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A REVIEW OF SURFACE-CRACK FRACTURE TESTING

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ABSTRACT

A brief historical review of surface-crack testing and analysis is given together with some examples of service failures due to surface cracks. The factors which complicate the analysis and interpretation of surface-crack fracture data are discussed. Current efforts to develop consensus recommendations for tensile testing of surface-crack specimens are summarized.

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SUMMARY

The current status of fracture testing with surface-crack specimens is described. The surface-crack specimen is a very realistic model of structures with defects which occur in service, but it is not a simple one. Many problems in the areas of stress intensity analysis, failure criteria, stable crack growth, and experimental technique remain to be solved. Thus, a Standard Method of Test for surface-crack specimens is not yet feasible. Nevertheless the surface-crack specimen can provide meaningful information when used in a simple modeling test, and reasonable guidelines for such tests are within the state of the art. Finally, it appears that the surface-crack specimen may prove to be most useful in applications where linear elastic fracture mechanics considerations are not valid and where fracture toughness values obtained from standard specimens would not be meaningful.

INTRODUCTION

There are several types of fracture specimens that have been developed over the past fifteen years. Of these, the surface-crack specimen is one of the most representative of structures with defects that actually occur in service. However, it is probably the most difficult of all to analyze. Its three-dimensional nature requires an extremely complex stress analysis. Extensive plastic flow and stable crack growth often occur prior to final fracture. As a result, calculated fracture toughness values are not always constant and are difficult to interpret and generalize. Only cursory recommendations for specimen preparation and testing have been published to date.

The purpose of this paper is to present the current status of fracture testing with surface-crack specimens. A brief historical review of surface-crack testing and analysis is given and the factors which complicate the analysis and interpretation of fracture data are discussed. Current efforts to develop consensus recommendations for tensile testing of surface-crack specimens are summarized and the areas in which further research is needed are cited.

RELEVANCE OF THE SURFACE-CRACK SPECIMEN

It has been well established in the literature (refs. 1 and 2) that many failures of aerospace structural components can be traced back to small surface defects. Such defects may have an irregular shape that cannot easily be described mathematically. But under cyclic service loads, even irregular defects tend to become semicircular or semielliptical in shape as the crack grows.

For example, figure 1 shows a crack that is typical of those which formed during fatigue testing of hydraulic cylinders (ref. 3). Figure 2 is a sketch of another fatigue crack that formed at a stress concentration in an aircraft wing fitting during a structural fatigue test (ref. 2). For these and many other cases, the semielliptical surface crack is a very realistic model of a flawed structural element.

HISTORICAL REVIEW

The history of the surface-crack specimen involves a number of milestones in testing and analysis which can be identified.

The first surface-crack specimen tests to be reported were run at the Naval Research Laboratory (refs. 4 and 5) and at the Douglas Aircraft Co. (refs. 6 and 7) around 1960. Randall (ref. 8) in 1966 studied the effect of crack size and shape on apparent plane-strain fracture toughness (K_{Ic}) values. In 1968, Corn (ref. 9) attempted to characterize the natural shape tendencies of surface cracks propagating under cyclic load. Hall (ref. 10) in 1970 compared apparent-K_{Ic} values from surface-crack specimens with those obtained from other types of specimens.

The analysis of surface-crack data according to fracture mechanics principles was made possible by Irwin (ref. 11), who in 1962 derived the stress intensity factor for an elliptical crack embedded in an infinite solid and estimated the maximum stress intensity factor for a semielliptical surface crack in a plate. Paris and Sih (ref. 12) in 1964 attempted to improve the applicability of Irwin's estimate to plates of finite thickness by means of analogies to existing two-dimensional solutions. Three-dimensional solutions using numerical methods that have been applied to the surface-crack problem include the alternating method by F. Smith (ref. 13) in 1966, the finite-difference method by Ayres (ref. 14) in 1968, the finite-element method by Miyamoto and Miyoshi (ref. 15) and by Levy and Marcal (ref. 16) in 1970, and the boundary-integral method presented by Cruse in 1972 (ref. 17). In 1971, C. W. Smith (ref. 18) presented a method of determining stress intensity factors by three-dimensional frozen-stress photoelasticity.

PROBLEMS IN ANALYSIS OF SURFACE-CRACK TEST DATA

Analysis of surface-crack fracture data is hampered mainly by three factors. These are the uncertainty in the basic elastic stress intensity analysis, the complex nature of crack-tip plastic flow, and the possibility of extensive stable crack growth prior to fracture.

Stress Intensity Analysis

In spite of the considerable amount of analytical effort just described, there is as yet no exact stress intensity solution for the general problem of a semielliptical surface crack in a plate of finite dimensions.

Irwin's approximate expression for the surface crack (ref. 11) was based on his exact solution for the elliptical crack in an infinite body and an analogy to the problem of an edge crack in a half-plane. He assumed that his approximation would provide a useful estimate of the maximum stress intensity factor for surface cracks whose depth was less than half the plate thickness. Indeed, his estimate did yield fairly constant fracture toughness values from tests of small surface cracks in relatively brittle high-strength rocket motor case steels (refs. 5 and 19).

A number of investigators (refs. 12, 13, 20-27) have attempted to extend Irwin's approximation to cases of cracks deeper than half-thickness. Following Paris and Sih (ref. 12), each method involves some kind of analogy to an alternate crack configuration which has some physical similarity and for which a solution is available. These approximations differ one from another, in some cases considerably as can be seen in figure 3 (taken from ref. 27). Shah and Kobayashi's approximation covers a wide range of crack depth-to-thickness and ellipticity and is probably the best approximation currently available.

Attempts to develop three-dimensional solutions have produced only limited results. Smith's numerical solutions for the semicircular (ref. 13) and circular-segment (ref. 26) cracks are thought to be fairly accurate, but only for these geometries. Other numerical methods are also restricted each to a specific geometry, and their accuracy is restricted by computational limitations. But numerical analyses do serve to illustrate the complexity of the general problem. For example, 2500 degrees of freedom are required to construct a simple three-dimensional finite-element model of a semielliptical surface crack (ref. 15), and as many as 10 000 degrees of freedom may be required (ref. 28) for an accurate solution. Then the computation must be repeated for each crack geometry (i.e., depth-to-thickness and ellipticity) of interest. This is clearly a formidable task.

These uncertainties in the computation of stress intensity factors lead in turn to difficulties in interpreting fracture toughness test data. It is not always possible to tell with certainty whether trends in test data represent a change in fracture mechanism or merely an inadequacy in the stress intensity analysis.

Crack-Tip Plasticity

Small-scale yielding at the tip of a crack in a two-dimensional body of infinite extent is reasonably well understood (ref. 29). But the analysis of plastic flow at the tip of a surface crack is complicated always by the three-dimensionality of the problem, usually by the presence of nearby stress-free surfaces, and often by large-scale yielding.

Some of this complexity can be seen in figure 4 (taken from ref. 14). As the load is increased, the plastic zone grows. At a certain load, zones of plasticity (zone 5 in fig. 4 and its mirror image) form on the back (uncracked) surface away from the crack plane. With further loading the plastic zones at the crack tip and on the back surface grow together and merge. A three-dimensional view of this plastic zone is shown in figure 5 (also taken from ref. 14).

It should be obvious that an extremely sophisticated elastoplastic analysis would be needed to accommodate such complex plastic flow. The critical stress intensity criterion, which is based on linear elastic theory, can be applied only when the plastic zone is small with respect to the crack and specimen dimensions. This requirement leads in turn to specimen size requirements that will be discussed later.

Stable Subcritical Crack Growth

It was recognized long ago (ref. 30) that surface cracks may grow in a stable manner under rising load. But this factor was generally ignored until recently, probably because there was no way to measure subsurface crack growth. Advances in crack-opening-displacement (COD) measurement techniques now allow at least a qualitative evaluation of stable crack growth. The term "COD" is used herein to denote the displacement of the crack faces at the origin of the semiellipse.

Figure 6 shows a typical experimental setup for surface-crack COD measurements. The distance between spotweld centers is the effective gage length, and this should be kept as small as possible. The brackets have knife edges to receive a standard clip gage.

Figure 7 shows an actual load-COD record from reference 31, and a photograph of the fracture face is inset. On the first major load cycle the trace is at first linear with rising load, which indicates elastic behavior. As the load is increased the trace rather abruptly departs from linearity, becoming nearly horizontal. Had the load been increased slightly, the specimen probably would have failed. Up to this point one cannot tell whether the deviation from linearity was due to crack-tip plasticity, stable crack growth, or a combination of both. But as the load is decreased, one can see that the slope of the unloading trace is less than the slope of the loading trace. This indicates that the crack has grown physically larger. At zero load there is a residual COD or zero-offset, which indicates that some of the deviation from linearity on loading must have been due to crack-tip plasticity. The specimen was then load-cycled at a lower stress to produce a visible marking band on the fracture surface. The process was then repeated three more times before the specimen failed. The marking bands are clearly visible on the fracture surface (inset) and delineate the four regions of stable growth.

Although COD measurement allows a qualitative evaluation of subcritical crack behavior, it cannot provide quantitative results for two reasons. First, there is not a suitable elastic stress analysis to relate COD to crack size and shape. Second, one cannot discriminate between actual crack growth and crack-tip plasticity except by unloading the specimen prior to fracture. Even if one could somehow measure the crack dimensions exactly and continuously, the application of such information is not clear.

When stable crack growth occurs, two events are of primary interest, the initiation of crack growth and the onset of instability. An operational definition of crack initiation (such as was developed for K_{Ic} testing, ref. 32) should be feasible, and the associated stress intensity factor should be relatable to plane-strain fracture toughness (K_{Ic}). The point of instability, however, is much more difficult to determine and in particular the crack size associated with instability is difficult to measure. Furthermore, when stable crack growth occurs the stress intensity factor associated with instability (fracture toughness) will vary with absolute crack size and also with crack size relative to specimen dimensions (ref. 33). A nominal fracture toughness based on maximum load and initial crack size will also vary in a somewhat similar manner. The magnitudes of these variations are generally greater for tough materials than for more brittle materials. The best hope for eventual understanding and quantifying of the stable growth of surface cracks appears to lie in the crack-growth-resistance (R-curve) concepts that are currently evolving (ref. 34) for two-dimensional specimens.

FRACTURE TOUGHNESS

The basic concept of fracture toughness has undergone considerable evolution. Originally it was hoped that the critical strain energy release rate (G_c) would be a unique material property that would characterize all sharp-crack fractures. It soon became apparent (ref. 19) that fracture toughness (based on maximum load) decreases with increasing specimen thickness, reaching a nearly constant minimum value as conditions of plane strain are approached. The designation K_{Ic} was given to this lower limit. Brown and Srawley (ref. 35) pointed out that crack-tip plasticity must be highly constrained in order to properly simulate a state of plane strain. In order to provide such constraint they suggested certain size requirements for K_{Ic} test specimens which were developed empirically. These size requirements became the foundation of the current Test Method (ref. 32), which now provides an operational definition of K_{Ic}.

The application of fracture toughness concepts to surface-crack specimen testing has also evolved. The second report of the ASTM Special Committee (ref. 19) suggested that K_{Ic} values could be determined from surface-crack specimen tests, and the fifth report (ref. 36) suggested that K_{Ic} values could be used to predict failure loads for surface-cracked structural components. These suggestions were based on the very limited data available at that time and on the concept of K_{Ic} as a vaguely-defined lower limit. Subsequent studies have shown that they represent idealizations of what can be a very complex fracture process.

Randall (ref. 8) studied the effect of crack size and shape on apparent fracture toughness values from surface-crack specimens of D6AC steel and titanium-6Al-4V. Unfortunately the data scatter was rather severe and tended to obscure any trends. However, after applying stress intensity correction factors based on the then-current state of the art, Randall concluded that apparent fracture toughness was nearly independent of crack size and shape for these two materials in their high-strength conditions but not for the same materials in much tougher heat-treat conditions. Shortly thereafter the concept of plane-strain size requirements was advanced (ref. 35). This at least partly explained some of Randall's results. Tougher materials require larger specimens to provide the same degree of plane-strain simulation, but Randall's specimens were all the same size. Thus the high-strength materials should have approached plane-strain conditions more closely than the tougher materials and apparent fracture toughness should indeed be more nearly constant for the high-strength conditions.

The size requirements of ASTM Test Method E399 were empirically developed specifically for the bend and compact specimens. Hall (ref. 10) attempted to empirically develop size requirements using surface-crack specimens of an aluminum and a titanium alloy. His results for the aluminum alloy are shown in figure 8, and similar results were obtained for the titanium alloy. For both alloys, calculated fracture toughness was reasonably constant as long as both the crack depth and the uncracked ligament depth (thickness minus crack depth) were both greater than $0.5(K_{IE}/\sigma_{ys})^2$, where σ_{ys} is the material yield strength. The designation K_{IE} is customarily given to toughness values obtained from surface-crack specimens, as distinguished from K_{Ic} values determined according to ASTM E399.

Hall also compared K_{IE} values from surface-crack specimens with K_{Ic} values determined according to ASTM E399-70T. The specimens were machined from thick plate so that thickness and crack propagation direction were the same. Results are shown in figure 9. The aluminum compact (CT) specimens gave consistently low toughness values, which was unexpected and was not explained. The titanium surface-crack (SF) specimens gave high toughness values at liquid nitrogen temperature, which also cannot be adequately explained. With these exceptions, toughness values from surface-crack specimens were in good agreement with those obtained from other specimen types. Although encouraging, Hall's results were not conclusive nor entirely consistent. But one should not expect K_{IE} and K_{Ic} values to be identical, since they are differently defined. K_{IE} values are customarily based on maximum observed load, while K_{Ic} values are based on the load corresponding to 2 percent crack extension.

In summary, the concept of fracture toughness associated with surface-crack specimens is still evolving. It appears that, if uncertainties associated with the stress intensity analysis can be minimized, apparent fracture toughness K_{IE} will be fairly constant provided that the crack depth and ligament depth are both greater than $0.5(K_{IE}/\sigma_{ys})^2$. At present K_{IE} is vaguely defined as the limiting value of toughness that is reached as specimens are made larger and larger. It also appears that, under directly comparable test conditions, K_{IE} and K_{Ic} values may be numerically similar, even though they are not (and should not be expected to be) identical. It should be noted that these summary statements are based on limited data and should be considered only tentative.

MODELING TESTS

Surface-crack specimens were originally chosen because they were very good models of the types of flaws found in service. This rationale is valid even if (or especially when) linear elastic fracture mechanics considerations are not applicable. That is, surface-crack specimens can be used in a simple modeling test even if fracture stresses are above yield or if section sizes are not large enough to simulate plane strain. However, one should not attempt to generalize such test data, for example to crack sizes or shapes or material thicknesses outside the test range.

It is reasonable to choose the surface crack configuration most closely resembling the type of flaw likely to occur in service. For example, lack of penetration in a one-pass weldment might best be modeled by a long shallow surface crack; or, a small fatigue crack grown from an etch pit by a nearly semicircular surface crack. The range of crack size and shape that must be covered will depend on the ultimate purpose of the test.

ASTM TASK GROUP ACTIVITY

ASTM Task Group E24.01.05 is preparing a report on fracture testing with surface-crack specimens. The primary purpose of that report is to propose a uniform procedure for the testing of surface-crack specimens using the best currently-available techniques. It is also intended to note the areas in which further research is needed. A secondary purpose is to ensure that forthcoming tests will include those measurements that may be useful for future analyses.

The scope of the report will be limited to the 'residual strength' test. The assumed object of the test is to estimate the residual tensile strength of a homogeneous plate of infinite length and width containing a semielliptical surface crack of specific dimensions; or, by means of a series of such tests, to estimate the residual strength as a function of crack size and shape. The specimen and instrumentation that are described will be usable (with appropriate constraints) for other types of tests as well.

Guidelines for specimen design will be given and the minimum test section length and width necessary to simulate an infinite plate estimated. Techniques for producing a sharp fatigue crack of prescribed length and depth will be discussed. COD measurement is encouraged and experimental measurement techniques will be described. No specific method of data analysis will be recommended since there are too many uncertainties as yet unresolved. The significant test results which should be reported will be identified. The use of surface-crack specimens for sustained-load testing and for cyclic crack growth rate testing will be discussed briefly.

FURTHER RESEARCH NEEDED

Further systematic studies to determine minimum test section width and length are needed. Additional studies of surface-crack shape change during fatigue cracking would be helpful. The maximum crack starter envelope size, minimum amount of fatigue crack extension, and maximum fatigue cracking load which will produce an effective sharp crack must be determined experimentally.

An exact stress intensity and displacement solution for the semi-elliptical surface crack in a finite plate would be extremely beneficial. Further analytical and experimental compliance (COD ÷ load) studies would be valuable, and some experimental details of compliance measurement must be resolved. Finally, the phenomenon of stable crack growth under rising load deserves concentrated study.

CONCLUDING REMARKS

In summary, the surface-crack specimen is a very realistic model of structures with defects which occur in service, but it is not a simple one. A satisfactory three-dimensional elastic stress analysis for surface cracks has yet to be developed, and an elastoplastic analysis is even more difficult. The phenomenon of surface crack growth-on-loading is not fully understood at present. Details regarding specimen sizing, crack preparation, and crack-opening-displacement measurements must be resolved. Thus, a Standard Method of Test for surface-crack specimens is not yet feasible.

Nevertheless, the surface-crack specimen is still quite useful, even if used only in a simple modeling test. Conservative guidelines for specimen sizing and crack preparation are within the state-of-the-art and reasonable estimates of stress intensity factors are available. Current crack-opening-displacement measurement techniques allow at least a qualitative interpretation of some fracture phenomena. The surface-crack specimen may prove to be most valuable in applications where linear elastic fracture mechanics considerations are not valid and where fracture toughness values obtained from standard specimens would not be meaningful.

REFERENCES

1. C. F. Tiffany and J. N. Masters: Fracture Toughness Testing and Its Applications, ASTM STP 381 1965, pp. 249-277.

2. C. D. Little and P. M. Bunting: The Surface Crack: Physical Problems and Computational Solutions, J. L. Swedlow, ed., ASME, 1972, pp. 11-42.

3. R. L. Moore, G. E. Nordmark and J. G. Kaufman: Eng. Frac. Mech., 1972, vol. 4, pp. 51-63.

4. C. D. Beacham and J. E. Srawley: Fracture Tests of Surface Cracked Specimens of AMS 6434 Steel Sheet, Memo. Rept. 1097, Naval Research Lab., 1960.

5. J. E. Srawley and C. D. Beacham: Metallic Materials for Low-Temperature Service, ASTM STP 302 1961, pp. 69-84.

6. C. S. Yen and S. L. Pendleberry: Technique for Making Shallow Cracks in Sheet Metals, Eng. Paper No. 1206, Douglas Aircraft Co., 1961.

7. C. S. Yen and S. L. Pendleberry: Trans. ASM, 1962, vol. 55, pp. 214-229.

8. P. N. Randall: Severity of Natural Flaws as Fracture Origins and a Study of the Surface-Cracked Specimen, AFML-TR-66-204, Air Force Materials Lab., 1966.

9. D. L. Corn: Eng. Frac. Mech., 1971, vol. 3, pp. 45-52.

10. L. R. Hall: Fracture Toughness Testing at Cryogenic Temperatures, ASTM STP 496 1971, pp. 40-60.

11. G. R. Irwin: J. Appl. Mech., 1962, vol. 29, pp. 651-654.

12. P. C. Paris and G. C. Sih: Fracture Toughness Testing and Its Applications, ASTM STP 381 1965, pp. 30-83.

13. F. W. Smith: Stress Intensity Factors for a Semi-Elliptical Surface Flaw, Structural Dev. Res. Memo No. 17, The Boeing Co., 1966.

14. D. J. Ayres: NASA TN D-4717, August 1968.

15. H. Miyamoto and T. Miyoshi: Les Congres et Colloques de L'Universite de Liege, 1971, vol. 61, pp. 137-155.

16. N. Levy and P. V. Marcal: Three-Dimensional Elastic-Plastic Stress and Strain Analysis for Fracture Mechanics. Phase I - Simple Flawed Specimens, HSSTP-TR-12, Brown Univ., 1970.

17. T. A. Cruse: Computers and Structures J., 1973, vol. 3, pp. 509-527.

18. G. R. Marrs and C. W. Smith: Stress Analysis and Growth of Cracks, ASTM STP 513 1972, pp. 22-36.

19. Mat. Res. Stand., 1961, vol. 1, pp. 389-393.

20. A. S. Kobayashi: On the Magnification Factors of Deep Surface Flaws, Structural Dev. Res. Memo No. 16, The Boeing Co., 1965.

21. A. S. Kobayashi and W. L. Moss: Proc. Second Int. Conf. on Fracture, Brighton, England 1969, pp. 31-45, Chapman and Hall Ltd.

22. F. W. Smith and M. J. Alavi: Proc. First Int. Pressure Vessel Conf., Delft, Holland October 1969, pt. 2, pp. 793-800, ASME.

23. R. W. Thresher: Ph.D. Thesis, Colorado State University, Fort Collins, Colorado, 1970.

24. J. R. Rice and N. Levy: J. Appl. Mech., 1972, vol. 39, pp. 185-194.

25. R. B. Anderson, A. G. Holms and T. W. Orange: NASA TN D-6054, October 1970.

26. F. W. Smith: The Surface Crack: Physical Problems and Computational Solutions, J. L. Swedlow, ed., ASME, 1972, pp. 125-152.

27. R. C. Shah and A. S. Kobayashi: The Surface Crack: Physical Problems and Computational Solutions, J. L. Swedlow, ed., ASME, 1972, pp. 79-124.

28. N. Levy, P. V. Marcal and J. R. Rice: Nucl. Eng Design, 1971, vol. 17, pp. 64-75..

29. J. R. Rice: Fatigue Crack Propagation, ASTM STP 415 1967, pp. 247-309.

30. ASTM Bull., 1960, pp. 29-39.

31. J. E. Collipriest: The Surface Crack: Physical Problems and Computational Solutions, J. L. Swedlow, ed., ASME, 1972, pp. 43-61.

32. J. E. Srawley and W. F. Brown, Jr.: Fracture Toughness Testing and Its Applications, ASTM STP 381 1965, pp. 133-198.

33. 1973 Book of ASTM Standards, Part 31, ASTM, 1973, pp. 960-979.

34. Fracture Toughness Evaluation by R-Curve Methods, ASTM STP 527 1973.

35. W. F. Brown, Jr., and J. E. Srawley: Plane Strain Crack Toughness Testing of High Strength Metallic Materials, ASTM STP 410 1967.

36. Mat. Res. Standards, 1964, pp. 107-119.

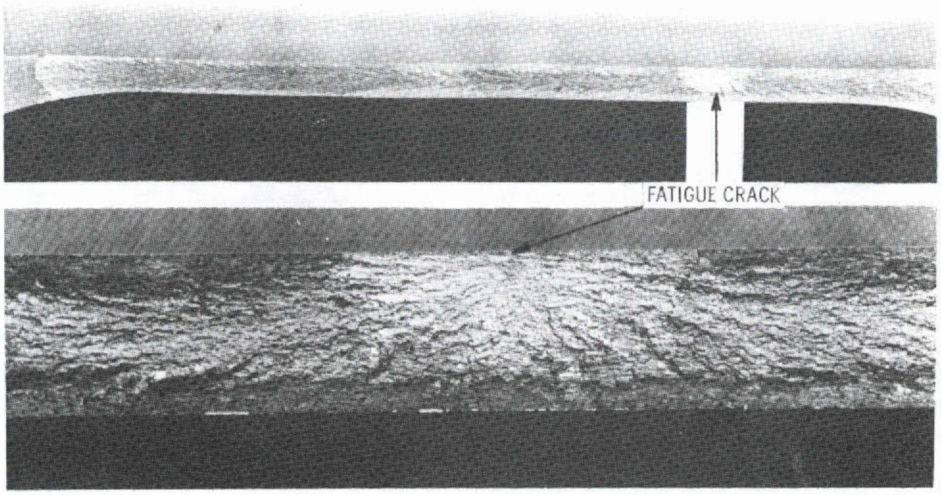

Figure 1. - Fatigue crack in 7075-T73 aluminum hydraulic cylinder (ref. 3).

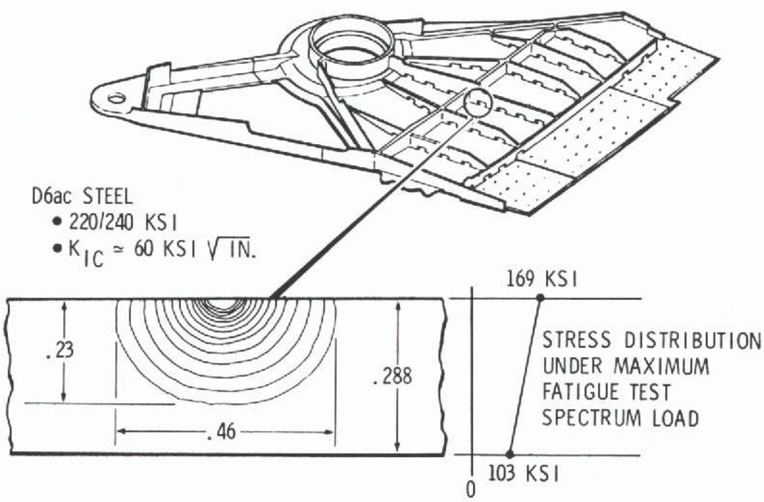

Figure 2. - Sketch of fatigue crack in aircraft wing pivot fitting (ref. 2).

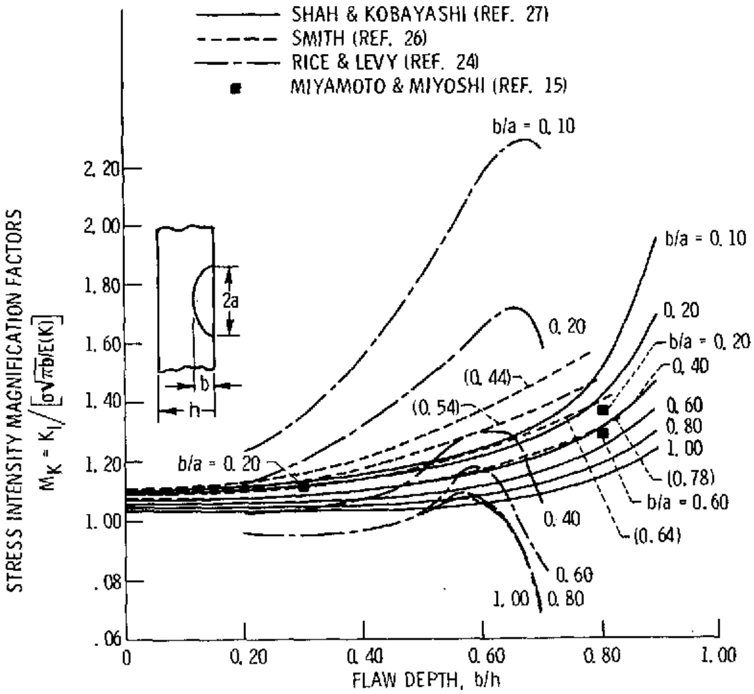

Figure 3. - Approximate stress intensity magnification factors.

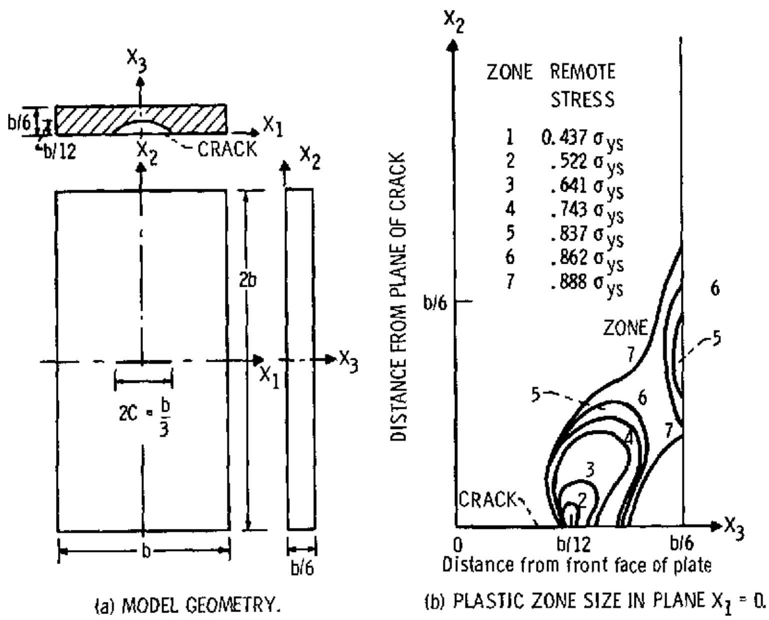

Figure 4. - Plastic zone sizes calculated by finite-difference method (ref. 14).

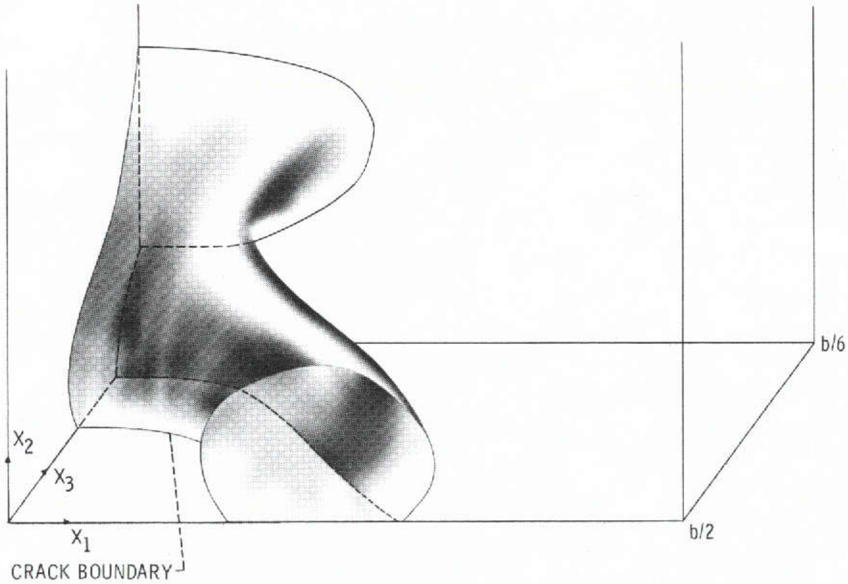

Figure 5. - Sketch of one quadrant of plastic zone (zone 7 in fig. 4).

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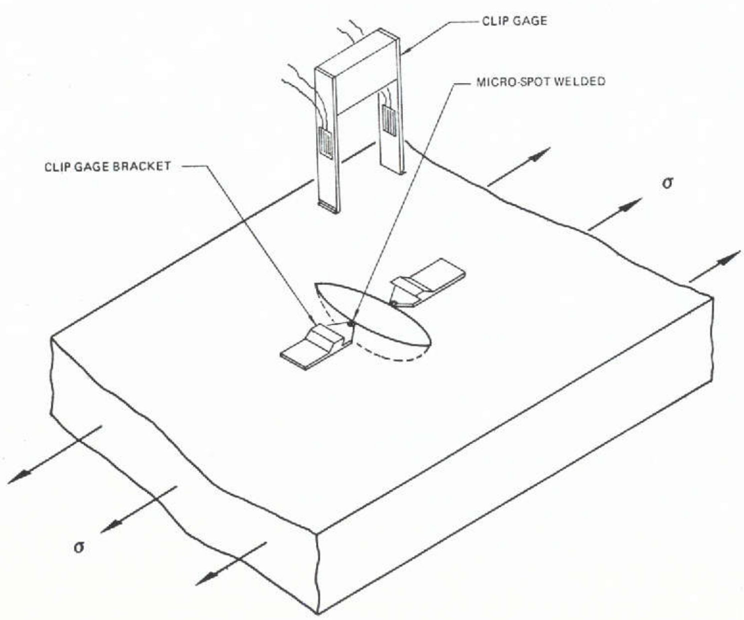

Figure 6. - Typical experimental setup for COD measurement.

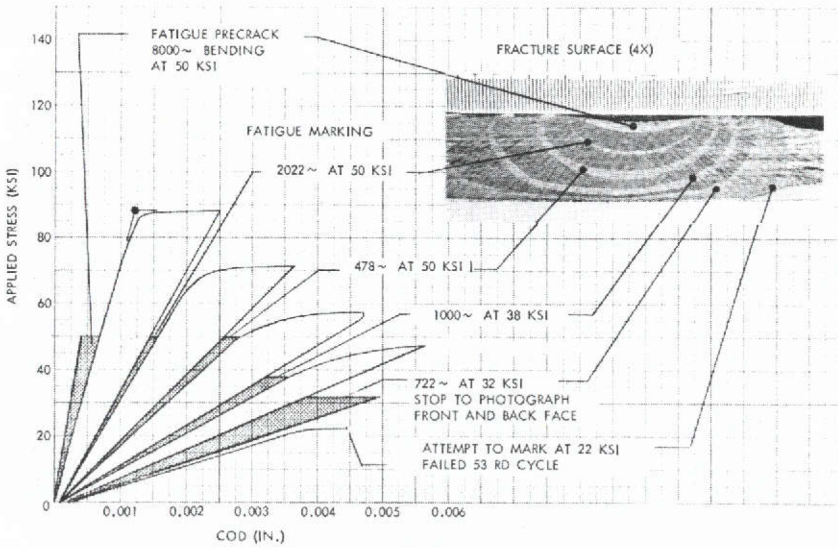

Figure 7. - Load-COD record and fracture face (Ti-6Al-4V-STA, 1/4 in. thick, ref. 31).

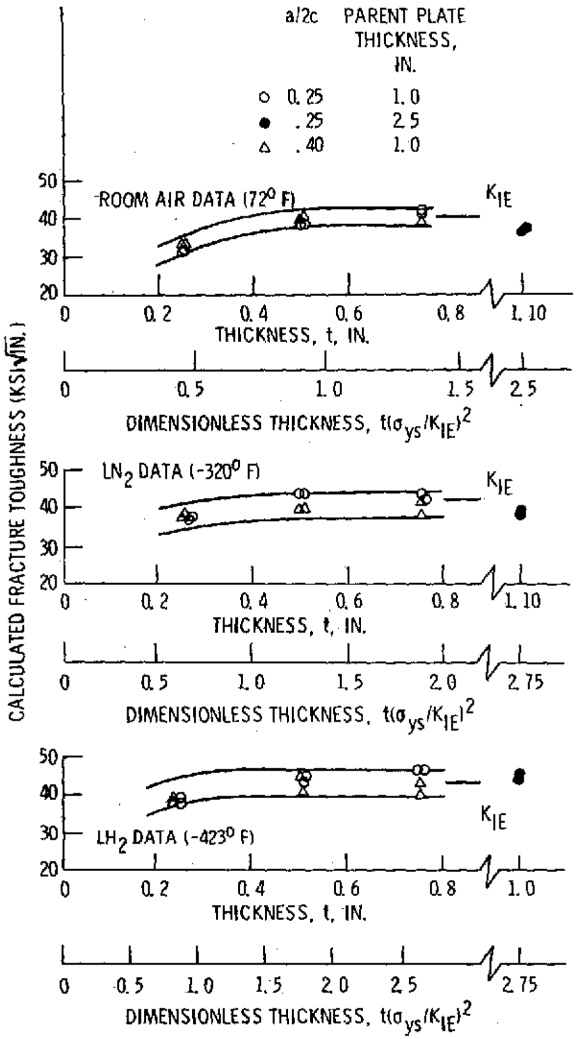

Figure 8. - Fracture toughness for 2219-T87 aluminum surface-crack specimens of various thicknesses (ref. 10).

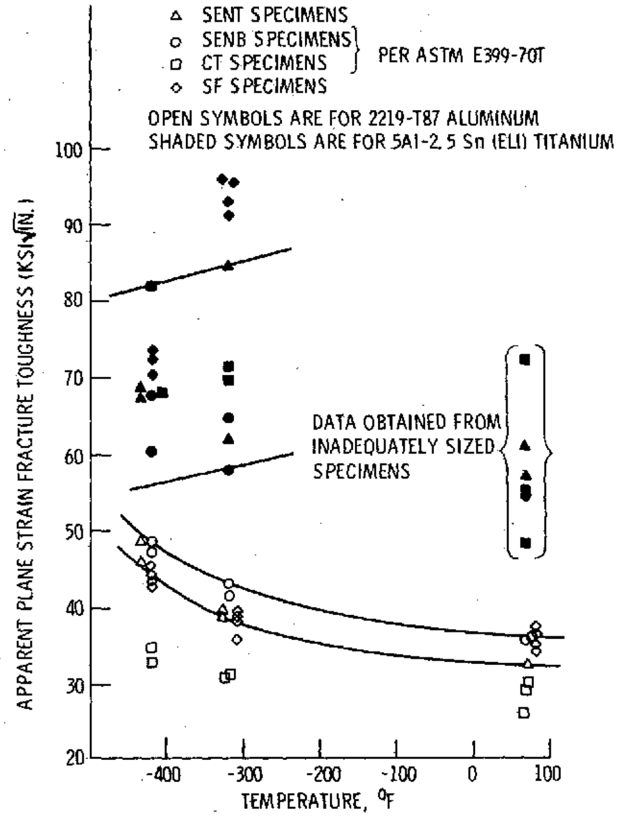

Figure 9. - Apparent plane-strain fracture toughness for aluminum and titanium specimens of various configurations (ref. 10).