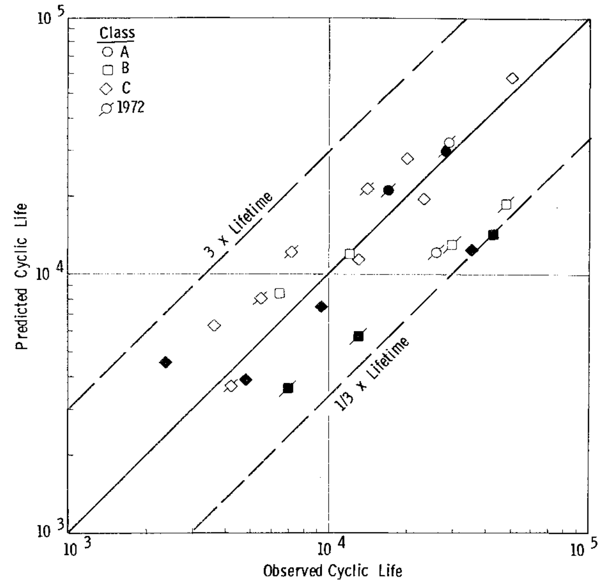

Fig. 10 **Residual life prediction from Inconel 718 sheet weldments, 1000° F, based on average stress conditions.**

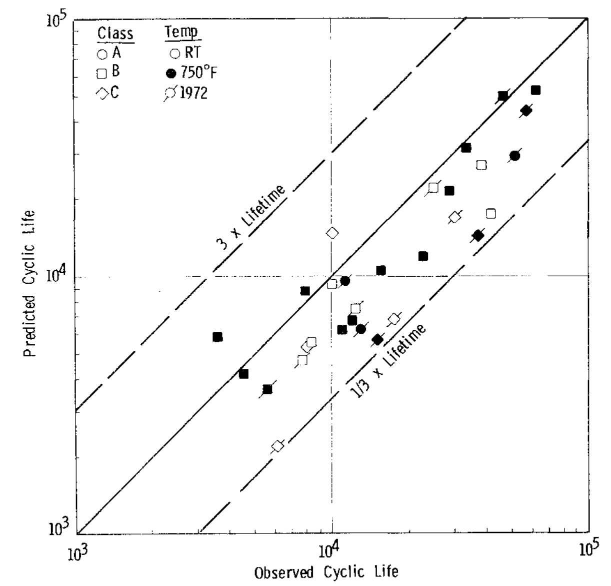

Fig. 11 **Residual life predictions of Ti-6Al-2Sn-4Zr-2Mo sheet weldments, based on average stress conditions.**

and account for the stress amplification factors of off-set and stress concentration prior to calculation of weld stress intensity. In this manner, the more extensive parent material property curves, and better defined material variability, may be used in life prediction. To facilitate the crack growth rate curve integration, a sigmoidal curve is plotted on a ln-ln basis and regression fitted to the expression:

$$\Delta a/\Delta N = e^B \times \hat{K}^P/\hat{K}^* \times \ln(\hat{K}^Q/\hat{K}^*) \times \ln(\hat{K}_c{}^D/\hat{K}^*)$$

where $\Delta a/\Delta N$ is the crack growth rate, in./cycle; K^*, the threshold stress intensity, ksi(in.) ½; Kc, the cyclic toughness ksi(in.) ½; and B, P, Q, and D, shape constants. The expression has proved convenient in fitting the many curves obtained and is flexible to include nonsymmetrical plots. A measure of the utility of the parent material property approach to weld life prediction can be made by comparing the actual test results of intentionally flawed welds with predicted values. The "flaws" judged of interest were semi-elliptical surface cracks, typically 10 mils × 30 mils in size and located at the weld bead interface. Results of tests on Inconel 718 and Ti-6-2-4-2 are shown plotted against predicted lifetimes in Figs. 10 and 11, respectively, using average surface stress values for each weld category.

The variability shown is typical for weldment life prediction and is, on the average, conservative. It seldom

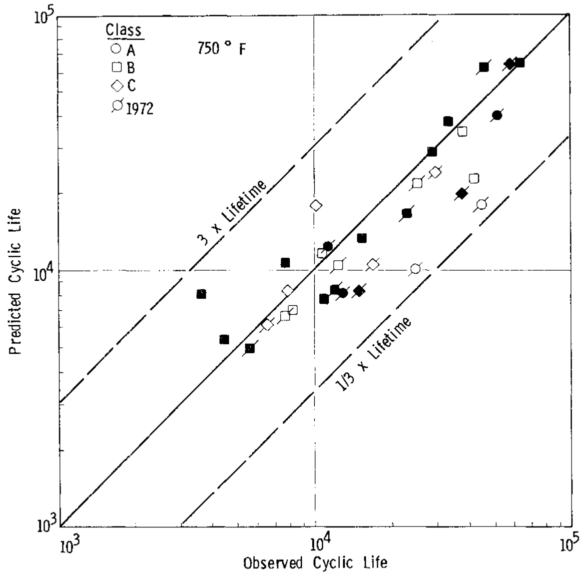

Fig. 12 Residual life prediction of Ti-6Al-2Sn-4Zr-2Mo sheet weldments, 750° F, based on measured K_t.

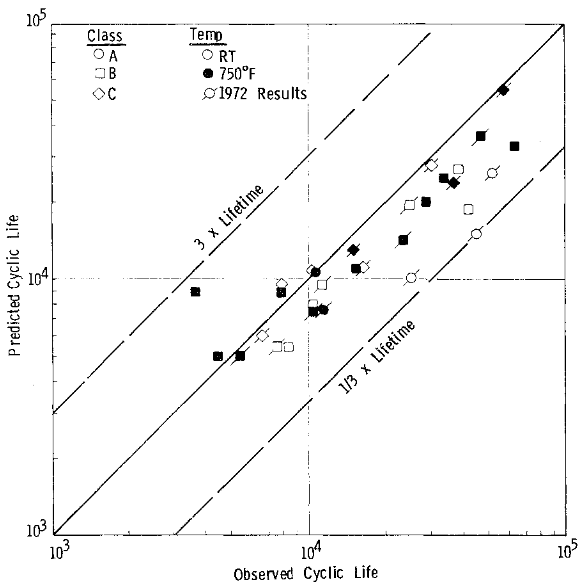

Fig. 13 Residual life predictions of Ti-6Al-2Sn-4Zr-2Mo sheet weldments, based on weldment cyclic crack growth rate.

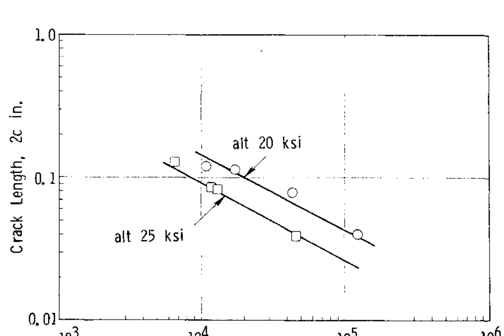

Fig. 14 Effect of crack size on Ti-6Al-2Sn-4Zr-2Mo residual life, *RT*.

varies more than a factor of three of the calculated life. Scatter of weldment fatigue data is greater than for the base material, and recent work has indicated typical minus three standard deviation lifetimes to be approximately one-fourth of the average cyclic life. Consequently, life predictions within a factor of three are not unreasonable, if a minimum property philosophy is used to dictate structural life. Variability in terms of stress is usually well within conventional design allowables, and improved life prediction can be achieved by assessment of individual weld details to more accurately specify off-set and stress concentration parameters. The data from Fig. 11 were re-evaluated in terms of individually calculated stress concentrations to yield the life prediction distribution shown in Fig. 12. A closer distribution has been effected, with the average ratio of predicted to observed life nearer to unity.

Production weldment experience in titanium alloys led to the observation that within Class A, B, and C limits, stress concentrations from the weld bead were similar. Titanium alloys usually exhibit an attractive, cosmetic weld appearance and seem not to approach the K_t of 3, identified for the lowest weld class. Assuming an essentially equivalent weld profile severity, it would seem that the actual weldment crack growth rate curve may be integrated directly, with weld flaw size the significant variable. Available weldment fatigue for Ti-6-2-4-2 were examined from this approach and lifetimes found to be predictable to an acceptable degree (Fig. 13). The strong influence of initial crack size on residual cyclic life can be seen in Fig. 14, where Class A, B, and C weldment data are plotted for nominal alternating stress conditions of 20 and 25 ksi. Further confidence needs to be generated in this simple predictive method in view of the application potenial. Initial observations suggest nickel-base alloys may not be treated in this manner since weld configurations, between identified class limits, seem to result in stress concentration differences. However, an investigation into the general utility of the simple approach seems warranted.

VII. Conclusions

1) A fracture mechanics approach to weldment cyclic life prediction was developed to include inherent flaws and local weld geometry details.

2) Life predictions to within a factor of three were achieved for Inconel 718 and titanium alloys over the life range $\sim 4 \times 10^3$ to 10^5 cycles.

3) For preliminary design purposes, a simple method to predict titanium weldment life is offered, avoiding application difficulties associated with the detailed design method with apparently comparable accuracy. Further evaluation of this method is suggested to develop a general materials approach.

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