7. FRACTURE TOUGHNESS MEASUREMENTS ON REACTOR STEELS

BY

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INTRODUCTION

In recent years fracture studies at the Risley Nuclear Laboratories (RNL) have concentrated on two steels, the ferritic A533B steel used on a world-wide basis for nuclear reactor pressure vessels, and the austenitic 316 steel which is of interest for use as a structural material in sodium cooled fast reactors. Although the two materials are metallurgically very different and would be used at different operating temperatures, the fracture studies have followed similar routes. A series of low temperature tests have been made to measure K_{Ic} values on A533B, but most of the studies have been in the area of elastic-plastic fracture mechanics and the parameters measured have been crack opening displacement (COD) and J integral values. The tests have been made using single edge notched bend (SENB) specimens or compact tension(CT) specimens. Material was available from a 158mm thick plate of fully heat treated A533 Grade B Class1 steel; this was manufactured in the UK. The objectives of the tests on this material were; to measure the plane strain fracture toughness and permit comparisons with A533 from other sources; to measure elastic-plastic toughness parameters over a wide temperature range; and to assess any variations of these properties throughout the plate. Since however the pressure vessel temperatures of most interest are on the upper shelf, the tests have been made predominantly at 20°C and 250°C. The austenitic 316 steel was available in the form of 50mm thick plate which was tested in the solution treated and dimensionally stabilised condition (2hr at 650°C and slow cooled). In addition tests have been made on a series of 6 weldments in 316 material. Much of the work carried out in the programme on these materials has been reported previously(1-6) and the purpose of this paper is to review some of the highlights.

LINEAR ELASTIC FRACTURE MECHANICS TESTS

Tests have been made on 25mm thick CT specimens of A533B according to the ASTM and

BSI recommended procedures. The tests were made to obtain valid plane strain fracture toughness values and to assess the variation of this parameter as a function of position in the plate, and test piece orientation. The results obtained are summarised in Fig 1 which shows average values from groups of valid and invalid tests for two regions in the plate, these were termed α and β and were very widely separated regions. Those of the results which were invalid failed to satisfy the criterion that the final pre-fatigue stress intensity factor level should be below prescribed limits. Since the extent of crack tip plasticity was very small it is not expected that the failure to satisfy this criterion would have a significant effect on the toughness values measured. No effect of specimen orientation on toughness was found, nor was there any effect attributable to the depth within the plate thickness from which the specimens were taken; there was however a significant effect attributable to the region of plate from which specimens were taken, the region α giving somewhat higher toughness than the region β. Where comparisons can be made the fracture toughness values measured on the UK material seem to be in agreement with data from US plate material, eg the data at -100°C is in good agreement with the K_{Ic} values in the range 34 to 59 $MNm^{-3/2}$ reported by Mager(7) (fig 1).

CRACK OPENING DISPLACEMENT STUDIES

Early tests on A533B specimens were made over the temperature range -60 to 250°C to assess the effect of temperature on COD values. These specimens were 25mm thick, SENB type and were pre-fatigued to give a final a/W ratio of 0.33. Testing was carried out in accordance with procedures recommended in BSI DD19(8). In contrast to the LEFM tests on this material it was observed that specimens from regions α gave similar properties to specimens from region β. The set of results obtained for specimens from the α region are summarised in Fig 2. The values shown are average values for about 4 tests which were made to assess through-plate variations, since no significant variation was observed the results give realistic average values. Figure 2 shows the COD values for failure by cleavage (δ_c), initiation of ductile crack growth (δ_i), and maximum load instability (δ_m). Cleavage failure is confined to temperatures below about 20°C; above this, ductile failure occurs following the attainment of a maximum load. Ductile cracking is observed in all specimens above -20°C; at -20°C this process is terminated abruptly by failure when cleavage occurs, but at 20°C and above tearing continues beyond maximum load. A significant observation is the reduction of both δ_i and δ_m with increasing temperature over this upper shelf region, indicating a reduction of toughness with increasing temperature.

Similar studies have been made on 316 austenitic steel using SENB specimens with thickness of 10, 20 and 50mm and a/W ratios of 0.35. These tests have been made over the range 20-550°C and Fig 3 shows the variation of COD values with temperature. For this material, cleavage does not of course occur and only δ_i and δ_m values are obtained. The initiation values (δ_i) are in good agreement for the 3 specimens sizes tested indicating some independence of geometry for this parameter. In contrast values of δ_m, although displaying some scatter, clearly indicate that δ_m increases as the specimen size increases. There is very little effect of temperature on the values measured, there probably being a slight overall decrease of both δ_i and δ_m with increasing temperature.

DETECTION OF DUCTILE CRACK INITIATION

Several methods have been used to detect the onset of ductile crack growth and thereby identify initiation toughness values. For the results shown in Fig 2 two methods were used, for most of the specimens initiation of ductile cracking was identified by means of an AC potential difference method, while for the remaining specimens, which gave unsatisfactory electrical records, the compliance method was used. For the latter method the clip gauge displacement-load point discplacement test record indicates a change in slope following initiation. The results of Fig 3 were based on a multi-specimen, R curve technique. With this method a series of interrupted tests are made to obtain a relationship between COD (or J) and the extent of ductile cracking (Δa); extraplation of such curves to zero crack growth indicates the value of δ_i. This method is considered to be the most reliable of the several methods available but for economies of both materials and testing time it would be attractive to establish a satisfactory single test method. Several single specimen methods have been examined for some 316 steel specimens and the initiation toughness values obtained have been compared with those from the multi-specimen method(5). The methods examined included both AC and DC potential difference methods, a compliance method, and several metallographic methods; it was found that none of the single specimen methods were completely satisfactory and they generally tended to result in over-estimates of initiation toughness as determined by the multi-specimen method. The single specimen methods tended to be most successful with materials of low ductility. Similar studies are continuing but for the present the multi-specimen method would be the basis used for initiation toughness measurements.

INSTABILITY

The effect of specimen geometry on the δ_m values of Fig 3 is of some importance, it has to be noted that the specimens have a square cross-section and so both thickness(B) and width (W) could influence the results obtained. It is expected that increasing thickness will lead to a reduction of the maximum load COD values as was observed for example, by Green and Knott(9) in a series of tests on mild steel specimens in which constant width (20mm) was maintained but thickness was varied over the range 5-70mm. In contrast to this, increasing specimen width (and hence increasing ligament) is expected to increase the maximum load COD values. The latter effect has been observed for several materials including tests by Fearnehough(10) on mild steel and by Griffis(11) on HY80. A comparison of these data for thickness effect and width effect indicates that maximum load COD values are much more sensitive to the width effect than the thickness effect. It is therefore to be expected that when both dimensions increase proportionally, as is the case for the 316 specimens shown in Fig 3, then the effects of increasing width on δ_m values will dominate. A simple model has been developed which relates δ_m and δ_i values (and also J_m and J_i values) obtained from tests on ductile materials of fairly low work hardening capacity(6). The basis of the model is that specimens exhibit instability (maximum load) when the net section stress on the ligament is equivalent to the UTS measured in uniaxial specimens. Allowance is made for the loss of section due to ductile tearing which occurs prior to instability. The model is only considered to apply when initiation of ductile cracking occurs at loads close to the general yield load, and therefore may not be applicable to very thick section specimens. Most of the suitable data in the literature has been analysed and found to be in good agreement with the model. The predicted effect of increasing ligament size (W-a) is to increase δ_m (or J_m) and the model therefore explains the results of Fig 3. It becomes clear also that maximum load toughness values have very little significance since such parameters are very geometry dependent. In contrast, toughness values at the initiation of ductile cracking have been widely reported as being generally independent of geometry for specimens above some minimum thickness(9-12) and accordingly, in the present state of knowledge, such toughness values are considered to be the most realistic for the characterisation of material toughness.

For application of elastic plastic fracture mechanics to structural components there is considerable incentive to be able to make use of any extra toughness available between ductile crack initiation and instability, rather than be confined to the use of initiation toughness values. In this connection it may be instructive to examine the load bearing capacity of specimens beyond ductile crack initiation. Figure 4 shows how J values vary with load for 3 series of A533B specimens tested to obtain R curves. The curves approach maximum load at the highest J values shown and apparently although there is a substantial increase of toughness between initiation and instability, as measured by J integral values, there is virtually no improvement in load bearing capacity after ductile cracking has initiated. Thus, in a corresponding structure operating under load control conditions, no benefit could be obtained from the increase in toughness between initiation and instability. However, the data of Fig 4 has been obtained from specimens that are only 25mm thick, and it would seem probable that for specimens having larger in-plane dimensions there would be a more substantial improvement in load bearing capacity between ductile crack initiation and instability. This is observed to be the case for 316 steel and is shown in Fig 5. This shows the improvement in load bearing capacity of SENB specimens between initiation and instability as a function of thickness. There is a substantial improvement with increasing thickness over the range 10-50mm. It is again to be noted however that since the specimen is of square section it is not clear if the benefits are due to the thickness effect, the width effect, or both. There is good reason to expect therefore that for large, thick section, structural components there is potential for the use of some post-initiation criterion which could reduce the degree of pessimism which may be inherent in the general use of initiation toughness parameters. The approaches currently being pursued by Paris and his co-workers(13), and also by Turner(14) offer the hope that a suitable method will be available in the future. Meanwhile it is the RNL view that initation toughness values have to be used to characterise materials and to carry out any assessments of critical defect sizes.

R CURVE STUDIES

For the above reasons current studies on A533B and 316 materials are designed to measure initiation toughness values and a multi-specimen procedure is used so that R curves are obtained. It is hoped that these will ultimately be of value if a post-initiation fracture criterion is developed; at the present time it would seem that such a criterion would be likely to incorporate the term dJ/da (or dδ/da). Recent data for A533B is presented in Fig 6 which shows J-Δa data for 20° and 250°C. J is estimated by means of the area under the load-load point displacement curves for a series of tests which have ben stopped after appropriate amounts of ductile crack growth. For each specimen the average crack growth is estimated after heat tinting by measurement at 3 or 9 stations across the specimen thickness, if 9 stations are used the two outer measurements, which are influenced by the shear lips, are ignored and the average of the remaining 7 measurements is used. Measurements of crack growth exclude the stretch zone which is easily identified, so that no blunting line procedure is necessary to identify the initiation toughness values as recommended in the ASTM-E24 procedure(15).

Figure 6 includes results for 25mm thick, 50mm wide CT and SENB specimens. It is evident that both the initiation toughness Ji and the crack growth resistance dJ/da decrease with temperature between 20 and 250°C. The same set of data has also been analysed using the E24 procedures and this resulted in higher initiation toughness values. The extent of the discrepancy in the values estimated by the two procedures depended on the slope of the R curve and increased with increasing dJ/da values, at 20°C for example, J_i values of 0.26 and 0.16 MNm^{-1} were obtained from the E24 and RNL procedures respectively. A limited programme has been carried out on A533B material to assess the effect of specimen geometry on toughness and crack growth resistance. The results of these tests are shown in Fig 7. All the specimens were 25mm thick and included SENB specimens 50mm and 25mm wide, having a/W ratios of either 0.6 or 0.3, together with CT specimens having an a/W ratio of 0.6. In general there are no major effects due to specimen size but there is a small apparent effect due to the a/W ratio for 25mm specimens, the two sets of results falling at the extremes of the scatter band. Further evidence of a similar effect is shown in Fig 8 which is for tests on mild steel SENB specimens of 25mm square section. The tests were on pre-cracked specimens having a/W ratios in the range 0.08 to 0.55 and indicated a very substantial effect of a/W ratio on both initiation toughness and crack growth resistance. The initiation toughness values for the shallow crack were about twice the values obtained with the deepest crack. It is believed that in the case of the shallow crack gross section yielding occurs, while the rotational constant r is very much less than for the deeper crack. The observation of improved toughness for shallow cracks could have important implications to the assessment of critical defect sizes of components. A component subject to severe loadings for example, would imply a small critical defect size on the basis of toughness studies using standard specimens, and it could be difficult to formulate a convincing safety argument for such a component. The test results of Fig 8 however imply that the real crack tolerance could be much better than that expected from standard specimens.

Further data on geometry effects have been obtained for 316 steel tested at 250°C. The results which are shown in Fig 9 are for SENB specimens having 10, 25 and 50mm square section; this series of tests, for which a/W was constant at 0.35, indicates that both initiation toughness and crack growth resistance are relatively insensitive to in-plane dimensions in the range studied. The overall conclusion therefore from the results shown in Figs 7,8,9, is that initiation toughness values and crack growth

resistance can be sensitive to a/W ratios although width and thickness variations over the range studied have no apparent effect.

A series of tests have been made to assess the toughness of welds in 316 material. Six welds were made and these covered a range of weld angles, welding processes, and ferrite contents. Tests were made on 10mm x 10mm SENB specimens at 370°C. The results, which are shown in Fig 10 in the form of a collective R curve, indicate that the variables have little effect on toughness but the initiation toughness value (δ_i) for the series of tests is substantially lower than that for 316 plate material. The low toughness of weld metal at such an elevated temperature underlines the need for some post-initiation toughness criteria.

CONCLUSIONS

Tests have been made on A533B and 316 steels to assess toughness values. Some of the tests have indicated that maximum load toughness parameters are dependent on geometry and therefore not satisfactory for the characterisation of material toughness. In contrast, toughness values based on the initiation of ductile cracking have been found to be independent of specimen thickness and width in the range studied, and should therefore be more reliable for critical defect size assessments. It is recognised that there is considerable incentive to permit some allowance to be made for the post-initiation toughness, which may exist, if ductile crack propagation requires an increasing load.

Tests on specimens having a range of a/W ratios have shown that the initiation toughness can increase for shallow crack situations. The use of standard specimens to measure toughness values could therefore be unduly pessimistic if the values are used to estimate critical defect sizes of structures subject to severe loadings.

For A533B steel it has been observed that both the initiation toughness and the crack growth resistance decrease significantly between 20° and 250°C, while for 316 weldment, tests at 370° have indicated initiation toughness values substantially lower than those obtained for plate material.

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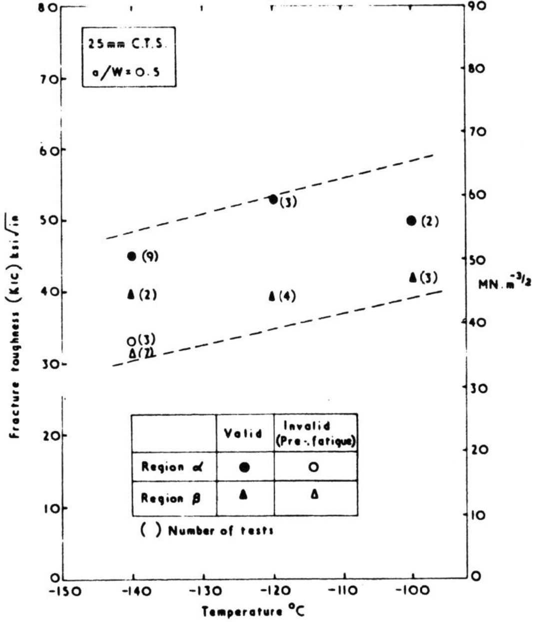

FIG.1 EFFECT OF TEMPERATURE ON PLANE STRAIN FRACTURE TOUGHNESS OF A533B

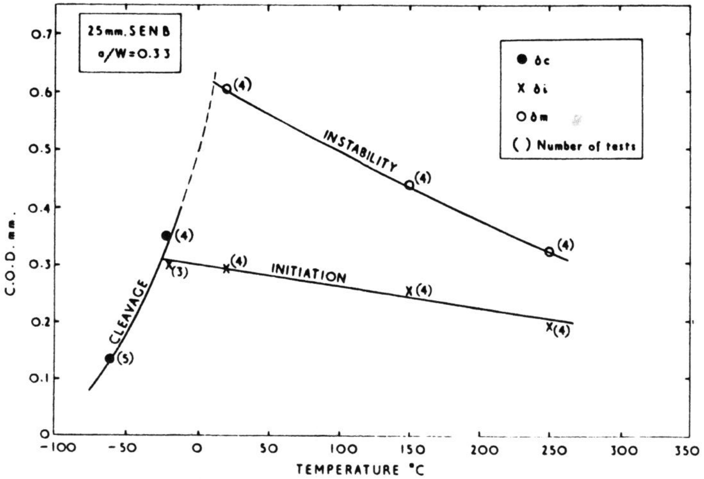

FIG. 2 EFFECT OF TEMPERATURE ON C.O.D. VALUES OF A533B SPECIMENS

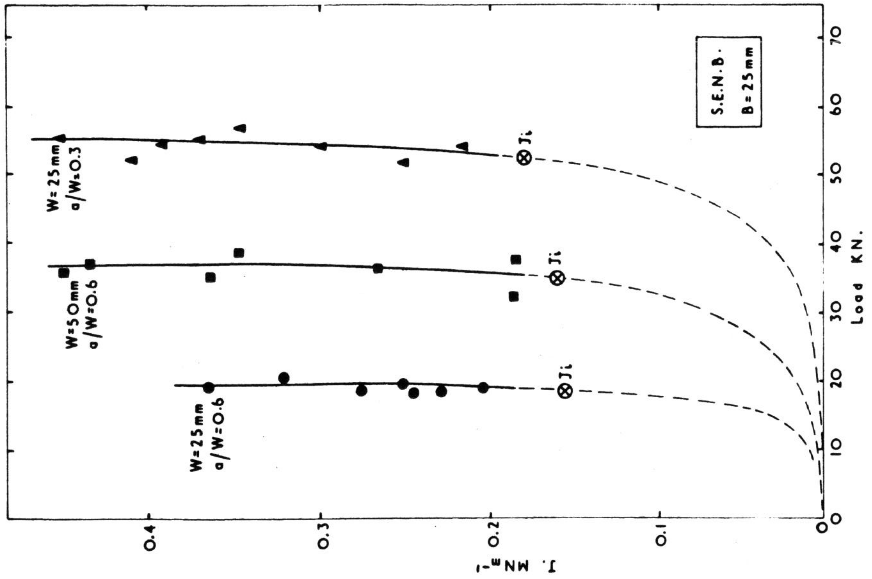

FIG.4 VARIATION OF J WITH LOAD AT END OF TEST FOR 3 SERIES OF TESTS ON A533B AT 20°C

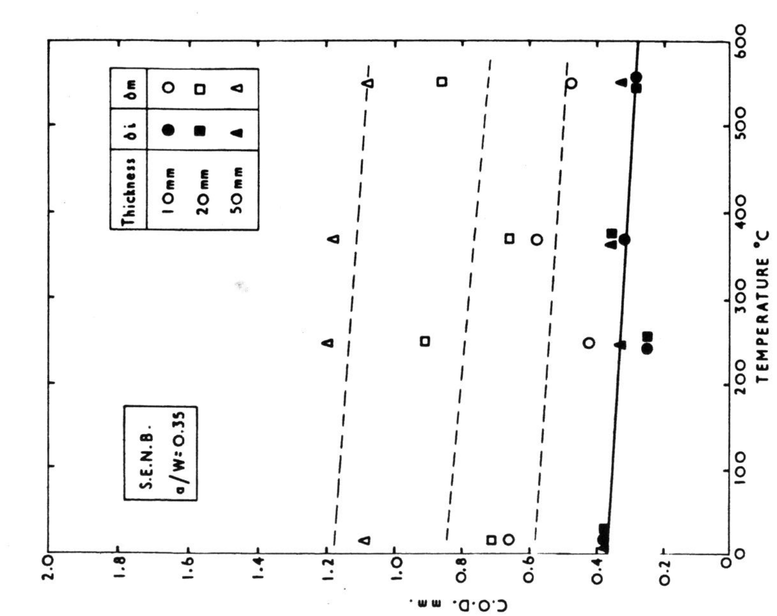

FIG.3 EFFECT OF TEMPERATURE ON COD VALUES OF 316 SPECIMENS

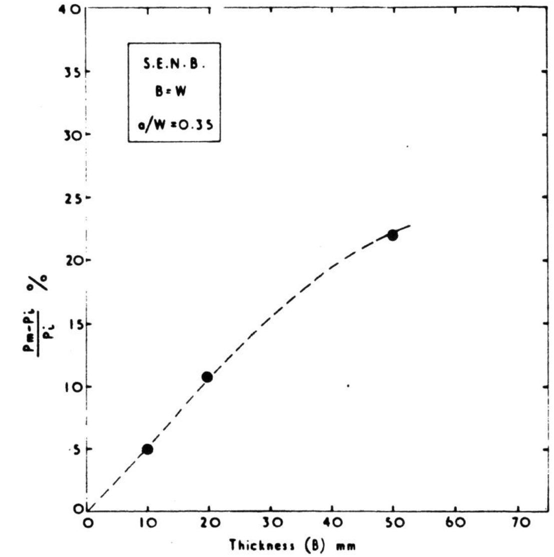

FIG.5 EFFECT OF THICKNESS ON POST-INITIATION LOAD BEARING CAPACITY OF 316 SPECIMENS

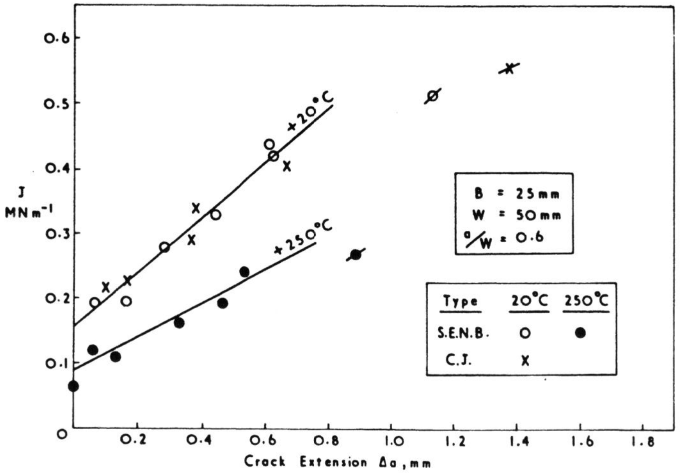

FIG.6 J-RESISTANCE CURVES FOR A533B STEEL

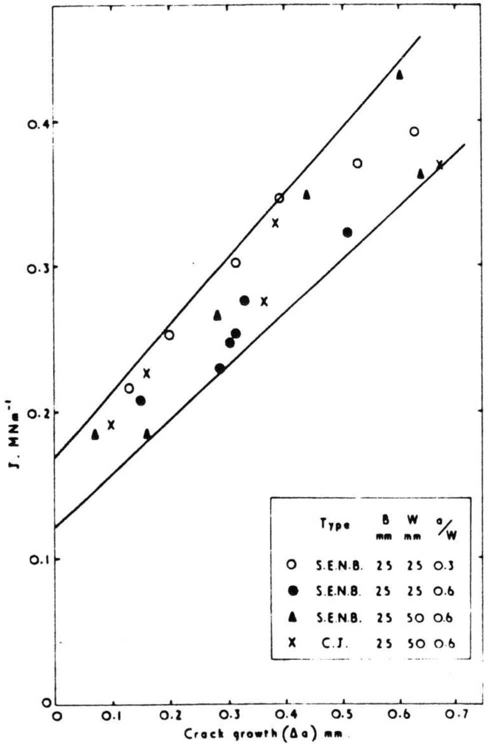

FIG. 7 EFFECT OF SPECIMEN GEOMETRY ON J - Δa DATA FOR A533B STEEL AT 20°C

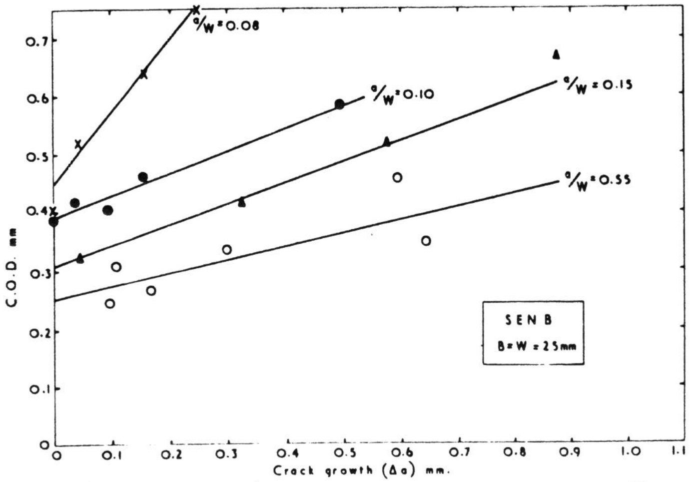

FIG. 8 EFFECT OF a/W RATIO ON COD-Δa DATA FOR MILD STEEL AT 20°C

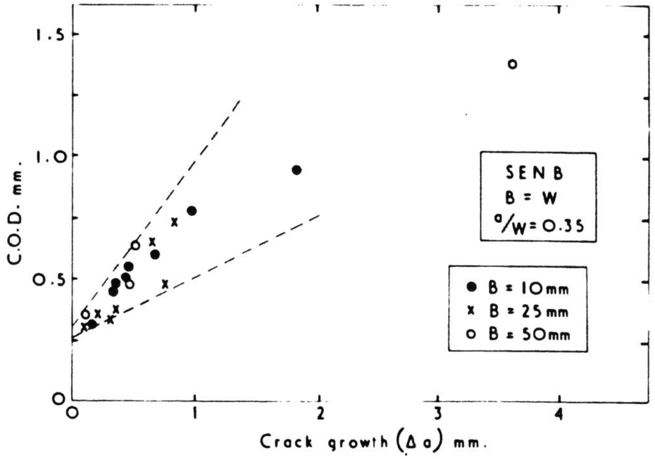

FIG. 9 COD-Δa DATA FOR 316 STEEL TESTED AT 250°C

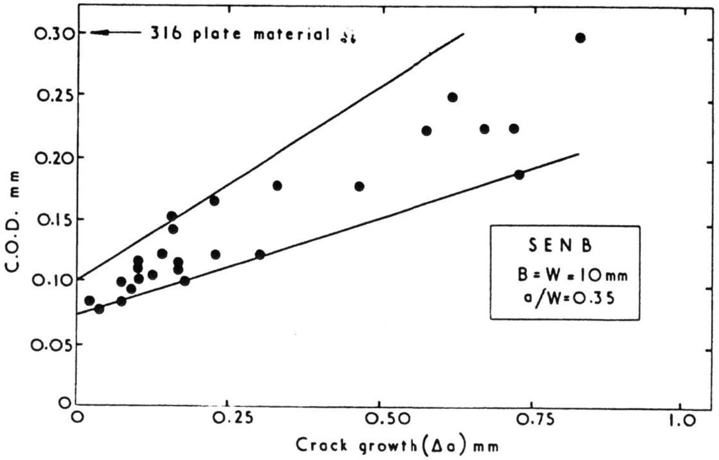

FIG. 10 COD - Δa DATA FOR 316 WELDMENTS TESTED AT 370°C