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Evaluation of HAZ Toughness by CTOD and Tensile Panels

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ABSTRACT The structural significance of the low crack tip opening displacement (CTOD) toughness of local brittle zones (LBZs) of offshore steel weldments is not yet a fully understood or commonly agreed issue. This problem has been approached by the testing and comparing of the toughness results of small scale CTOD and centre cracked tensile (CCT) panel tests. This paper presents results concerning the effect of notch depth (a/W) and loading mode (bending or tension) on LBZ fracture behaviour.

The bead-on-plate submerged arc welds on both sides of the 30 mm thick StE 460 steel plate were made with the weld axes coinciding but leaving part of the base metal at mid-thickness. The CTOD and CCT specimens were prepared in such a manner that the fatigue cracks would intersect the LBZs at two locations. Both type of tests were carried out at room temperature with the a/W ratio of 0.1, 0.3, and 0.5.

CTOD tests exhibit cleavage fractures initiated from LBZs for all a/W ratios. The apparent CTOD toughness increased with decreasing crack depth due to extensive ductile tearing prior to cleavage fracture. However, all CCT specimens showed fully ductile crack growth through the LBZs without triggering a cleavage fracture. The results demonstrate the fundamental differences in the outcomes of the small scale CTOD and tensile panel tests concerning the structural significance of LBZs. The CTOD and J–R curves were also determined for CCT specimens and it was observed that J–R curves exhibit dependence on a/W ratio.

Introduction

With recent attention on the local brittle zone (LBZ) of weld heat affected zones (HAZ), considerable concern has often been expressed as to whether crack tip opening displacement (CTOD) testing with its deep notched specimens is an appropriate tool for assessing the significance of LBZs in offshore steels or not. The CTOD test has a potential to pick-up (with its sharp fatigue crack) the most brittle and often isolated zone of the HAZ, despite the experimental difficulties. If the CTOD test piece samples the LBZ correctly, the toughness is often found to be extremely low. The occurrence of such a low toughness values (even when steel and weldments are sound) is claimed to be unrealistic since many offshore structures with LBZ containing weld joints are still in service and apparently the presence of such brittle zones adjacent to the fusion line (i.e., coarse grained HAZ, CGHAZ) does not endanger the integrity

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of the structures **(1)**. Therefore it has been argued that low CTOD toughness values may reflect the toughness of the microstructurally brittle zone and not the global fracture behaviour of the welded joints.

For this reason, the centre cracked tensile (CCT) panel tests (wide plates) with various notch types were extensively used by many investigators to obtain an appropriate answer to the question of the structural significance of LBZs. However, the results of these tests give somewhat different views which can lead to uncertainty on the differences between CCT and CTOD tests regarding the low toughness fracture behaviour of the LBZs. For example, Denys and McHenry reported **(2)** that 'the results of the surface notched wide plates in tension generally indicate that LBZs don't trigger brittle fracture' and they concluded that the LBZs are not significant as far as the surface notched tensile wide plates are concerned. However, Webster and Walker **(3)**, found that 'the LBZs undoubtedly influence the behaviour of both wide plate and CTOD tests'. Furthermore, Nakano *et al.* **(4)** concluded that 'the lower bound surface notched wide plate test result correlated reasonably with the lower bound CTOD test result indicating that the CTOD method can predict lower bound behaviour'. Recently, the through-thickness notched HAZ wide plates (on arctic grade steel weldments) tested by Bala *et al.* **(5)** at the Welding Institute of Canada failed by sudden brittle fracture without any ductile tearing.

These examples can certainly be extended but here it may be sufficient to demonstrate that there is still widespread recognition of the need to achieve a better understanding of the LBZ fracture behaviour on CTOD and tensile panel tests.

In order to study the various aspects of the LBZs, a comprehensive research programme has been carried out at the GKSS Research Centre together with various institutes and companies. Some of the results have already been published elsewhere **(6)–(8)**. This paper deals with the fracture behaviour and analysis aspects of some CTOD and CCT tests of this programme. Particular attention has been given to the question as to whether crack depth (a/W) and loading mode effects can also be responsible for the varying fracture behaviour of the LBZs.

Material and experimental procedure

The bead-on-plate submerged arc welds at a heat input of 3 kJ/mm, on both sides of the 30 mm thick StE 460 steel plate were made with the weld axes coinciding, as shown in Fig. 1. High hardness values (280–300 HV) were obtained at the CGHAZ during the hardness survey of the weldments. The yield stresses were 460 and 620 MPa and tensile strength values were 625 and 770 MPa for the base and weld metals respectively. In order to isolate the effects of specimen geometry and LBZ size on the fracture behaviour of LBZs, both CTOD and CCT specimen types were notched, to sample identical proportions of LBZ, HAZ, weld, and plate material. The notch configurations used to achieve this are shown in Fig. 2. With this notch preparation (so called double cross bond), 20 mm thick single edge notched bend (SENB), compact tension (CT) and CCT specimens were prepared, as shown in Fig. 2. The a/W ratios used were approximately 0.1, 0.3, and 0.5 for SENB and CCT specimens with constant thickness. The CT specimens were tested with the a/w ratio of 0.5. Fatigue pre-cracking was carried out with the special 'step-wise high R ratio' fatigue pre-cracking procedure **(7)(9)** for all specimens. This pre-cracking technique is used successfully at GKSS Research Centre for as-welded specimens to obtain a valid crack front.

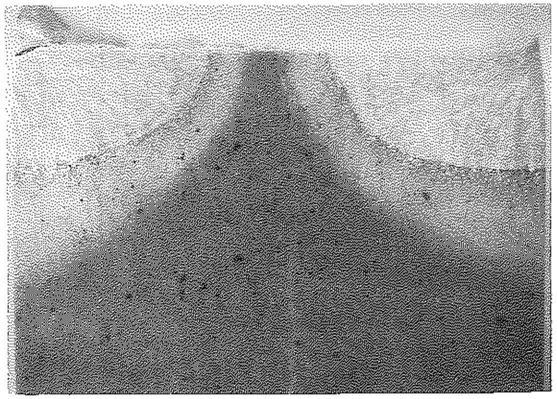

Fig 1 Cross-section of the double cross bond specimen for HAZ/LBZ testing

All specimens were tested at room temperature. The CTOD values were calculated in accordance with BS 5762 : 1979 **(10)** and also directly measured with δ_5 clip gauges **(11)** on the specimen's side surface at the original fatigue crack tip over a gauge length of 5 mm. The DC potential drop technique was used for monitoring stable crack growth of all specimens. Load, elongation, crack mouth opening displacement (CMOD) and CTOD (with two δ_5 clip gauges) responses (as shown in Fig. 3) were recorded with the computerised data acquisition system during the testing of the tensile panels. The CCT specimens (two for each a/W ratio, in total six plates) were unloaded after the attainment of maximum load in order to prevent damage to the instrumentation of the specimens.

Results and discussion

CTOD tests

Figure 4 shows the load versus CMOD curves for SENB specimens with various a/W ratios. The arrows indicate the initiation of brittle fractures (pop-ins). Microstructural and fractographic examinations on sectioned and broken specimens revealed that the CGHAZs (LBZs) are the sites of cleavage initi-

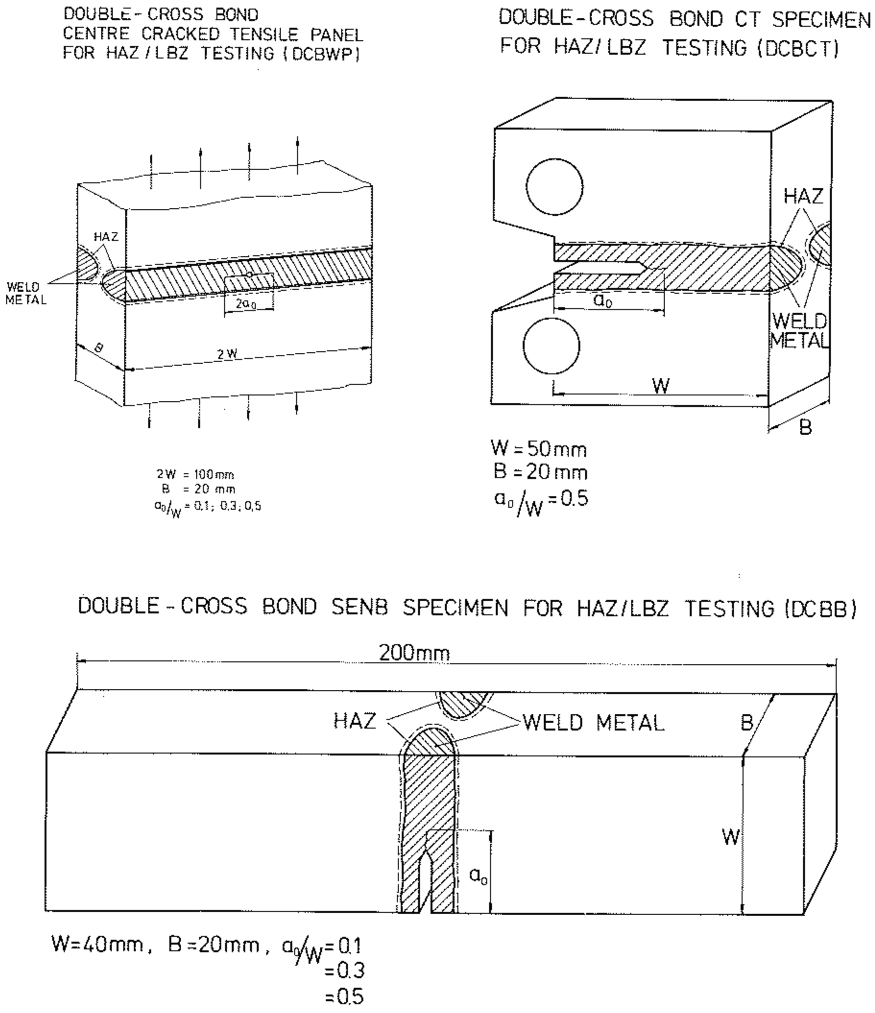

Fig 2 Double cross bond specimen types

ations (see Fig. 9). Clearly, the cleavage initiations on shallow notched specimens preceded by a larger amount of CMOD those of deep notched ones.

As expected, the load required to cause cleavage fracture for a constant thickness should be increased as a/W ratio decreases. The amount of CMOD preceding cleavage initiation varied (despite the presence of LBZs right at the crack tips) with the notch depth, as shown in Fig. 4. This indicates that identically sized and located LBZs do *not* always lead to low toughness fracture values. The susceptibility of LBZs to cleavage fracture therefore appears to depend on the notch depth of the specimen.

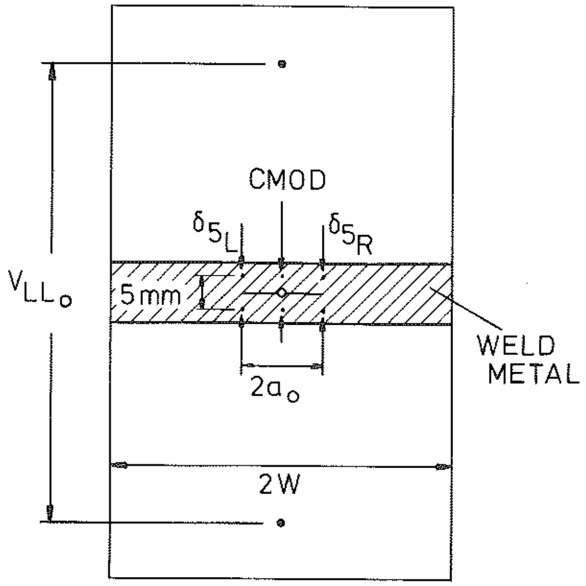

Fig 3 Clip gauges and linear transducer positions for measuring the CTOD, CMOD, and overall elongation on CCT specimen (δ_{5L}: CTOD left; δ_{5R}: CTOD right)

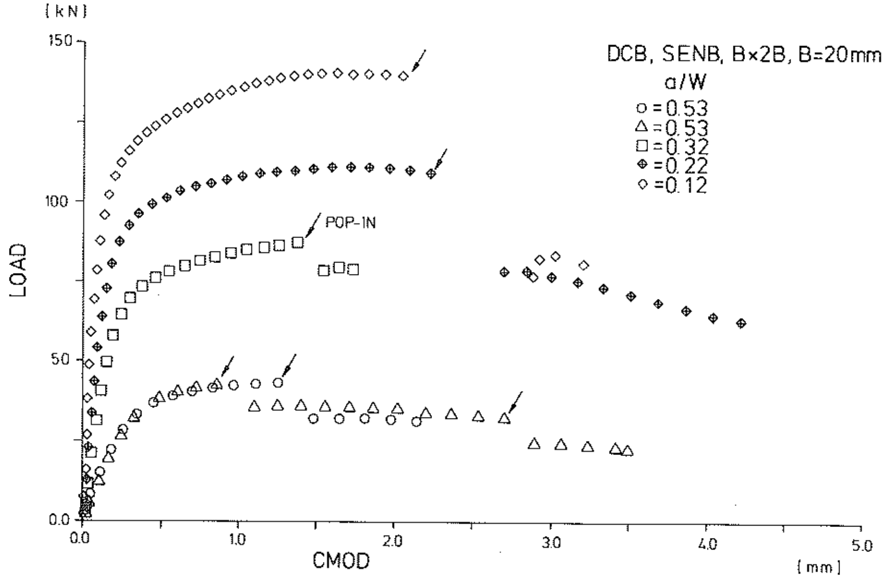

Fig 4 The load versus CMOD curves for SENB specimens with various a/W ratios

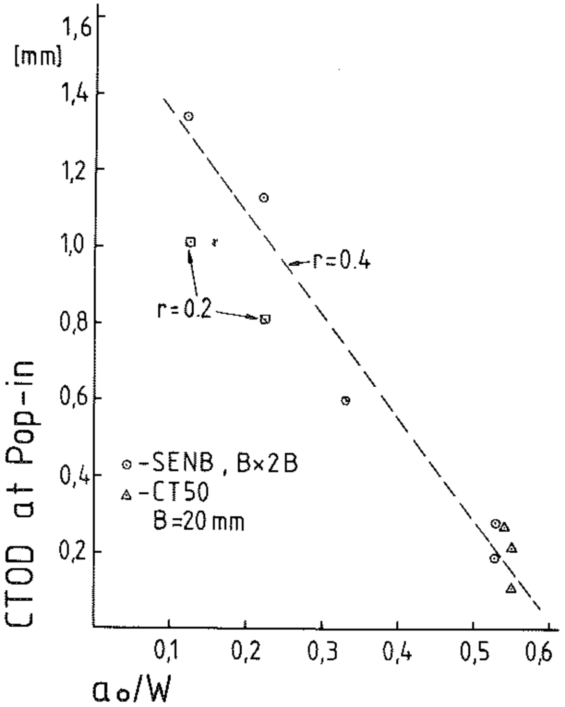

Fig 5 **The correlation between CTOD values (at pop-in) and a/W ratios of SENB specimens**

Figure 5 shows the dependence of calculated CTOD (at pop-in initiation points) values on a/W ratio. The CTOD values for SENB (and CT) were calculated according to BS 5762 : 1979 with the rotation factor, r, as 0.4.

These results are shown in Fig. 5 and they suggest that CTOD at pop-in values increases *strongly* with decreasing a/W ratio. This effect can be related to the reduction of stress-triaxiality (constraint) ahead of the shallow crack tip due to the plastic deformation spreading to the faces of the specimen (back face yielding). Therefore, the development of the plastic hinge at 40 percent of the ligament, $0.4\ (W - a)$, may not occur in very shallow notched specimens, since plastic deformation is not necessarily confined to the uncracked ligament. Consequently, the actual CTOD may be overestimated **(8)(12)** using the BS 5762 : 1979 formula with $r = 0.4$ for shallow notched specimens.

Due to the existence of possible inaccuracies in use of the BS 5762 : 1979 formula for determining CTOD values of SENB specimens with $a/W < 0.2$, the appropriate rotation factor was experimentally determined with the use of CTOD values of δ_5 clip gauges. In Fig. 6, the CTOD values of BS 5762 : 1979 and δ_5 clip gauges are plotted and a very good agreement between them can be observed (rotation factors of 0.2 and 0.4 were used for shallow and deep notched specimens respectively). By simply substituting the directly measured CTOD (δ_5) values into the BS 5762 : 1979 formula, one can determine the rotation factor for every a/W ratio, as shown in Fig. 7. In this figure, the determined rotation factor, k, ($k = 1/r$) for SENB specimens is plotted against crack growth for various a/W ratios. The r values determined with this technique confirm the common use of 0.4 value for deep notched specimens as shown in Fig. 7. The results also indicate that the rotation factor of 0.2 ($k = 5$) seems to be appropriate to use for SENB specimens with $a/W < 0.2$. Hence, the CTOD values of shallow notched specimens with $a/W = 0.1$ and 0.2 were recalculated and values are shown in Fig. 5. However, CTOD still increases with decreasing a/W ratio but less strongly so when the BS 5762 formula is used for all a/W ratios. Hence, this analysis clearly shows that the elastic–plastic fracture toughness values at initiation of pop-in are higher for shallow cracked specimens than deep notched ones (even if $r = 0.2$ value is used for shallow notched SENB specimens). Therefore, the CTOD estimation scheme for shallow cracked weld specimens must be further studied in order to obtain an elastic–plastic fracture toughness value independent of specimen geometry.

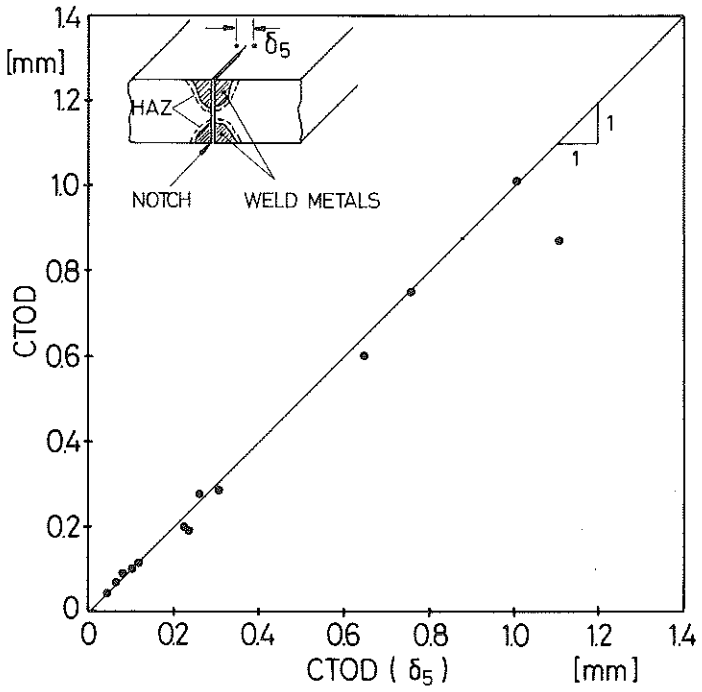

Fig 6 **The relationship between CTOD (BS 5762 : 1979) and δ_5 measurements for SENB specimens ($r = 0.2$ and 0.4 values were used for shallow and deep notched specimens, respectively)**

Ductile tearing prior to cleavage fracture

It is often experienced that, in CTOD testing of the HAZ, the fatigue crack tip may not sample the weakest zone (LBZ) of interest. This can result in some

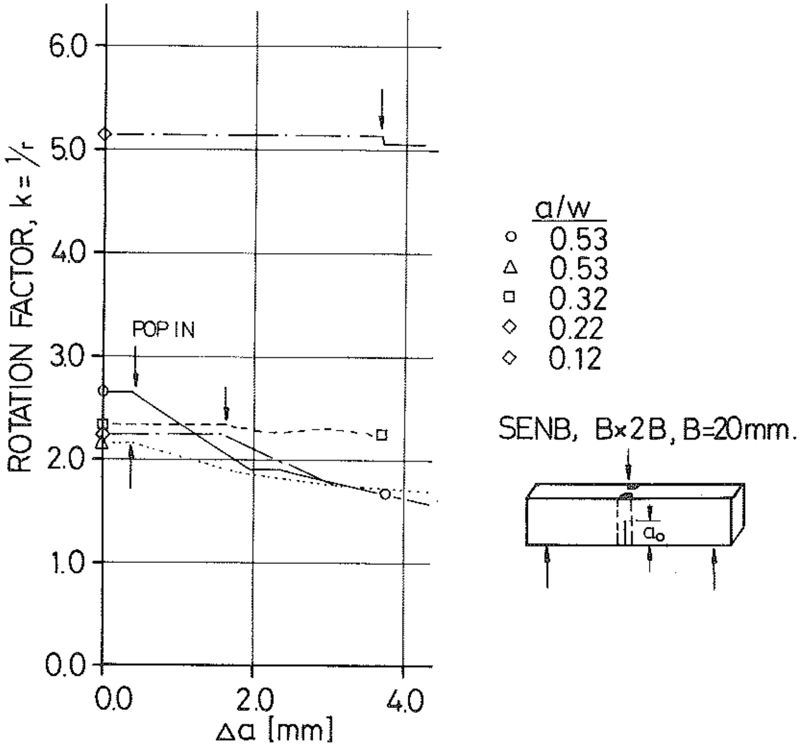

Fig 7 The determined rotation factor of SENB specimens versus crack length for various *a/W* ratios

amount of ductile tearing, depending on the distance from the crack tip to the weakest zone (LBZ). However, with the notch type used in this study, it was at first expected to eliminate this problem by placing the LBZs right at the crack tip (cleavage fracture expected to initiate by a 'weakest link' mechanism from the two LBZs right at the crack tip).

But it was observed, as shown in Fig. 8, that as the crack depth decreases the amount of ductile tearing increases. It seems that the stress state ahead of the shallow crack became insufficient (due to the loss of constraint) in providing the necessary critical strain condition to initiate a cleavage crack from a pre-existing weakest link. So it can be concluded from Fig. 8 that the initiation of cleavage fracture from pre-existing LBZs, for shallow notched specimens becomes only possible with the crack depth increase resulting from ductile tearing. Such ductile crack growth causes high strain rates to develop in the plastic zone ahead of the crack tip **(13)**. This, in turn, can increase the yield stress ahead of the crack tip sufficiently so that cleavage initiation and consequently fracture mode conversion can take place **(14)**.

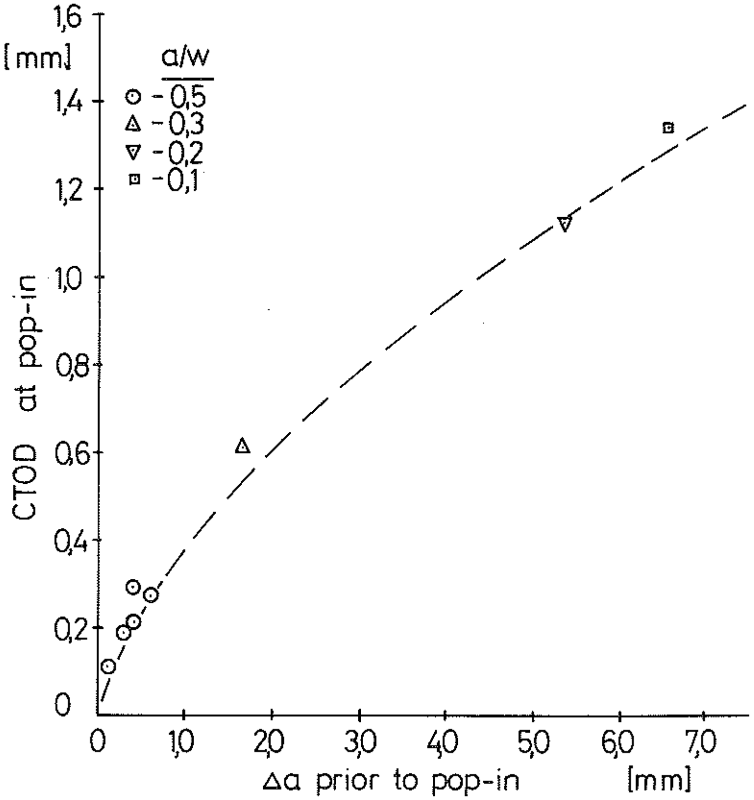

Fig 8 Relationship between CTOD pop-in values and ductile tearing prior to pop-in for SENB specimens

However, one may also argue the possible 'protecting effect' of the adjacent base and weld metals (with their high toughness) on the relatively small LBZs. The weld and base metals will not fail in a brittle manner, and in fact they can be left behind by the possible micro-cleavage crack advance which may initiate from the LBZs at low CTOD values. In turn, base and weld metals may somehow hold the micro-cleavage crack stable by keeping the crack tip closed (protecting effect) and consequently increasing the apparent toughness of the specimen. By this mechanism, despite the presence of the weakest links at the crack tip, extensive ductile tearing can take place until the shallow crack reaches sufficient constraint to cause a brittle fracture. However fractographic examinations showed the presence of small quasi-cleavage and/or large void-like flat fracture appearance at the fusion line region (LBZ) sites during the stable crack growth regime for example, as shown in Fig. 9. In the case of deep notched specimens, of course, higher constraint can provide the critical condition more readily for cleavage initiation without considerable ductile tearing.

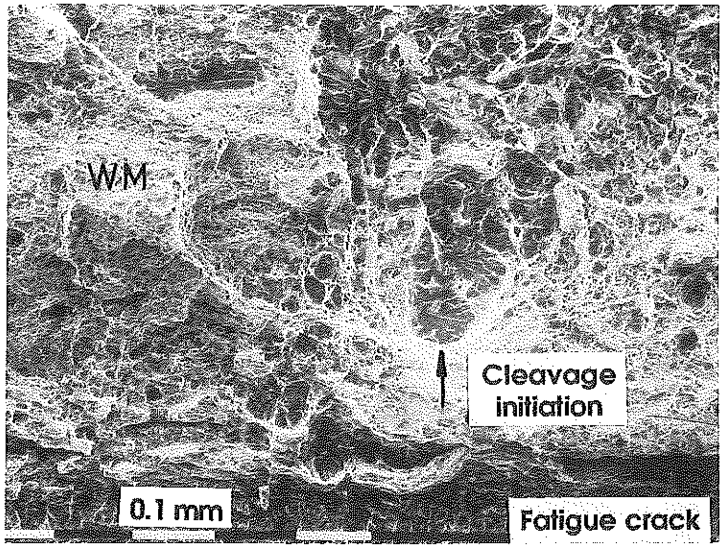

Fig 9 **Fractography of the SENB specimen with $a/W = 0.5$**

Hence, the amount of ductile tearing prior to cleavage fracture appears to be strongly dependent on a/W ratio. This means that the 'low toughness' of the LBZs cannot possibly dominate the fracture behaviour of the welded joints on CTOD specimens, if sufficient constraint is not available at the crack tip. It implies that the LBZs may simply be considered as locations at which brittle microstructural phases exist but 'behave well' if the defect depth is small.

Centre cracked tensile panel tests

Figure 10 presents curves of load versus CMOD for all the CCT specimens. Contrary to the CTOD specimens (see Fig. 4), no cleavage fractures were observed and all the plates failed in a fully ductile fashion. The presence of LBZs at the crack tips did not, therefore, lead to loss of ductility. Hence, Fig. 10 indicates that low toughness of the LBZs was not a fracture controlling factor for any crack lengths used in these experiments.

The CTOD (δ_5) and overall elongation of the plates (over a gauge length of 165 mm), V_{LL}, measurements were plotted in Fig. 11 for all six specimens. The CTOD (δ_5) values increased linearly, after a short initial stage, with overall elongation for the specimens with a/W ratio of 0.3 and 0.5. The curves of these specimens were nearly the same due to the occurrence of net section yielding (NSY) in both cases. In the short cracked specimens ($a/W = 0.1$) the CTOD (δ_5) did not increase linearly in a continuous manner with the V_{LL} (only up to 1 mm elongation) due to the gross section yielding (GSY) of the specimens. Once GSY occurs, the applied strain will be distributed along the entire length of the welded panel and the CTOD will no longer be proportional with the applied strain (**15**). The linear relationship became obvious after a large amount of strain ($V_{LL} > 5.5$ mm) as shown in Fig. 11, for the specimens of $a/W = 0.1$. The δ_5–V_{LL} relationship will be examined in more detail in a future communication.

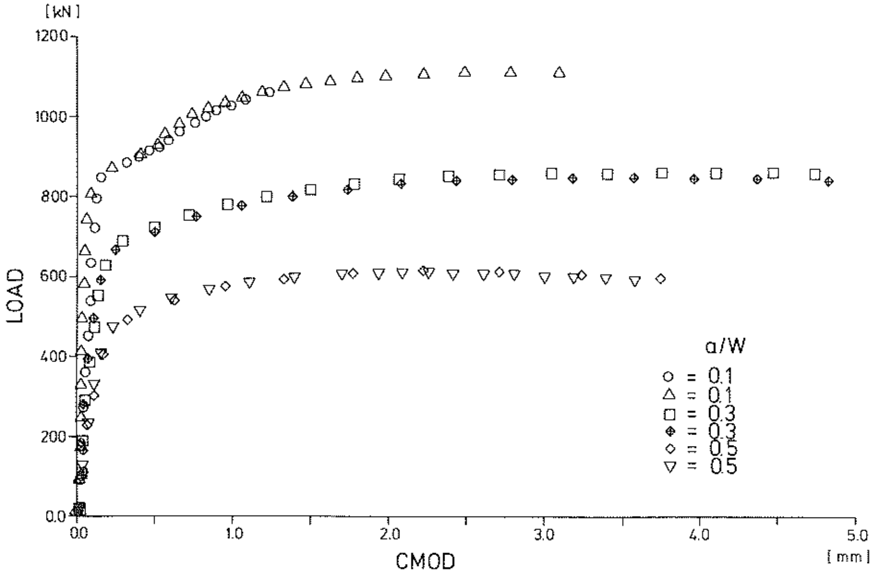

Fig 10 **The load versus CMOD curves of centre cracked tensile panels**

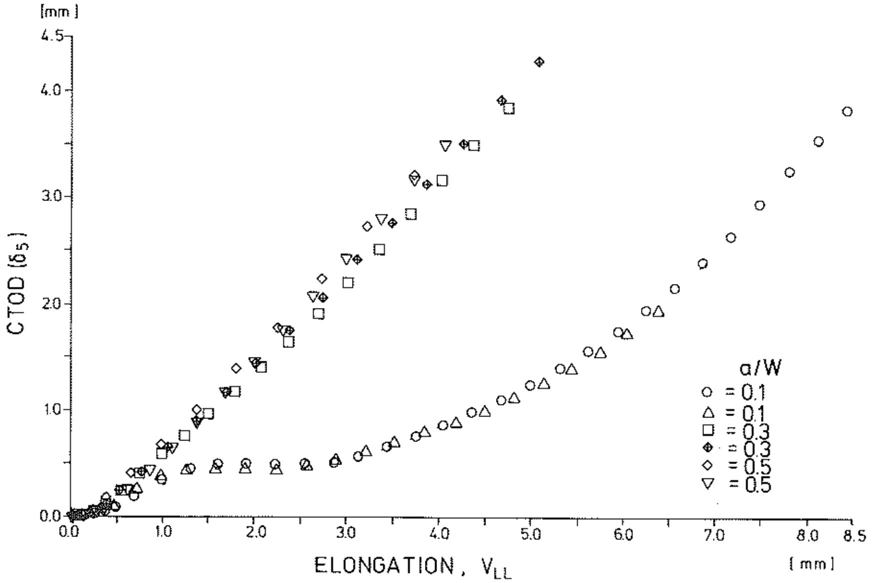

Fig 11 **Relationship between CTOD (δ_5) measurements and overall elongation of the CCT specimens**

Crack growth resistance curves

The CTOD (δ_5), CMOD and J integral versus crack extension, Δa, curves generated from CCT specimens are shown in Figs 12, 13, and 14. Figure 12 shows that CTOD (δ_5) begins with an essentially identical resistance curve for all a/W ratios and remains within a narrow scatter band over the whole range of crack growth. It can be seen that the R curves are not exhibiting any sign of brittle crack extension or effect of crack tip heterogeneity. These results also indicate the geometry independent nature of the CTOD (δ_5) measurements which is an essential requirement for an appropriate crack driving force parameter in the elastic–plastic fracture mechanics analysis of the welded joints, and thus CTOD (δ_5) values can be considered as being a 'near crack tip quantity'.

Figure 13 shows the CMOD R curves behaviour. In this case, CMOD measurements at the crack mouth (with the same gauge length as CTOD (δ_5), as shown in Fig. 3), are obviously of an average nature and thus may not be sufficiently accurate, since remote deformation may cause distortion of the crack mouth. Indeed, larger scatter than Fig. 12 can be observed on Fig. 13. Nevertheless, it can be an attractive quantity from a practical point of view, because it can also avoid the gross effects of remote plastic deformation on the R curves, as this is the case for CTOD (δ_5) R curves.

The J–R curves are shown in Fig. 14 for all specimens. The value of J was estimated according to the equation modified for crack growth by Schwalbe and Hellmann **(16)**. It is known that the evaluation of the J integral makes use of the overall elongation of the specimen to describe the local instability at the crack tips. This, of course, causes a major source of uncertainty since the remote plastic deformation away from the crack tips certainly elevates the J integral artificially. This can cause an invalid J integral evaluation of the CCT specimens in GSY condition. Hence, Fig. 14 implies that for short cracked specimens ($a/W = 0.1$) where general yielding occurred, the J integral inferred

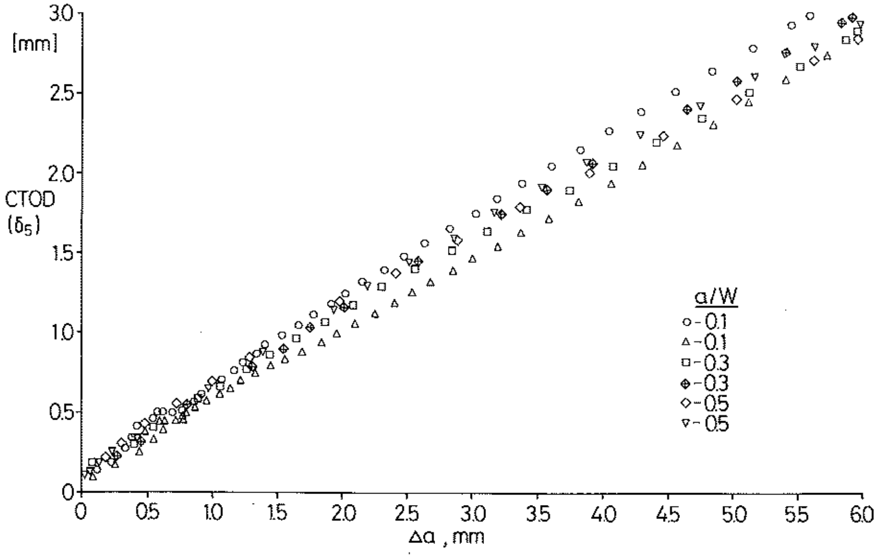

Fig 12 **CTOD (δ_5) *R* curves of CCT specimens**

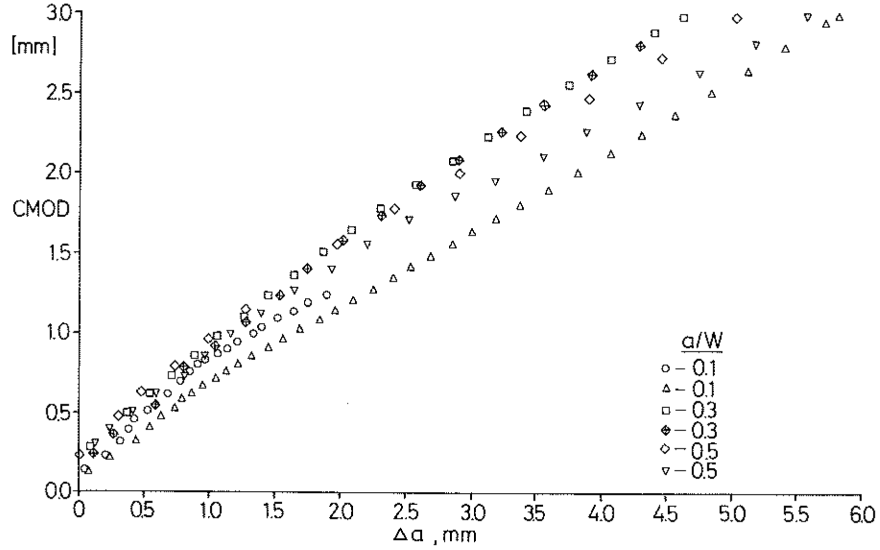

Fig 13 **CMOD versus crack extension curves of CCT specimens (CMOD *R* curves)**

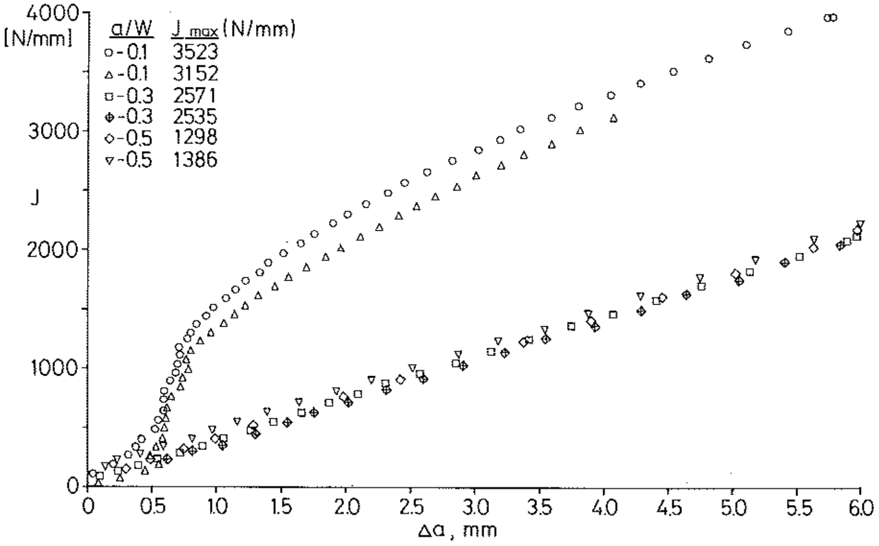

Fig 14 ***J–R* curves of CCT specimens**

from V_{LL} must not be used to construct R curves, as also concluded in **(16)** for some plain base metals.

Thus, it has been clearly demonstrated that the CTOD (δ_5) technique can provide 'configuration-independent' valid R curves, over an extended range of crack growth, while this is not possible with the J integral (if the J integral is determined using V_{LL}). Consequently, if R curves of welds of short and long cracked CCT specimens are required for comparison, the CTOD (δ_5) technique can provide potential advantages.

With regard to the comparison of CTOD and CCT tests, this investigation revealed that the presence of LBZs at the crack tip of the CTOD specimen provides readily 'weakest link' to cause cleavage fracture (despite their size being relatively small) depending on the a/W ratio – the smaller the a/W ratio the larger the ductile tearing occurs. However, further loss of constraint with CCT specimens leads to a fully ductile failure mode regardless of LBZ presence at the crack tips and a/W ratios of the specimens studied here. Furthermore, in the light of the observed fully ductile failure mode of the CCT specimens, one can conclude that the *LBZs may not be significant* and the degree of conservatism of the CTOD results might be large and thus instability predictions based on this conservatism might well not be realistic.

Conclusions

This investigation was performed on CTOD and centre cracked tensile panels to determine the effects of crack length (a/W) and loading mode (in bending and tension) on the fracture behaviour of local brittle zones.

The results clearly demonstrate the fundamental differences in the outcomes of the small scale CTOD and tensile panel tests concerning the significance of LBZs. In order to evaluate the structural significance of the LBZs and their instabilities in various conditions, the major differences between shallow and deep notched CTOD specimens and between the CTOD and tensile panel tests should be taken into account. The obvious conservatism of the deep notched LBZ CTOD specimen results should not be generalized and interpreted as a common fracture behaviour of the LBZs.

To be more specific, the results of this study can be concluded as follows.

- A fundamental effect of loading mode on LBZ fracture behaviour can be observed. The CTOD tests exhibited pop-ins (initiated from LBZs) for all a/W ratios. However, all tensile panels showed fully ductile failure without triggering a pop-in from existing LBZs at the crack tips.
- The apparent CTOD toughness of the LBZs increased with decreasing crack depth to width ratio (a/W) due to the reduction of tri-axiality ahead of the crack tip, and/or extensive ductile tearing prior to cleavage fracture. The amount of ductile tearing prior to cleavage fracture appears to be dependent on the a/W ratio.

- It is shown that the CTOD (δ_5) technique can provide configuration-independent R curves over an extended range of crack growth on centre cracked tensile panels. However, for short cracked specimens where general yielding occurs, the J integral will be considerably influenced by remote plastic deformations; consequently, the J integral (inferred from conventional V_{LL} measurements) should not be used to construct R curves.

Acknowledgements

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