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FRACTURE TESTING WITH SURFACE CRACK SPECIMENS

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ABSTRACT

Recommendations are given for the design, preparation, and static fracture testing of surface-crack specimens based on the current state of the art. The recommendations are preceded by background information including discussions of stress intensity factors, crack opening displacements, and fracture toughness values associated with surface-crack specimens. Cyclic-load and sustained-load tests are discussed briefly. Recommendations for further research are included.

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SUMMARY

The primary purpose of this paper is to propose uniform procedures for the design and testing of surface crack specimens. The scope of the paper will be limited to the residual strength test. The specimen and instrumentation to be described will be usable (within certain limitations) for cyclic-load or sustained-load tests as well, but these tests will be discussed only briefly.

Recommendations are given for the design, preparation, and static fracture testing of surface crack specimens based on the current state of the art. The recommendations are preceded by background information including discussions of stress intensity factors, crack opening displacements, and fracture toughness values associated with surface crack specimens. Recommendations for further research are included.

INTRODUCTION

Early in 1920, A. A. Griffith reported [1] that "In the course of an investigation of the effect of surface scratches on the mechanical strength of solids, some general conclusions were reached which appear to have a direct bearing on the problem of rupture . . . " Although he was originally concerned with problems of surface defects, Griffith used the more tractable analytical model of a through-thickness crack to develop his theory. As amended by Irwin [2] and Orowan [3], this theory became the foundation of modern linear elastic fracture mechanics.

In 1959 an ASTM special committee was formed [4] to assist in solving fracture problems involving high-strength solid rocket motor cases. Although these fractures were often traceable to small surface cracks, the committee, like Griffith nearly 40 years earlier, turned to more tractable analytical models and test specimens. Since 1959 the ten-member special committee has become ASTM Committee E 24 and has developed several ASTM test methods and recommended practices. The Committee has also formed a Task Group to develop guidelines for the evaluation of fracture characteristics of materials through tension tests of specimens containing part-through cracks. This paper is based in part on discussions and communications with members of that Task Group.

The primary purpose of this paper is to propose uniform procedures for the design and static testing of surface crack specimens based on the current state of the art. This paper is also intended to note the areas where further systematic research is needed to more fully understand the problem and to develop more definitive test methods. A secondary purpose is to encourage the taking of experimental measurements which are not directly useful now but which are expected to be so in the near future.

The scope of this paper will be limited to the residual strength test. The object of such a test is to determine the residual tensile strength of a homogeneous sheet or plate specimen containing a semielliptical surface crack of specific dimensions; or, by means of a series of such tests, to determine residual strength as a function of crack size and shape. The specimen and instrumentation to be described will be usable (within certain limitations) for cyclic-load or sustained-load tests as well, but these will be discussed only briefly.

BACKGROUND

Historical Milestones

The history of the surface crack specimen includes a number of milestones in testing and analysis. These serve to identify significant steps toward the solution of the problem and to place them in historical perspective.

The first surface crack specimen tests to be reported were run independently and concurrently at the Naval Research Laboratory [5, 6] and at the Douglas Aircraft Co. [7, 8] around 1960. Randall [9] in 1966 studied the effect of crack size and shape on apparent plane-strain fracture toughness (K_{Ic}) values. He also used crack-opening-displacement measurements as qualitative indicators of crack tip deformation phenomena. In 1968, Corn [10] attempted to characterize the natural shape tendencies of surface cracks propagating under cyclic loading. Hall [11] in 1970 compared apparent K_{Ic} values from surface crack specimens with those obtained from other specimen types.

The analysis of surface crack data according to fracture mechanics principles was made possible by Irwin [12] in 1962. From an earlier work by Green and Sneddon [13] he 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 [14] 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. In 1966, F. W. Smith [15] solved the problem of a semicircular surface crack in a finite-thickness plate by a numerical method. Ayres [16] applied a finite difference elastoplastic solution to one semielliptical surface crack geometry in 1968. In 1970, Miyamoto and Miyoshi [7] and Levy and Marcal [18] presented finite element analyses, again for specific geometries. Marrs and Smith [19] presented a method of determining stress intensity factors in plastic models by three-dimensional photoelasticity in 1971. In 1972, Cruse [20] analyzed a semicircular surface crack using boundary integral equations.

Stress Intensity Factors

As yet there is no exact stress intensity solution for the general problem of a semielliptical surface crack in a plate of finite dimensions. Irwin [12] presented an exact solution for the elliptical crack embedded in an infinite solid under tension. He also gave an approximate expression for the maximum stress intensity factor for a semielliptical surface crack in a plate, which was based on an analogy to the problem of an edge crack in a half-plane. He assumed that his approximation would provide a useful stress intensity estimate for $a < c$ and $a < t/2$ (see Fig. 1 for nomenclature). Indeed, his estimate did provide fairly constant fracture toughness values from tests of small surface cracks in relatively brittle high-strength rocket motor case steels [6, 21].

A number of investigators [14, 15, 22-29] have attempted to extend the applicability of Irwin's approximation to surface cracks deeper than half thickness. 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 approximate methods differ one from another, and in some cases the calculated stress intensity factors differ considerably [29, 30]. Several methods have been compared [27-29, 31] on the basis of their ability to produce constant fracture toughness values from selected sets of experimental data, but no one approximation has yet been shown to be clearly superior.

Attempts to develop three-dimensional solutions have produced only limited results. Smith's numerical solutions for the semicircular [15] and circular-segment [28] surface cracks are thought to be fairly accurate (except near the intersection of the crack and the cracked surface). Other numerical methods [16-18, 20] have treated only specific geometries, and their accuracies are restricted by computational limitations.

Most of the solutions and approximations just discussed consider only the cracked plate under uniform tensile load. Only a few [15, 24, 26, 29] have considered the case of linearly varying (bending) stress, and none have yet considered higher-order variations.

Crack Opening Displacement

Experimenters have learned that valuable information can be obtained from crack-opening-displacement (COD) measurements on surface-crack specimens. The term "COD" is used herein to denote the displacement of the crack faces on the cracked surface at the midpoint of the crack (see Fig. 2); the same term is sometimes used by others to denote displacement at the crack tip. Randall [9] was apparently the first to measure surface-crack COD. His specimens were instrumented primarily to observe possible pop-in behavior, but from the load-COD records he was able to infer the presence of significant crack tip plastic flow. Tiffany et al [32] used COD measurements as qualitative indicators of subcritical crack growth. Collipriest [33, 34] and Ehret [35] have attempted to make quantitative use of COD measurements, and some recent COD data are included in Ref. 36.

Examples of COD trends for several possible fracture phenomena are shown in Fig. 2. Straight-line segments (OB, DC, GJ) indicate elastic deflections, and their slopes are functions of crack size and shape. Nonlinearities (AC, AF, JL) may be due to crack growth, crack tip plastic flow, or a combination of both. The cause of the nonlinearity can sometimes be determined by unloading the specimen prior to fracture; a change in slope (unloading versus loading) is indicative of actual crack growth and zero offset is indicative of crack tip plastic flow. Path OBH in Fig. 2 represents the classical Griffith-type brittle fracture. With real materials, several other paths are possible.

Crack tip plastic flow, subcritical crack growth, or a combination of both may result in the nonlinear path AC. If the crack is sufficiently deep and the material sufficiently tough so that the crack tip plastic zone penetrates the thickness prior to fracture, a path such as AF may result. Or, the crack may pop in (AD) to a new stable shape (DC). Once an instability point (C, B, or F) has been reached the crack may then propagate catastrophically (CH, BH, or FH) or it may arrest (G) as a through-thickness crack; with further loading the specimen behaves (GJL) as a through-crack specimen.

Figure 3 shows an actual load-COD record from Ref. 34, and a photograph of the fracture face is inset. The first major load cycle exhibits linear behavior on loading, nonlinearity due to crack growth and plasticity, change in slope on unloading, and zero offset. The specimen was then load-cycled at a low 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 subcritical growth.

Quantitative analysis of COD measurements from surface crack specimens is hampered by several factors. One is the lack of an elastic solution for COD as a function of crack size and shape. Green and Sneddon [13] give the complete displacement solution for the elliptical crack in an infinite body, and Smith [15] gives an approximate COD value for the semicircular surface crack in a half-space. There are no other analytical expressions available, but one empirical expression [34, 35] has been developed. Another problem is that the effect of measurement-point gage length has not been identified. Analyses have shown that COD for the center-crack [37] and the three-point-bend [38] specimens are functions of gage length, but there is no corresponding analysis for the surface crack. This problem can be minimized by making the gage length as near zero as possible.

It is hoped that this report will point out the need for more analytical and experimental work in this area. In the meantime, experimenters should not be discouraged by the lack of analytical tools. COD measurements can provide valuable qualitative insight into fracture phenomena. If test records are preserved and adequately documented, they may be analyzable in the near future.

Fracture Toughness

The basic concept of fracture toughness has undergone considerable evolution. Originally it was hoped that the critical strain energy release rate ($\mathcal{G}_c$) would be a unique material property that would characterize all sharp-crack fractures. It soon became apparent [21] 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 [39] 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 empirically-developed size requirements for bend and compact specimens. These size requirements became the foundation of the ASTM Test for Plane-Strain Fracture Toughness of Metallic Materials (E 399 - 74), which now provides an operational definition of K_{Ic}.

The application of fracture toughness concepts to surface crack specimen testing has also been evolving. The second report of the ASTM special committee [21] suggested that K_{Ic} could be determined from surface crack specimen tests, and the fifth report [40] 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 and on the concept of K_{Ic} as a vaguely-defined lower limit. Subsequent studies have indicated that they represent idealizations of what can be a very complex fracture process.

Randall [9] studied the effect of crack size and shape on apparent fracture toughness values from surface crack specimens of D6AC steel and of titanium-6Al-4V. He 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 a plane strain size requirement was advanced [39], which at least partly explains 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. It appears that his specimens were not large enough to simulate plane strain conditions for the tougher materials.

The size requirements of ASTM E 399-74 were developed specifically for the bend and compact specimens. Hall [11] attempted to empirically determine size requirements for surface crack specimens. In his tests, calculated fracture toughness was reasonably constant as long as the crack depth (a) and the uncracked ligament depth (t-a, Fig. 1) were both greater than about 0.5 $(K_{IE}/\sigma_{ys})^2$, where σ_{ys} is the material yield strength. The designation K_{IE} is customarily given to apparent toughness values obtained from surface crack specimens, as distinguished from K_{Ic} values determined according to ASTM E 399. The tests reported in Ref. 41 support at least part of Hall's findings.

It is not a simple, straightforward matter to obtain a constant fracture toughness value (or to correlate fracture stress with crack dimensions, which is equivalent) over a wide range of crack size and shape. One impediment to analysis is the interaction between the stress intensity analysis and the failure criterion, both of which have particular uncertainties when applied to real materials. It is often difficult to determine whether fracture data trends are due to inexactness of the stress intensity calculation or to deficiencies in the failure criterion. In addition to the basic Irwin criterion, several semi empirical failure criteria [42-45] have been advanced. These methods show varying degrees of ability to produce constant toughness values from selected sets of data, but none has yet proven to be universally applicable. Another complicating factor is stable subcritical crack growth. 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 [46]. Also, if the crack grows a significant amount it may no longer be semielliptical, which further confounds analysis.

Hall [11] also compared K_{IE} values from surface-crack specimens with K_{Ic} values determined from bend and compact specimens according to ASTM E 399-70T. The specimens were machined from thick plate so that all cracks propagated in the thickness direction. Although encouraging, Hall's results were not conclusive nor entirely consistent. Actually, one should not expect K_{IE} and K_{Ic} values to be identical, since they are differently defined. K_{IE} values are based on maximum load while K_{Ic} values are based on the load corresponding to 2 percent crack extension. This consideration was pointed out earlier by Collipriest [33].

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 the 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 as tentative.

RECOMMENDATIONS

Rationale and Test Planning

Surface crack specimens were originally chosen because they were very good models of the types of flaws found in service. But because the surface crack specimen is such a realistic model, it is subject to the same complicated phenomena that often occur with natural cracks in real structures. In spite of these obstacles the original rationale is still 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 the specimen thickness is 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. A crack size range which results in a fracture stress range from near ultimate tensile strength to about 80 percent of hardware operating stress will generally be adequate for design purposes.

Specimen Design

A typical surface crack fracture specimen and the notation and conventions used herein are shown in Fig. 1. Grip details have been omitted, since grip design may depend on specimen size and the available test fixtures. Small specimens ($W \leq 4$ in. or 10 cm, approximately) are usually loaded through a single pin and clevis on each end. Larger specimens are usually bolted (using a multiple-hole pattern) to adapter plates which in turn are loaded through large single pins. In general, the only requirements are that the gripping arrangements be strong enough to carry the maximum expected load and that they allow uniform distribution of load over the specimen cross-section.

Since surface crack specimens are usually tested to model a flaw in an actual or intended structure, the specimen thickness should be the same as in the intended application. The specimen test section should be long enough and wide enough to simulate an infinite plate, since corrections for finite length and width are not available. If the specimen is too narrow, the stress distribution around the crack will be altered and the fracture stress will usually be lowered. However, overconservatism may drastically increase testing machine load requirements. Unfortunately only a few systematic tests have been reported [35, 36, 47]. These tests suggest that a specimen width 5 times the crack length will be adequate for practically all surface crack tests. Earlier recommendations [39, 40], based on analogy to through crack specimens, are probably inadequate. Test section length is seldom a practical problem, and no systematic minimum-length tests with surface crack specimens can be found in the literature. However, a test section length twice the section width is generally considered sufficient.

In summary, the following criteria should ensure a valid simulation of an infinite plate with a surface crack:

$$t = \text{Service thickness}$$

$$W \geq 5 \times 2c$$

$$L \geq 2 \times W$$

Specimens somewhat shorter or narrower may provide equally valid simulations. However, there are not enough systematic test data to provide accurate guidelines, and the burden of proof must necessarily rest on the experimenter. Should these width and length criteria exceed the actual service dimensions then, of course, the service dimensions should be used, but one should not then attempt to generalize data from such tests.

Specimen Preparation

Here the object is to produce a fatigue crack whose configuration is regular (that is, a half-ellipse or a segment of a circle), whose depth and length are fairly close to predetermined target values, and whose subsequent fracture behavior will not be influenced by any detail of the preparation process. Regularity of crack configuration is primarily a function of material homogeneity and fatigue load uniformity. The former is usually beyond control but the latter is straightforward.

Although crack starters can be produced in some materials by arc burns [9] or by localized hydrogen embrittlement [5], machining methods are preferred today because they offer better dimensional control and can be used on almost all materials. Slitting with thin jewelers' saws of various diameters and electrical discharge machining (EDM) with shaped electrodes are the most popular methods.

Fatigue crack size and shape control is more of an art than a science at present. While the crack length can be monitored visually, the crack depth cannot. Different experimenters have each developed their own techniques, generally based on a considerable history of trial and error. However, there appear to be basically two techniques.

One approach is to vary the starter size and shape or the stress field or both to achieve the desired final configuration. For example, Corn [10] determined "preferred propagation paths" (plots of crack depth against crack length) for cracks grown in axial tension or in bending fatigue from small starters. Cracks (or starters) not on these paths should tend to approach them with further cycling. In axial tension, cracks grown from simulated point defects tend to remain nearly semicircular as they grow; in bending, the ratio a/2c tends to decrease with increasing cyclic propagation. The propagation path for a given starter configuration can be determined experimentally by alternately fatigue cycling and marking (low-stress cycling). Then the specimen is broken and points on the propagation path obtained by measuring the marking bands on the fracture face. When propagation paths have been determined for several starter configurations, the starter size which should give the desired final size and shape can be selected and the crack depth inferred fairly closely from measurements of the crack length.

The other approach to crack size and shape control is to use a very sharp starter of very nearly the desired final dimensions. If the fatigue crack is then grown only a short distance, the crack shape will not change very much.

Although this approach would seem to be simpler, its proper use requires considerable experience. The fatigue crack is sometimes resistant to initiation around the entire periphery of the starter. If a circular-segment starter is extended only a short distance, the fatigue crack will usually be a segment of a circle rather than a semiellipse, and this may introduce additional uncertainties into the data analysis.

It should be noted that crack propagation paths may be material dependent even if the materials are isotropic, and will be width-dependent if the specimen is not wide enough to simulate an infinite plate. It should also be noted that compliance measurements [33-35] and ultrasonic measurements [48-49] may be used to give at least a qualitative real-time indication of crack depth change.

For most through-crack fracture specimens the procedures that must be followed to produce an effective sharp fatigue crack are well established. Analyses and experiments have defined the maximum permissible envelope within which the fatigue crack and its starter must lie. Experiments have established the maximum allowable stress intensity factor during fatigue cracking (K_f) as a fraction of the plane strain fracture toughness (K_{Ic}) or as a function of the elastic modulus (E), and also the amount of fatigue crack extension needed to eliminate the influence of the starter geometry. Stress intensity factor analyses (K-calibrations) provide the basis by which these findings can be transferred from one specimen type to another. Unfortunately there has been no comparable effort to determine proper crack preparation procedures for surface crack specimens. Thus we must rely wherever possible on procedures developed for through crack specimens. Certain requirements from ASTM E 399-74 should, in principle, be applicable to surface-crack specimens as well, and these (with the appropriate section number in parentheses) are paraphrased in the following:

(a) The fatigue crack and its starter must lie entirely within an imaginary 30^{o} wedge whose apex is at the crack tip (7.2.2).

(b) The fatigue crack extension shall be not less than 5 percent of the final crack length and not less than 0.05 in. (1.3 mm) (7.2.3).

(c) Fatigue cracking shall be conducted with the specimen fully heat treated to the condition in which it is to be tested (7.4).

(d) Fatigue cracking by cantilever bending is prohibited (7.4.1).

(e) The value of K_f shall be known with an error of not more than 5 percent (7.4.1).

(f) For at least the final 2 1/2 percent of the final crack length, the ratio K_f/E shall not exceed 0.002 $in^{1/2}$ (0.00032 $m^{1/2}$). Furthermore, K_f must not exceed $0.6 \times K_{Ic}$ (7.4.2).

(g) The load ratio $R = K_{min}/K_{max}$ should not exceed 0.1 (7.4.3).

(h) When fatigue cracking is conducted at a temperature T_1 and testing at a different temperature T_2, then $(K_f/\sigma_{ys})_{T_1}$ must not exceed $0.6 \times (K_{Ic}/\sigma_{ys})_{T_2}$ (7.4.4). The requirement on K_f/E is presumably unchanged, probably since elastic moduli are seldom as sensitive to temperature as are yield strengths.

Items (a) and (b) should probably be applied around the entire periphery of the surface crack. The first requirement of item (b) is feasible, but the second can be applied only when the crack depth is to be greater than about 0.06 in. (1.5 mm). Items (c) and (g) can be applied directly to the surface crack specimen. Since cantilever bending does not present a crack planarity problem with surface cracks, item (d) need not apply. Item (e) and the first requirement of item (f) cannot be strictly applied at present for lack of a rigorous elastic stress intensity analysis, but an estimate of K_f can be made using the bast approximate analysis currently available. Item (h) and the second requirement of item (f) cannot be applied for lack of an unequivocal operational definition of K_{Ic} (or K_{IE}) for surface crack specimens.

From the preceeding discussion the following guidelines for fatigue cracking of surface crack specimens can be extracted:

(1) Fatigue crack with the specimen in the heat-treat condition in which it is to be tested. Axial tension or cantilever bending are the most common modes of loading.

(2) Whenever it is physically possible, the crack should be extended at least 0.05 in. (1.3 mm); in any event the fatigue crack extension must not be less than 5 percent of the final crack length, and the crack and its starter must lie entirely within an imaginary 30^{o} wedge whose apex is at the crack tip. These two-dimensional descriptions shall apply around the entire crack front, that is, in all planes normal to tangents to all points on the crack periphery (see Fig. 4).

(3) The load ratio R shall not be greater than 0.1.

(4) For at least the final 2 1/2 percent of the total crack depth, the ratio K_f/E should not exceed 0.002 $in^{1/2}$ (0.00032 $m^{1/2}$). Until more exact stress intensity solutions are available, use the best approximations currently available (such as [28] for circular-segment cracks or [29] for semielliptical cracks) and document the fatigue cracking loads and crack dimensions.

Instrumentation

An instrumentation system for surface-crack COD measurements should meet the following general requirements. System gain, resolution, and stability must be sufficient to provide an interpretable test record. If COD measurements during cyclic loading of the specimen are anticipated, the system gain should not change nor should the zero setting shift significantly for the duration of the test or between recalibrations. Gage length should be as small as possible. The method of attaching the gage (or clips) to the specimen must not alter either the material properties in the vicinity of the crack tip or the specimen compliance.

The clip gage described in ASTM E 399 should be an adequate transducer. Modern DC amplifiers can supply more than enough gain, and stability should be adequate if the strain gage excitation level is properly chosen [50]. If this clip gage is to be used cyclically, some attention should be given to the fatigue life of the strain gages [51]. In order to make the gage length as small as possible, small brackets or clips (Fig. 5) with integral knife edges are often microspotwelded to the specimen as near as possible to the crack; the effective gage length is then the distance between the spot centers. If the crack is large enough, knife edges can sometimes be machined into the cracked face of the specimen itself [11]. The knife-edge geometry specified in ASTM E 399 should be appropriate. While other transducers and attachment methods are possible, the clip gage and spotwelded bracket are currently the most popular.

An experimentally determined parameter which is considered useful in the analysis of nuclear reactor pressure vessels is the gross strain crack tolerance. Gross strain is defined as the strain at the crack location, normal to the crack plane, that would exist if the crack were not there. Methods of measurement and application are described in Refs. 52 and 53.

Propagation of a surface crack entirely through the specimen thickness (breakthrough) under either monotonic or cyclic load is often an event of interest.

If the test is conducted in room air, visual observation under oblique lighting is sometimes sufficient. But for most environmental tests that is, in cryogenic liquids or aggressive fluids), remote-reading instrumentation is necessary One approach is to bond a frangible wire to the back face of the specimen immediately behind the crack and connect it to a simple continuity circuit. Another method is to clamp a pressure or vacuum chamber to the back face; when breakthrough occurs, pressure or vacuum is lost causing a sensitive pressure switch to be actuated.

Test Procedure

Customary test procedure today is similar to good conventional tensile testing practice. Examples of such practice may be found in the ASTM Methods for Tension Testing of Metallic Materials (E 8) and for Sharp-Notch Tension Testing of High-Strength Sheet Materials (E 338). There apparently has been no systematic study of the effects of load-train misalignment on subsequent surface-crack fracture behavior. Thus it is important to align the specimen as carefully as possible. Universal joints or other self-aligning devices in the load train are desirable. When testing large specimens with multiple-bolt-grips it is sometimes helpful to temporarily attach an extensometer to each edge of the specimen to verify uniformity of loading.

There is no clear-cut preference for either load control or displacement control in testing, nor any indication to date of a significant difference in test results. However, it seems reasonable to use the type of control more closely resembling the anticipated service conditions. Load or cross-head rates are customarily chosen so that failure occurs within one to three minutes after the start of loading.

In post-fracture examinations, polarized lighting [54] often brings out subtle details of crack growth history on the fracture face. Optical micrometers (traveling microscopes) are often used to measure crack dimensions, or enlarged photomacrographs of the fracture face can be measured with a precision scale if the magnification is accurately known. If an irregular crack (i.e., one having a shape other than a half-ellipse or a segment of a circle) is not photographed, enough dimensional measurements should be taken so that the crack front contour can be reconstructed.

Analysis and Reporting

A specific method of data analysis cannt be recommended at present since, as discussed earlier, the analysis of surface crack fracture data is far from a closed issue. A plot of gross fracture stress against some measure of crack size is the simplest and most generally useful way to display data. In most cases the parameter a/Φ^2 (where Φ is a dimensionless function of crack ellipticity [12, 13]) is as good a measure of crack size as any. For tests involving deep cracks in thin sections it is sometimes useful to plot gross fracture stress against crack length [41].

In reporting test results, analysis of the data is not nearly as important as the reporting of <u>all</u> pertinent information. At the present time, analysis of the data is essentially optional. As a minimum, the following should be reported:

(1) Material and heat treatment. If the toughness of the material is known to be sensitive to heat-treatment parameters such as quench rate (D6AC steel) or annealing history (titanium alloys), these should be described in detail.

(2) Crack and load orientation with respect to material grain direction.

(3) Conventional tensile properties and elastic modulus using specimens from the same lot of material (if the material is uncommon, a full

stress-strain curve is desirable).

(4) Crack starter depth, length, shape, and method of production.

(5) Type of loading for fatigue cracking, maximum load or stress, R-ratio, and cyclic frequency.

(6) Initial (starter plus fatigue) crack depth, length, and shape.

(7) Width, length, and thickness of specimen test section.

(8) Test temperature, environment, and method of control.

(9) Maximum load or corresponding gross-section stress.

(10) Estimated precision and accuracy of the measurements above and of all major instrumentation.

If the following information is available, it should also be reported:

(11) Chemical analysis of material and source of analysis.

(12) Number of fatigue-cracking cycles from first visible microcrack to finished size.

(13) Elastic compliance (COD ÷ load) for each test, COD gage length, and at least "typical" load-COD curves. If space or other considerations prohibit the presentation of all available load-COD curves, the curves should be preserved and thoroughly documented for future reference.

(14) Loads or stresses corresponding to observed significant events such as pop-in and breakthrough.

(15) Gross strain to fracture and measurement gage length.

(16) Miscellaneous measurements such as hardness and Poisson's ratio.

Other Tests Using Surface Crack Specimens

As stated earlier, the specimen configuration, preparation, and instrumentation that have been described are usable for other than residual strength tests. However, certain constraints are peculiar to each test.

Surface-crack specimens have been used to determine crack propagation characteristics under sustained load in both benign and aggressive environments [32, 55, 56]. The maximum cyclic load (or stress intensity) during fatigue cracking must be substantially less than that to be sustained during the test, otherwise an erroneously high apparent threshold will be indicated. Also, if the material exhibits any stable crack growth on rising load, the sustained test load should be applied with the specimen already in the test environment. If the specimen is loaded in air and then introduced to the environment, a higher threshold may be indicated.

Surface-crack specimens have also been used to determine crack propagation characteristics under cyclic load. A major problem in such testing is that the parameter of interest is the change in crack depth, which usually cannot be measured directly. Ultrasonic [48] and compliance-derivative [34] methods have been used to infer the depth of a propagating crack in real-time. Note that the specimen size requirements discussed earlier should be established based on the largest final surface-crack size of interest.

Recommended Further Research

Further systematic studies to determine minimum test section width and length are desirable. Additional studies of surface-crack shape change during fatigue cracking would greatly reduce the amount of trial and error needed by experimenters new to the field. Experimental determination of the maximum crack starter envelope and the minimum fatigue crack extension would also be valuable. The maximum fatigue cracking load (or K_f/E) needs to be determined, and the effect of load-train misalignment needs to be examined.

An exact stress intensity and displacement solution for the semielliptical surface crack in a finite plate would be extremely beneficial. Until such is available, a series of fracture tests covering a wide range of crack size and shape in a brittle metal might allow the endorsement of one of the available stress intensity approximations. Further analytical and experimental compliance studies would be most valuable. The maximum allowable COD gage length must be determined, and alternate transducers and methods of attachment should be considered.

Finally, the phenomenon of stable crack growth under rising load deserves concentrated study. It is possible that some of the of the R-curve concepts [57] developed for thin-sheet testing can be applied to surface crack specimens.

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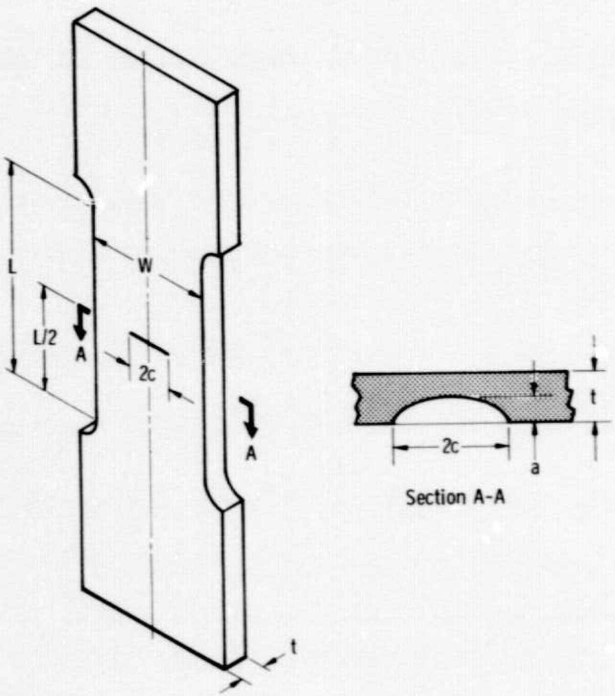

Figure 1. - Typical surface-crack specimen (grip details omitted) and nomenclature.

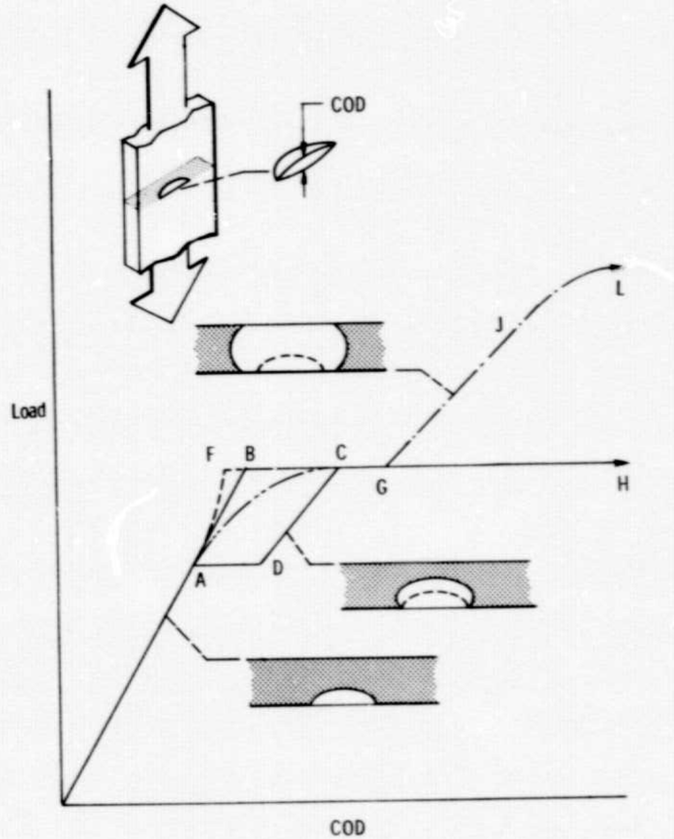

Figure 2. - Surface-crack opening displacement (COD) trends for several possible fracture phenom·na.

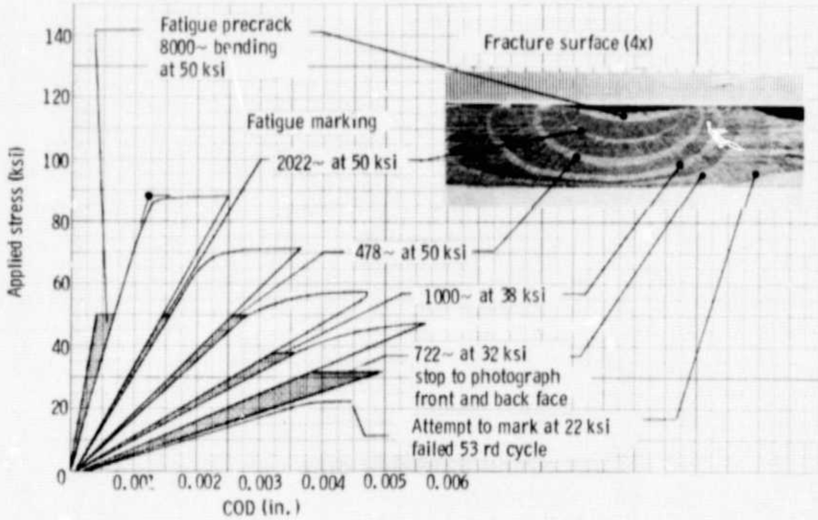

Figure 3. - Load-COD record and fracture face (Ti-6Al-4V-STA, 1/4 in. thick, ref. 34).

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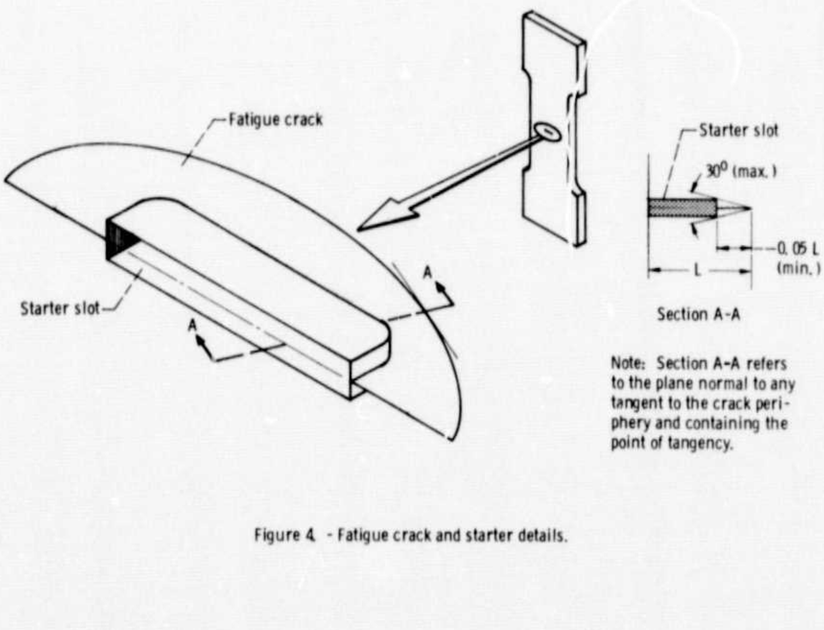

Figure 4. - Fatigue crack and starter details.

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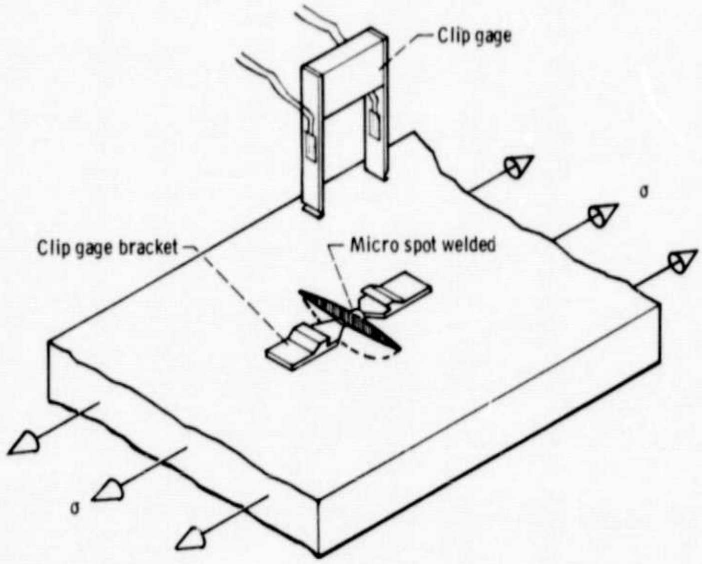

Figure 5. - Typical experimental setup for COD measurement.