PAPER 15 (SESSION I)

Fracture initiation in welded joints of ferritic steels

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Summary

An examination of fracture testing techniques concludes that plane strain tests are relevant below the transition temperature in structural steels and crack opening displacement (COD) tests in and above the transition range – the two approaches being entirely compatible. Some results are presented to demonstrate this compatibility, and further results on the measurement and application of COD are also presented.

Discussion of the application of fracture mechanics techniques to weldments of ferritic steels shows the importance of carrying out tests on all regions of the weldment to establish the worst case. The major factors controlling toughness in weld metal, heat affected zone and parent plate are considered and suggestions made to enable the worst regions to be located without extensive sampling.

Introduction

The development and standardisation of linear fracture mechanics techniques by the ASTM E24 committee have led to widely accepted procedures for measuring plane strain fracture toughness of high strength materials [1]. In lower strength materials, however, it is frequently not possible to obtain valid measurements of plane strain fracture toughness at normal loading rates and temperatures for the thicknesses commonly used. General engineering practice to avoid fracture with such materials has been based upon the transition temperature approach. It has become clear over the years that the transition of fracture toughness with temperature shown by lower strength materials, as with the transition of fracture toughness with thickness in high strength materials [2, 3], is due to deviation from plane strain conditions. In addition to the plastic zone size/thickness controlled transition it is necessary to invoke a dependence of plane strain fracture toughness and yield stress on temperature and strain rate to explain transitional behaviour with temperature fully.

In materials which show transitional behaviour over a particular temperature range for a given thickness it is not possible to make plane strain fracture toughness measurements in the transition range using that thickness. Some alternative means of measuring fracture toughness is necessary. An appreciable effort has been expended in examining the validity of the crack opening displacement (COD) approach to measuring fracture toughness in and above transition regions [4, 5]. This approach has always been regarded as completely compatible with linear fracture mechanics and as providing a necessary extension when fracture is preceded by significant yielding [6, 7].

The lower strength materials which are sensitive to temperature are also commonly found to be sensitive to strain rate. This leads to a difference in performance between fracture from a stationary crack and continued crack extension with a moving crack. It has become convention to define fracture initiation as the first onset of fracture from a pre-existing crack. Fracture propagation is then considered to be subsequent crack extension. For these definitions the strain rate relevant to fracture initiation depends upon that applied to a structure whereas the strain rate for fracture propagation is always extremely high.

COD as a measure of fracture toughness

The occurrence of yielding at the crack tip brings with it separation of the crack surfaces even at the tip, and it has been suggested that the value of crack opening displacement at fracture is a measure of toughness analogous to K_c (4-6). From this analogy it has been inferred that critical COD measurements obtained from laboratory tests can be compared with opening displacements calculated for different combinations of applied stress and crack length in a structure. Some evidence in support of this inference is given in Fig. 1. This shows results of notched bend and notched tension specimens of a 2¼ in thick mild steel (Z), with analysis and properties as shown in Table 1. The bend specimens were 2¼ in square with a 0·45 in deep notch and were tested over a span of 9 in. Results of tests on specimens with 0·003 in root radius and with fatigue crack notches are both shown. The notched tension tests were carried out on 3 ft square × 2¼ in thick plates with symmetrical edge notches (0·003 in root radius) of the depths shown. In Fig. 1 the results are plotted for critical COD to fracture against temperature and it can be seen that both types of specimen show transitional behaviour over a similar temperature range. The effect of crack length in the tension specimens is within the general scatter of results inherent to fracture tests in a transition range.

Measurement of COD

Whilst the fundamental parameter of general yielding fracture mechanics analyses is crack opening displacement at the crack tip, there are a number of experimental difficulties in making such a measurement. The paddle type of COD meter [6], developed to measure COD close to a crack tip, is not suitable for widespread application in different laboratories. The instrument is particularly sensitive to positioning of the paddle near the crack tip and appreciable errors can be introduced by small variations in instrument operation. Provided these potential errors are known to users, the instrument can give satisfactory results, but for more widespread application a system less prone to errors is desirable. For these reasons an attempt has been made to generalise the relationship between displacement at the open end of a crack and that at the crack tip. The former measurement can readily be made with the double beam clip gauge instrumentation now universally used for linear fracture mechanics tests [1]. The gauge can easily be calibrated to give absolute displacement values as additional information to the basic linear fracture mechanics requirement of linear behaviour. For notched bend specimens slip line field theory shows the yielding pattern to take place by a hinge mechanism around a central rigid region of material [8]. Assuming this form of deformation the relationship between opening displacement at the crack tip and at other positions within the crack can be calculated as a function of the geometry of the specimen. Modifications to previous analyses [4] suggest that the ratio of measured COD at a position z above the crack tip to the true COD at the crack tip should be dependent upon the ratio of z to the remaining ligament of material below the crack tip. Measurements have been made on a range of specimen sizes with a range of notch depths to establish experimentally the relationship between displacement measurements by a clip gauge and COD measurements at the crack tip. Tests were carried out on specimens from 0·4 in square up to 5½ in square with notch depth to specimen depth ratios between 0·2 and 0·5. The results of these calibrations are shown in Fig. 2. It can be seen that when plotted in terms of the parameters suggested by the slip line field analysis the results fall near to a single curve which enables true COD measurements to be inferred from clip gauge readings on notched bend specimens. Further verification of these results is desirable by theoretical and experimental techniques.

Compatibility of K_{1c} and COD

A programme of work has recently been carried out to make plane strain fracture toughness (K_{1c}) and crack opening displacement measurements on the same specimens. The 3 in *CKS* (compact K_{1c} specimen, or two pin loaded *WOL* specimens [9]) type of fracture mechanics specimens was chosen for these tests. The material used was a mild steel (W) with analysis and properties as shown in Table 1. Tests were carried out over a range of temperatures from −196 °C up to −20 °C using standard clip gauge and other linear fracture mechanics instrumentation. Valid K_{1c} results were obtained at temperatures up to −80 °C. The results for plane strain fracture toughness against temperature are shown in Fig. 3. The specimen tested at −20 °C was monitored both with a clip gauge instrumentation and with a device to measure crack opening displacement at a position 0·3 in from the fatigue crack tip. The relationship between the clip gauge and COD measurements is shown in Fig. 4. In order to obtain the true crack opening displacement at the crack tip it was necessary to apply a correction for the deformation of the crack close to its tip and a further correction to allow for bending effects [18]. The first correction was made using analyses by Wells [10] based on finite element computer analyses of the displacements within a crack under limited elastic plastic loading. The second correction was based on the assumption that a *CKS* specimen deforms in a similar way to a notched bend specimen (by a hinge mechanism as shown by slip line field theory) but this correction is small. The corrected relationship between clip gauge measurements and COD values is also shown in Fig. 4. Using this relationship it was possible to calculate the critical values of crack opening displacement at fracture in all the *CKS* specimens tested. In Fig. 5 the results of these tests are plotted in terms of $(K_Q/\sigma_y)^2$ against ζ/e_y. The results show a linear relationship with the two quantities being equal for values of $(K_Q/\sigma_y)^2$ less than 3, as predicted by the various theoretical analyses for crack opening displacement.

Application to welded joints

Examination of casualties usually shows that brittle fractures in welded structures initiate from welding defects such as cracks. Most forms of cracking, which occur during welding or post weld heat treatment, are such that the crack tips are located either in weld metal or in heat affected zone (HAZ) regions. Since it is the local microstructure adjacent to the crack tip which is of major importance in deciding whether fracture initiation will occur, it is vital that careful consideration is given to assessing risks of fracture initiation from defects in weld metal and HAZ regions as well as the parent plate.

Figure 6 shows the transition of COD to fracture with temperature for parent plate, HAZ and weld metal regions for a low alloy (Mn-Cr-Mo-V) steel, and illustrates that substantial differences in toughness can and do exist between these regions. The data, which is comparative only, was obtained from notched specimens of 0·4 in thickness tested in slow bending, and the HAZ specimens were extracted from single run welds made with a heat input of 26 kJ/in. Changes in welding process and procedure can give rise to wide variations in transitional behaviour. For the purpose of material selection for a specific application, it is essential also to take into account the geometric effects of plate thickness. Assessment of transitional behaviour can only be made by testing full plate thickness notched specimens and the rate of loading should be that anticipated in service to take account of the effect of strain rate

on toughness. In addition, where feasible, notches should be given fatigue crack extensions since there is an effect of notch root radius on toughness and fatigue cracking is the most convenient way of producing cracks of natural sharpness.

The main objective in the fracture mechanics approach to the toughness testing of structural steels as discussed here is to establish that region of a weldment showing the least resistance to fracture initiation. Ideally this requires either the measurement of plane strain toughness or the determination of the transition in COD to fracture with temperature for each region. In practice, the approach can be simplified by carrying out tests based on welding and metallurgical experience and at the minimum anticipated service temperature only, thus establishing the critical K_{1c} or COD value for unstable fracture in the worst region of the weldment. Testing can be restricted to procedure test samples for critical joints in the structure and confined to investigating the extremes of heat input and preheat anticipated during fabrication.

The alternative approach of considering resistance to fracture propagation has been discussed extensively by Pellini [14]. This assumes that initiation may always occur in locally embrittled areas and hence that toughness values should be measured under dynamic conditions [11]. In general the approach is safe but conservative, and in view of its considerable coverage it will not be discussed here. The object of the present paper is to focus attention on the potential use of cheaper materials by designing against fracture initiation.

On welded samples the effect of factors such as crack tip position, thermal straining effects at existing defects and single run and multi-pass welding must be fully appreciated where fracture initiation is being specifically investigated. It is convenient to discuss these factors in relation to the various regions of a weldment.

Heat affected zone

The fracture initiation resistance of HAZ regions depends primarily on the chemical composition of the material, the preheat temperature and heat input of the welding process used, and the heat sink conditions as affected by plate thickness. The dominant factor in HAZ toughness is the nature of the microstructure. Martensitic microstructures produced by faster cooling rates in C/Mn steels and by a range of cooling rates in alloy steels tend to have high strength but a poor toughness/strength ratio. This is particularly the case in single run welds where tempering effects are absent, or when hydrogen is present in the lattice, giving rise to very brittle behaviour. Upper bainite microstructures have poor cleavage fracture toughness but are not as strong as martensites. At slow cooling rates pearlite/ferrite structures may occur in some C/Mn steels, but slow cooling rates in welding imply relatively long times at high temperatures, and grain size and other effects become important. The prior austenite grain size is greatest adjacent to the fusion boundary and decreases progressively with increasing distance from the fusion boundary. For a given heat input this region of maximum grain size generally shows a lower fracture toughness than other parts of the HAZ and it is important therefore to attempt to locate the fatigue crack tip of the fracture specimen in this grain coarsened region. Considerable grain growth occurs with high heat input processes such as electroslag welding. Burning effects caused by the liquation of sulphide eutectics at austenite grain boundaries which occurs in steels with a relatively high sulphur content, may accompany the grain growth and deteriorate the toughness further. Normally there is no difficulty in locating the crack tip in the grain coarsened region of electroslag and consumable guide weldments but with multipass welds there is considerable irregularity of the fusion boundary due to penetration of individual weld runs and in practice the crack tip will sample several regions of the transformed HAZ.

Grain refining and tempering effects of succeeding runs in multipass welds usually improve the toughness of HAZ regions relative to the toughness of the HAZ of a single weld run. However, when hydrogen induced cracks occur they often form in the HAZ of the bead which forms the weld toe, a bead which is not refined or tempered by further runs. In practice, it is easier to fabricate crack notched specimens of full plate thickness in which the crack tip is located in the HAZ of a multi-run weld. However, to determine transitional behaviour, some effort must be directed towards establishing a technique for determining the toughness of single run HAZ regions using full plate thickness specimens, since this may be the worst case condition.

A specific situation that requires consideration in any comprehensive assessment of HAZ toughness is the possibility of thermal strain occurring at the tip of existing cracks during welding. This situation can arise during multipass or repair welding where, for example, a crack is formed at some intermediate stage and further welding is required to complete the joint. An example is shown in Fig. 7. Thermal strain caused by the deposition of the outer bead has been concentrated at the tip of the crack which formed prior to the repair being carried out. Some deterioration in the toughness of this local microstructure adjacent to the crack tip can be expected. It is possible to incorporate this effect in COD test specimens, by preparing samples in which notches are present during the welding cycle [16], and therefore to establish the degree of any embrittlement caused in this manner. The additional embrittlement by thermal straining cannot be observed in the light microscope, but can be detected by transmission electron microscopy or by microhardness techniques.

Weld metal

The fracture initiation resistance of weld metal, in addition to the thermal factors controlling cooling rates, depends on factors such as the composition of the filler wire, the amount of parent plate dilution, and the type, composition and distribution of deoxidation products formed during solidification. The basic microstructure depends upon the weld metal composition and cooling rate, but since cooling takes place from the melting point the detailed microstructures in weld metal are different from the HAZ and there can be pronounced effects on toughness from the solidification pattern. Due to transformation occurring at relatively fast cooling rates it is usually found that weld metal has a higher yield strength than plate material of the same composition, and in structural steels this increased yield is still present even with weld metal carbon level much lower than the plate. The introduction and efficient removal of deoxidation products depend on flux/metal chemical reactions at high temperatures, and hence weld metal inclusion content for deposits of the same nominal type and composition are found to depend strongly on the flux formulated by individual manufacturers. With structural steels basic fluxes are often the most effective to give good toughness.

As with the HAZ, the microstructure of a multipass weld contains regions of refined metal and regions which have not been refined or tempered by succeeding passes. It is feasible that hydrogen cracking, post weld heat treatment cracking and solidification cracking could exist in both refined and as deposited areas, and therefore where possible, the fracture initiation resistance of both regions should be assessed. As with the HAZ, in practice it is difficult to locate the fatigue crack tip in one or other of the regions and usually both are sampled in any one specimen. Further work is required to devise a specimen type suitable for examining the transition behaviour of as deposited weld metal and incorporating the geometric effects of plate thickness at the same time.

A feature of high heat input processes, apart from abnormal grain growth is the possibility of marked segregation occurring at the weld centre line. This occurs in situations where solidification proceeds from more than one surface. It is important to establish whether this form of planar weakness exists and therefore it is advisable where possible to notch and fatigue crack fracture specimens along the weld centre line.

Thermal straining effects at existing defects can occur in weld metal as well as HAZ regions and can be investigated using a modification of the specimen shown in Fig. 8.

One factor which affects toughness requirements for weld metal is the relative strength of plate and weld metal. For a butt weld stressed transverse to its length there appears to be some protection for weld metal overmatching in strength provided there is sufficient fracture toughness to be in the field of general yielding fracture mechanics.

Parent plate

In low alloy steels it is usual for the HAZ to show a lower resistance to fracture initiation than the parent plate. However, in plain C and *C/Mn* steels at normal heat inputs, it is found typically that the HAZ has the greater toughness. In certain situations, the parent plate toughness can be degraded sufficiently to become the controlling factor as regards fracture initiation in a weldment. Although it may be argued that there is only a remote chance of finding cracklike defects in the parent plate at the fabrication stage capable of initiating fast fractures on proof loading or in service, it is considered nevertheless advisable to regard the degraded toughness of the parent plate as the worst case condition. The thermal strain concentration effect at the tip of a defect described previously in HAZ considerations can be of overwhelming importance in C and *C/Mn* steels. This effect has been shown to be primarily responsible for fractures occurring below general yield in standard notched and welded Wells' wide plate tests when carried out at ambient temperatures [15, 16]. Embrittlement is a result of a marked increase in dislocation density local to the defect tip and is partially a result of dynamic strain ageing effects occurring in the parent plate microstructure [17]. This requires investigation in any assessment of fracture initiation resistance of mild steel weldments.

Conclusions

In weldments of ferritic steels it is essential when considering risks of unstable fracture to distinguish between initiation and propagation of fracture. For an assessment of resistance to fracture initiation tests should be carried out on samples representative of parent material, heat affected zone and weld metal. The tests can either set out to measure plane strain fracture toughness (K_{1c}) or crack opening displacement (COD) to fracture. These two approaches are compatible, plane strain fracture toughness being relevant below a transition and critical COD in and above the transition. Clip gauge instrumentation can be used in both cases. For application of results of fracture tests to predicting critical flaw sizes in structures it is possible to use linear fracture mechanics as a lower bound when valid K_{1c} results cannot be obtained, but in the transition range when critical COD values are used it is necessary to reproduce thickness, strain rate and local embrittlement effects from service into the tests. Care is necessary when applying transition temperature concepts to constrained situations such as surface cracks, and also when considering long cracks in pressure vessels where bulging may occur.

In weld metals and heat affected zones the toughness is dependent on chemical composition and thermal history. The most fruitful path for research is to pursue the fundamental relationships between microstructure and fracture toughness, and between welding conditions, microstructure and chemical composition. There appears to be a relationship between poor fracture toughness and susceptibility to metallurgical weld defects, such that weld cracks may often lie in material with poor resistance to fracture initiation. Apart from basic microstructural factors, hot straining can have a strong adverse effect on fracture toughness, and in weld metals solidification pattern, inclusion content and relative strength compared to the parent plate can influence toughness considerations.

Acknowledgment

The authors wish to acknowledge assistance in design and construction of test equipment and in obtaining experimental results from Mr B. A. Wakefield, Mr B. J. Ginn and other colleagues at the Welding Institute.

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Table 1

Composition and properties of two mild steels

Steel	*C*	*Mn*	*Si*	*S*	*P*	*Yield stress tons/in²*	*U.T.S. tons/in²*	*% E*	*% R. of A.*	*Temp. °C for 20 ft·lbs C_V*
W	0·14	1·15	0·14	0·030	0·025	17·1	29·0	35	50	−15
Z	0·17	0·83	0·08	0·041	0·026	13·5	27·8	35·8	64·3	+5

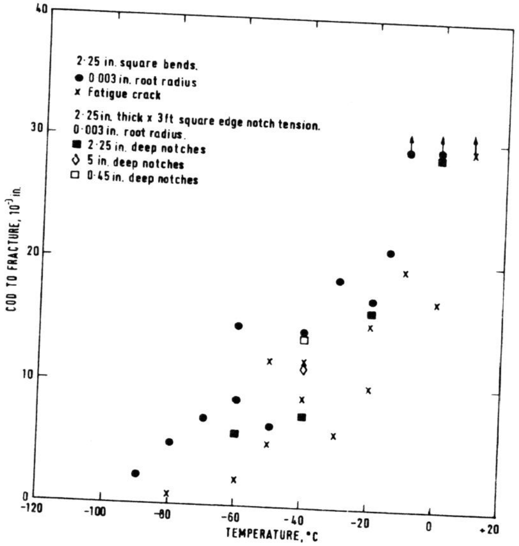

Fig. 1. Results of crack opening displacement tests on notched bend and notched tension specimens for a mild steel (Z).

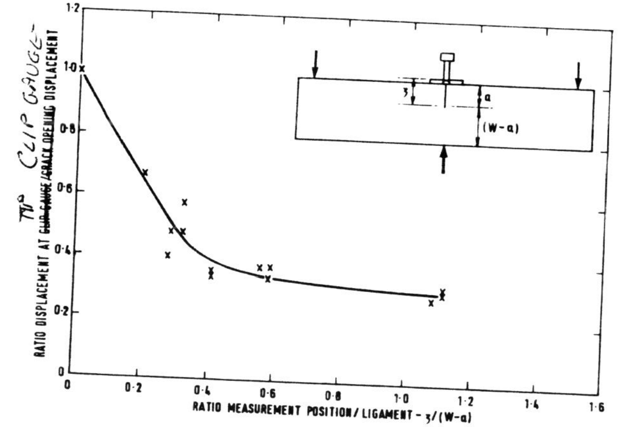

Fig. 2. Relationship between clip gauge and COD measurements for notched bend specimens.

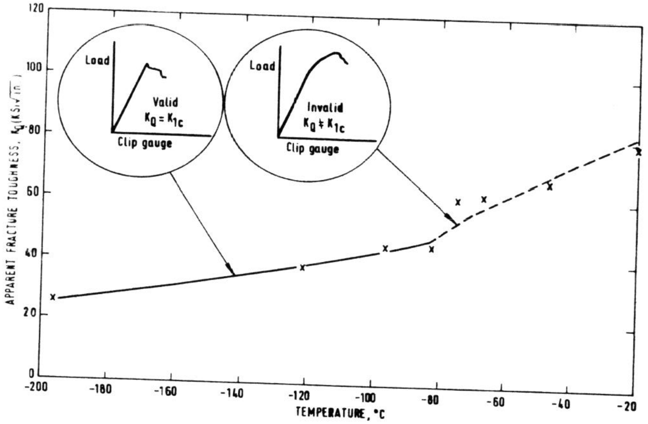

Fig. 3. Variation of plane strain fracture toughness with temperature for a mild steel (*W*).

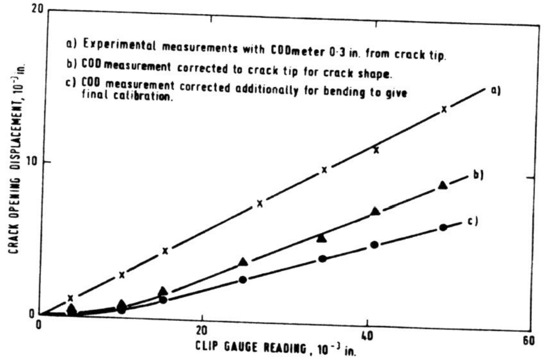

Fig. 4. Calibration of clip gauge and COD measurements for 3 in *WOL* specimens with corrections for bending and crack distortion.

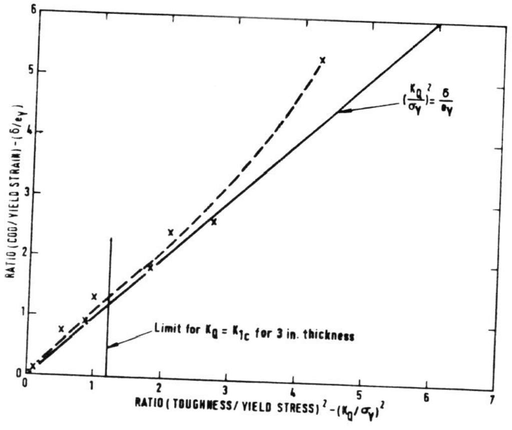

Fig. 5. The equivalence of linear elastic and general yielding fracture mechanics parameters determined experimentally from fracture tests.

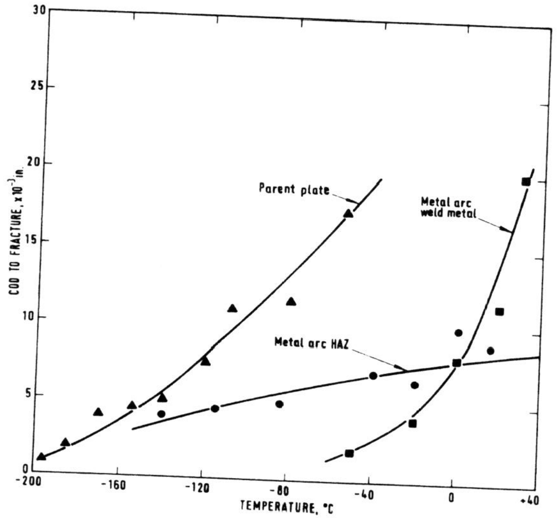

Fig. 6. Transitional behaviour with temperature for parent plate HAZ and weld metal in a low alloy steel.

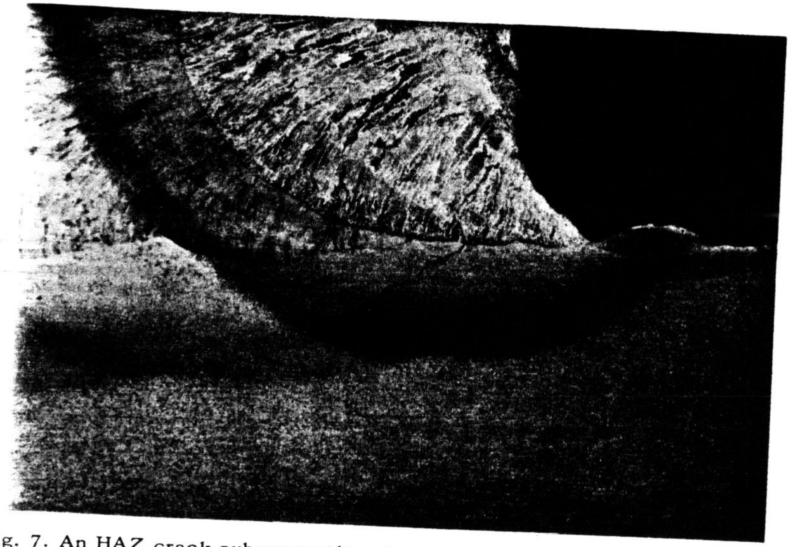

Fig. 7. An HAZ crack subsequently subjected to thermal straining by repair welding.