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THE INFLUENCE OF SPECIMEN CONFIGURATION ON YIELD ZONE FORMATION AND FRACTURE RESISTANCE

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INTRODUCTION

The mechanism of plane stress fracture, is frequently associated with the formation of plastic zones that extend ahead of the crack tip to distances in excess of the material thickness, although net section stresses remain elastic. Unstable fracture is usually preceded by stable crack growth, i.e., initiation occurs at loads well below maximum. Efforts to characterize this mode of crack extension have been based almost exclusively on the resistance curve concept, [1], which has recently received considerable attention [2, 3] and is the subject of an ASTM recommended procedure [4]. The concept appears to offer a means of establishing both the manner in which fracture toughness varies and cracks extend prior to instability. However, it has recently been shown experimentally, that the resistance curve and hence toughness, are subject to variations at a given thickness, particularly due to changes in specimen configuration [5, 6].

The first part of this paper described briefly the crack growth resistance curve concept, followed by a section describing the experimental methods used to obtain the curves. A description is then given of the results of an elastic-plastic finite element analysis, which has been used in an attempt to explain the differences observed in the fracture characteristics revealed by the experimental results.

THE CRACK GROWTH RESISTANCE CURVE CONCEPT

The fundamental concept of crack growth resistance is an extension of the Griffith-Irwin energy balance analysis, to instances where some measure of stable crack growth occurs prior to instability. The crack growth resistance, R, is defined as the work required to produce a unit area of crack extension. In materials where the thickness is such as to permit stable crack growth, R is not a constant quantity, but in general increases, as the crack extends from its initial length a_0. This variation of R when plotted as a function of crack length is referred to as a crack growth resistance curve (R-curve). Figure 1 shows an R-curve typical of thin section failure.

All structural materials have an inherent resistance to crack growth, i.e., in the presence of a flaw, failure does not occur at the first application of load. Thus in order that a crack can grow in a stable manner some energy must be supplied. This quantity of energy, often referred to as the crack driving force, is equivalent to the elastic energy released per unit area of crack extension G, which is related to both the applied load

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and the instantaneous crack length. Thus in Figure 1 a family of G curves exists, each curve representing a specific load. When stable crack extension occurs, the elastic energy release rate must equal the crack growth resistance and this condition is represented by the points of intersection of the G curves with the R-curve, as shown in Figure 1. Crack extension at these points is stable, since any increment of growth provides a greater increase in R than in G, and an increase in load is then required for further growth. Eventually, however, a point arises where the G curve becomes tangential to the R-curve, at which the increase in R no longer matches that of G and instability occurs. This point provides a critical value of the elastic energy release rate, G_c, which defines the fracture toughness value K_c (K_c = EG_c for plane stress). An inescapable conclusion of the R-curve concept is that, at any particular material thickness, there is no single value of K_c, if that thickness is such as to permit stable crack growth. This result is a consequence of the shape of the G curves, which are derived from the elastic compliance of the cracked structure.

The resistance that develops against fast fracture is partly associated with the formation of the zone of plastically deformed material at the crack tip. The larger the plastic zone becomes, the greater the amount of irrecoverable work that must be done prior to fracture. The toughness increases with specimen width and approaches a maximum value assymptotically. Thus, the more readily a material yields, the wider the specimen must become in order to completely describe the R-curve and make the test meaningful.

The R-curve concept thus appears to offer valuable information in an investigation of thin sheet fracture. In cases where final failure occurs at a load considerably greater than that necessary to initiate crack extension, the concept can be used to determine both critical toughness values and their associated critical crack lengths. However, an important question bearing examination is whether any variation in specimen configuration will lead to a change in crack tip yielding, which affects the amount of irrecoverable work done and hence the fracture resistance. To examine the possible consequences of such variations, testing on specimens of different configuration was undertaken.

TESTS AND RESULTS

Results have been obtained from tests conducted on a number of aluminum alloys [5, 6] at two different thicknesses (1.6 mm and 3 mm) using centre cracked sheets (CCS) and compact tension specimens (CTS) up to 750 mm wide. In [5] the CTS configuration was that required for plane strain test specimens [4], whereas in [6] the CTS dimensional ratios were changed to improve stability of crack growth direction. However, in all cases experimental compliance calibrations were obtained independently for each specimen type. All tests were carried out under displacement control and the use of anti-buckling guides was essential to inhibit deflections normal to the plane of the specimens.

For each fracture test, a record of applied load against crack opening displacement was obtained. A typical test record commences with a straight line, the slope of which relates elastic crack opening to the applied load. Following initial deviation from linearity due to yield at the crack tip, subsequent deviation can be attributed to greater amounts of yielding which may be combined with stable tearing of the material. It is not possible to separate these two effects from the test record alone. During the tests in [5] an additional photographic record was taken with

each photograph being related to its appropriate point on the load-displacement record by an event marker, thus permitting measurement of stable tearing at known intervals during the test.

From the load-displacement records and the compliance calibrations, it is possible to determine the effective crack length, a_e, at any load and thus to construct the R-curves. In order to present the results in the more usual units of stress intensity, crack growth resistance is expressed as K_R where

$$K_R = \frac{PY_1\sqrt{a_e}}{BW} \quad \text{for a CCS} \tag{1}$$

and

$$K_R = \frac{PY_2}{BW^{1/2}} \quad \text{for a CTS} \tag{2}$$

Y_1 and Y_2 are the non-dimensional compliance functions appropriate to each specimen type [4, 7, 8]. Results are shown in Figures 2, 3 and 6 for three aluminum alloys, L71, L104 and Hiduminium 48. The fracture behaviour of the latter differs somewhat from that of the L class alloys, tending to exhibit greater amounts of yielding and lesser amounts of stable tearing. The open circles on the curves represent the value of K_c for the widest specimen tested, calculated using the critical value of a_e. In an attempt to explain the obvious differences in resistance curve shape and toughness for the two specimen types, a finite element analysis was undertaken.

FINITE ELEMENT ANALYSIS

Using three node constant strain triangular elements it had been shown [9] that for plane strain conditions, the area of yielded elements at the crack tip was much larger in a CCS than a CTS at the same elastic K value. In addition, yielding in the first element occurred at a higher K value in the CTS. In view of the fact that toughness is related to crack tip plastic zone size a more refined analysis, under plane stress conditions, was conducted to examine plastic zone size, load-displacement curves and near tip crack opening displacement (COD), for the two specimen configurations.

Finite element meshes with crack aspect ratios, a/w equal to 0.35, 0.5 and 0.75 were automatically generated for the eight node quadrilateral isoparametric finite element, with local refinement at the crack tip, using BERSAFE [10]. As a result of symmetry, 90 elements represented one half of the CTS: and 104 elements represented one quarter of the CCS. The stress-strain curve adopted was for an elastic linear work hardening material, characterized by 2760 $MN.m^{-2}$ per unit strain. The accuracy of the meshes used was assessed by comparing the elastic solution for Y_1 and Y_2, at a/w = 0.5 with analytical results. For the CCS a value of 2.120 compares with 2.104 [7] and for the CTS 9.56 compares with 9.60 [4]. Figure 4 shows the development of the plastic zone through the numerical integration points of the elements for the CCS and CTS at two equal K values.

DISCUSSION OF RESULTS

The R-curve concept is an extension of linear elastic fracture mechanics to situations of contained yielding. At present, a commonly accepted criterion for defining the limit of application of elastic analysis, is that net section stress levels at failure should not exceed 80% of yield. In the CCS specimens, the L71 and L104 net section stresses were as low as 45% of yield, but for Hi48 failure occurred just below general yield on the net section. For a CTS such a simple limit cannot be readily defined, due to the complex stress distribution across the ligament.

It can be seen from Figure 2, for L71, that at lower K_R values the CTS curve is marginally steeper than the CCS curve. As the K_R values increase however, the slope of the R-curve for the CTS decreases, indicating that a limiting value of K_R will be attained. Whilst this feature is not evident for the CCS, it does not imply that it will not occur at much greater widths. For Hi48, Figure 3, neither specimen type exhibits a tendency towards a limiting value of K_R at the width tested.

From the photographic evidence it was apparent that Hi48 exhibited relatively small amounts of stable crack extension before failure. As a result, the finite element analysis more closely replicated the behaviour. Thus use was made of the analytical load-displacement record to obtain a theoretical R-curve for the two specimen types, shown in Figure 5. As can be seen, the relative shape and disposition of the R-curves for the two specimen types are the same as those obtained for Hi48 and for the lower values of K_R in L71. (NB: A comparison with Figure 6 must not be made because the crack increment ordinate is based on a different quantity.) That the CTS R-curve is steeper can be explained by the fact that the elastic K value to produce equivalent plastic zone sizes, (i.e., which represent increases in compliance crack lengths), is higher for a CTS than a CCS, as shown by the results of the finite element analysis, Figure 4. In addition, for $a_e - a_o$ as an increasing percentage of a_o, the term Y_2 of equation (2) increases more rapidly than $Y_1\sqrt{a_e}$ of equation (1), such that the value of K_R in a CTS increases at a greater rate.

As shown in Figures 2 and 3 the values of K_c are lower in the CTS than the CCS. This behaviour was common to almost every test result reported in [6, 11] for many different comparative widths. It was shown in [6] that extrapolation of photographic records of stable crack growth, back to initiation for both specimen types, indicated that it occurred at the same K_{Ii} value. Using the results of the finite element analysis, an examination of the variation in COD, as reflected by the displacement of the second node behind the crack tip, (i.e., avoiding the excessively deformed crack tip region), as a function of K_R indicates almost identical behaviour for the two specimen types. Thus, a common COD for initiation would indicate a common K_{Ii} in keeping with experimental evidence. However, if this argument is extended to assume that a common COD exists at failure, then similar K_c values would be predicted, which is in conflict with experimental results. Hence it would appear that although initiation occurs at a common COD in each specimen type, the critical toughness is influenced by the extent of stable tearing prior to failure.

In Figure 6, K_R curves [11] are plotted for L104, which has a similar specification to L71, as a function of absolute crack length (i.e., the stable tearing contribution). It can be seen that the CTS's exhibit much more stable crack extension at all K_R values than CCS's. Thus, any similarity in compliance R-curves for the different specimens at lower K_R values, is not a consequence of identical crack tip behaviour.

With regard to the lower limiting value of K_R shown by L71 and L104 in CTS specimens, this can be explained in terms of the plastic zone size. As an example, consider two specimens, having identical configuration, but

materials with different levels of ductility. The material with the lower ductility will exhibit lower toughness, and this can be attributed to the smaller plastic zone size. Now, in a comparison of a CCS and a CTS, of identical material, the stress distribution ahead of the crack in the CTS is such that the plastic zone is constrained, and cannot develop to the same size as in the CCS. It is this constraint which inhibits the level of maximum toughness in the CTS.

CONCLUDING REMARKS

It has been demonstrated experimentally, by tests on specimens of different configuration, but of equivalent width, that material at a specified thickness will not have a single characterising R-curve or toughness. The variations observed in differing configurations can be explained in terms of the plastic zone development at the crack tip, which has been examined by finite element analysis.

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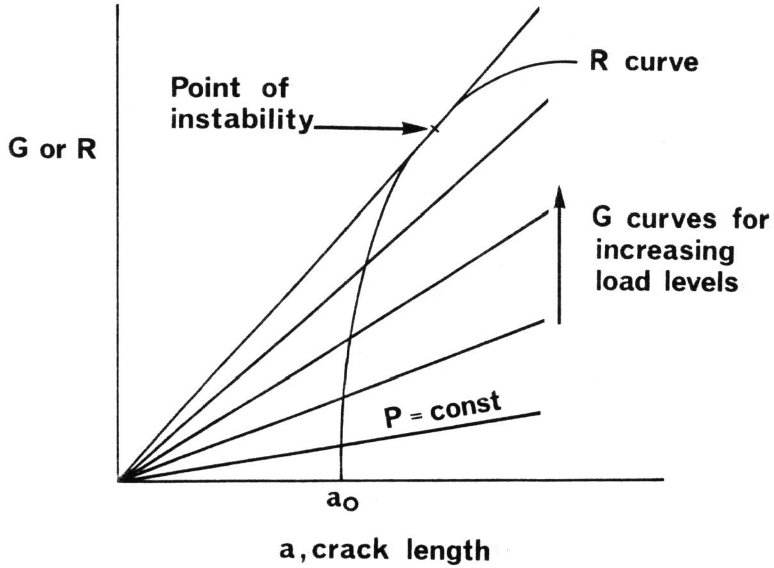

Figure 1 Schematic Representation of G-R Curve Relationship

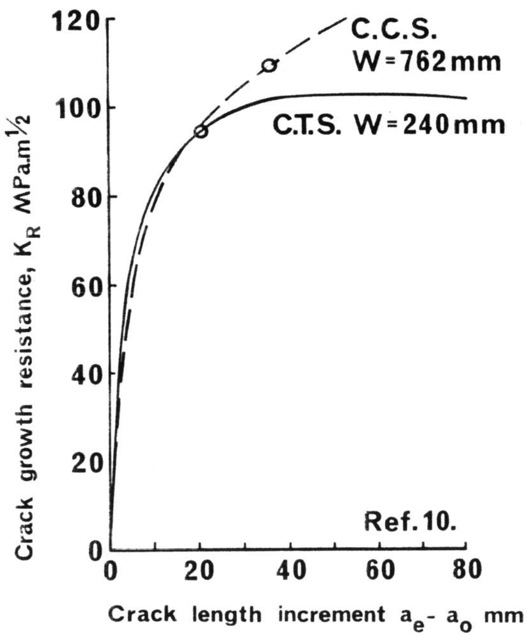

Figure 2 Compliance Indicated Resistance Curves for L71 for Centre Crack Sheets and Compact Tension Specimens

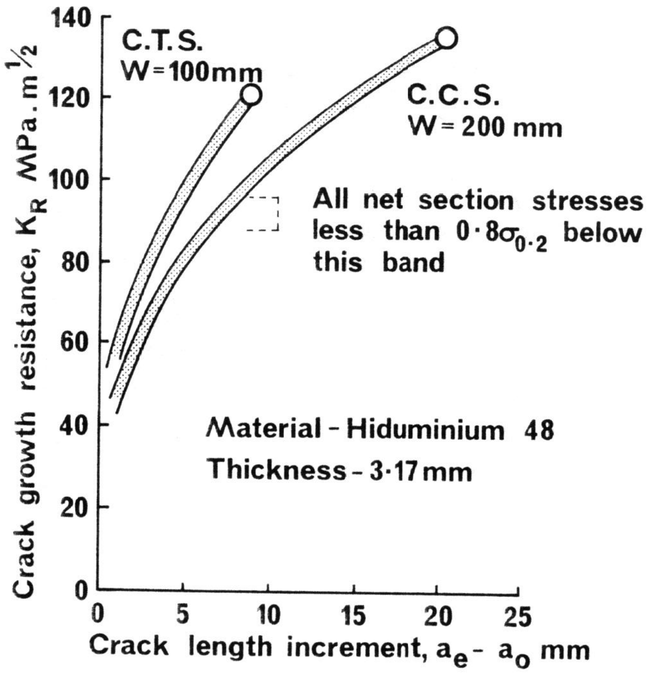

Figure 3 Compliance Indicated Resistance Curves for Hi48 for Centre Crack Sheets and Compact Tension Specimens

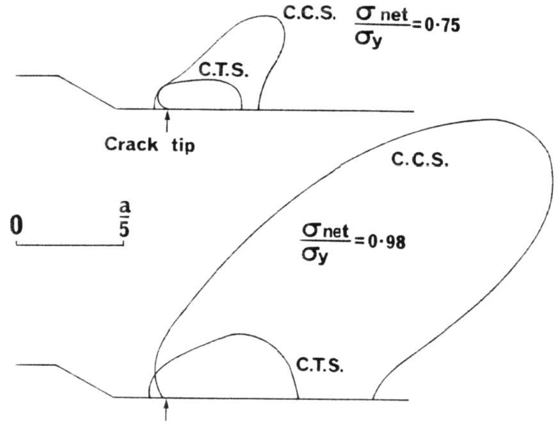

Figure 4 Plastic Zone Profile for Centre Crack Sheets and Compact Tension Specimens at Two Different Stress Intensity Levels

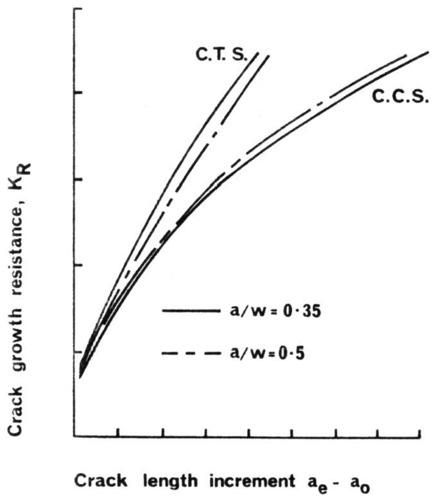

Figure 5 Compliance Indicated Resistance Curves Determined from Elastic-Plastic Finite Element Analysis

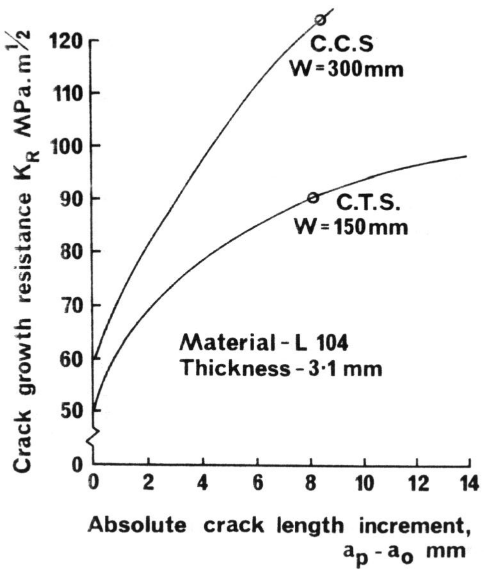

Figure 6 Resistance Curves for L104 for Centre Crack Sheet and Compact Tension Specimens as a Function of Measured Absolute Crack Length