*D. T. Read**

Weldment Fracture Toughness Measurements using T-CTOD Specimens

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ABSTRACT The T-CTOD specimen is a welded three-point-bend fracture toughness specimen in which the crack is cut transverse to the weldment, so that the crack front samples base metal, weld metal, and heat affected zone (HAZ).

In a program to examine the usefulness of the T-CTOD specimen, the T-CTOD and a more conventional HAZ-CTOD geometry were used to test two materials, StE 355, which is a C–Mn, banded-ferrite–pearlite steel suited for offshore structural applications, and 2 1/4 Cr 1 Mo steel (CM steel), which is used in high-temperature pressure vessels which are hydrostatically tested at ambient temperatures. The goals were to locate the most brittle zone in the weldments and to evaluate its toughness. Because cleavage was the fracture mode of interest, the StE 355 was tested at −30°C and the CM steel was tested at room temperature. To simulate structural cracks, all notches originated at the plate surface and progressed into the thickness. Three relative crack depths were used: $a/W = 0.1$, 0.2, and 0.5. To maintain constant microstructure at the crack tip, these a/W values were achieved by holding the crack depth constant at 4 mm and machining W as needed.

Three major difficulties were encountered with the T-CTOD specimen: crack front curvature; scatter in measured toughness values; and, uncertainty about the location of the fracture origin. The crack front curvature is associated with the residual stresses from welding and with the strength mismatch between weld and base metal. The scatter is associated with statistical weakest-link fracture in a local brittle zone (LBZ). The uncertainty about the origin location results from the ambiguity of the river patterns.

The location of the most brittle zone in both weldment types tested was in the subcritical HAZ, which is actually outside of the etchable HAZ. Toughness values below the base metal values were observed there; however, it must be recognised that brittleness of the material outside the etchable HAZ is not characteristic of all steels.

The difficulties encountered with the T-CTOD specimen reduce its appeal. Nevertheless it has the significant advantage that the crack front samples the whole weldment, allowing a test which requires no assumptions about the location of the local brittle zone (LBZ).

Introduction

For ferritic steels in the brittle-to-ductile transition range of temperatures, the material fracture toughness can be measured using well-established test methods. However, the results are subject to a high degree of variability (**1**) and scatter. The scatter forces us to ask, 'What is the correct toughness value?' The correct toughness value leads to the proper balance between structural safety and efficiency. Weldment tests are especially susceptible to scatter because each weld contains a variety of microstructures. Key issues in toughness testing of weldments are the location of the brittle zone and the significance of pop-ins.

* Materials Reliability Division, National Institute of Standards and Technology, Boulder, Colorado 80303, USA.

This paper reports a study on an adaptation of the Kinzel specimen (2), named the T-CTOD specimen. It incorporates the recently developed practices of elastic–plastic fracture mechanics in the test procedure and in the analysis. The principal advantage of this specimen is that the crack front passes through base- and weld-metal and through the heat affected zone (HAZ), so that each region of the weldment is sampled. The disadvantage arises when small zones of brittle microstructure, known as local brittle zones (LBZ), are present. According to the statistics of weak-link fracture, the scatter observed in a set of toughness measurements increases as the amount of LBZ along the crack front decreases, simply because each element of LBZ has only a probability of actually being brittle.

Two steels were tested using the new T-CTOD specimen and more conventional HAZ-CTOD specimens. The overall goal was to determine whether the T-CTOD specimen provides a candidate 'correct' fracture toughness value. The specific objectives were to find out whether the T-CTOD specimen could be used to, first, determine the location, and second, evaluate the toughness of the most brittle zone within these weldments.

Materials

Base plate

Two materials were used: an offshore-structural steel, called StE 355, and a 2 1/4 Cr-1 Mo pressure vessel steel, designated A387 Gr 22 steel. The StE 355 was made according to specification DIN 17 102, grade SB 36 F, and is similar to BS 4360-50D. The plate was rolled to a thickness of 60 mm and normalised. The A387 Gr 22 steel was made to ASTM specification A387D, grade 22, as a 50 mm (2 in) thick plate in the annealed condition. This steel is intended primarily for boilers and pressure vessels for elevated temperature service. Tensile properties are listed in Table 1. The chemical compositions of both steels were within specification, and are listed in the detailed report of this study (3).

Welds

The weldments in both plates simulated repair welds. The grooves were 20 mm (3/4 in) wide by 20 mm (3/4 in) deep. The welds were made by the manual

Table 1 Tensile properties of the specimen materials

	Yield strength (MPa)	*Ultimate strength (MPa)*	*Elongation (percent)*	*Reduction of area (percent)*
StE 355:				
Base	390	512	24	NA
Weld	468	563	32	77
A387 Gr 22:				
Base	206	550	31	75
Weld	767	843	23	66

metal arc (SMA) process. The brand names of the electrodes are given in (4); the chemical compositions of the deposited welds are listed elsewhere.

The welds in the StE 355 were made without preheat using 5 mm diameter electrodes. Thirteen passes were used to fill the groove. The heat input was reported as 2×10^4 J/cm. According to the usual practice for this material, these welds were given no postweld heat treatment (PWHT). The welds in the A387 Gr 22 were made with a preheat of 200°C using 4 mm diameter electrodes. Twenty-one passes were used to fill the groove. The heat input was reported as 1.8×10^4 J/cm. These weldments received no PWHT, contrary to the usual practice for this material. One of the purposes of this study was to document the effect of the omission of the recommended PWHT on the A387 Gr 22 weldments. The tensile properties of the weld metals are given in Table 1.

Test plan

The test specimen geometry adopted here is referred to as the T-CTOD specimen. The initial T stands for transverse and refers to the orientation of the crack plane transverse to the weld direction (see Fig. 1). The CTOD specimen is well known in elastic–plastic fracture mechanics. It is a three-point-bend

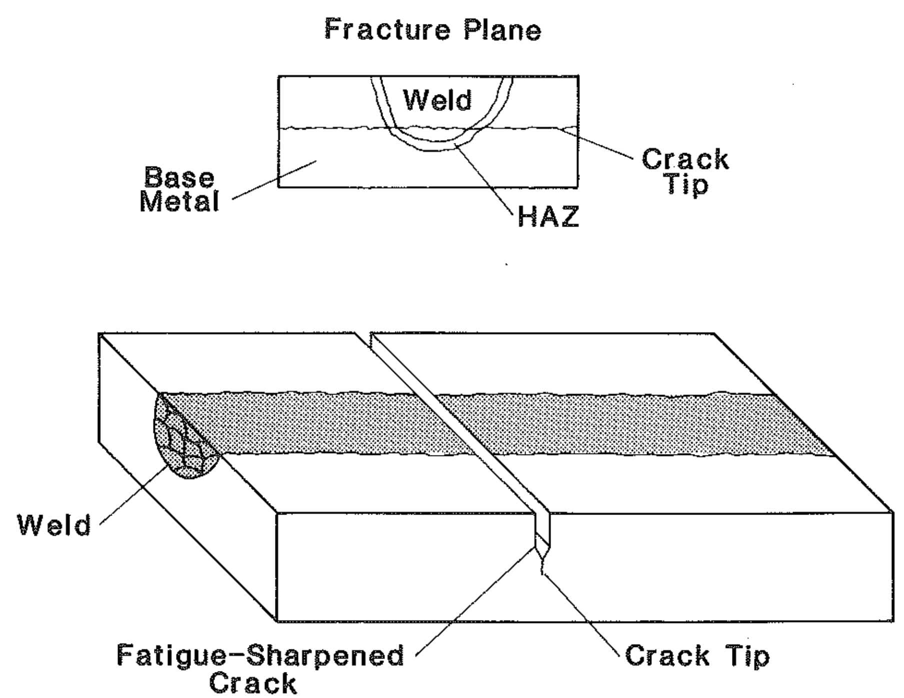

Fig 1 The T-CTOD specimen

specimen with a fatigue-sharpened crack. To simulate flaws which might be detected during in-service inspections, cracks originating from the plate surface and propagating through the plate thickness were chosen here. This differs from the more usual weldment CTOD specimen (5), where the crack originates as a through-thickness notch and propagates along the weld direction. Crack orientation for propagation in the plate thickness or short transverse direction is recognised in (5) as a means of testing the HAZ toughness when production welds must be simulated and in (6) as suitable for materials research.

Specimens oriented so that the crack plane was parallel to the weld direction and perpendicular to the plate surface (Fig. 2) were used as a check on the T-CTOD results. These specimens had the crack tip in the HAZ and are called HAZ-CTOD specimens. In all specimens, the crack opening stress is transverse to the base plate rolling direction. The crack tips in the HAZ-CTOD specimens were placed to sample the most brittle location in the weldment, using the assumption that the most brittle location corresponded to the suspected fracture initiation sites on the T-CTOD specimen fracture surfaces.

To sample a range of values of normalised crack depth, a/W, while always sampling the same location in the weldment, the crack depth, a, was held constant at 4 mm while the specimen width, W, was machined to obtain a/W values of 0.1, 0.2, and 0.5. Table 2 gives the number of specimens of each type actually tested.

Although the test plan called for specimens of different widths, the precracking was done before the narrow specimens were machined to their final widths, so that all the specimens would have the same crack tip preparation. The notch depth before precracking was 2.7 mm for all specimens. The crack length after precracking ranged up to 6.9 mm, but averaged about 5 mm, although the goal was 4 mm precracks. All precracks in a given material and

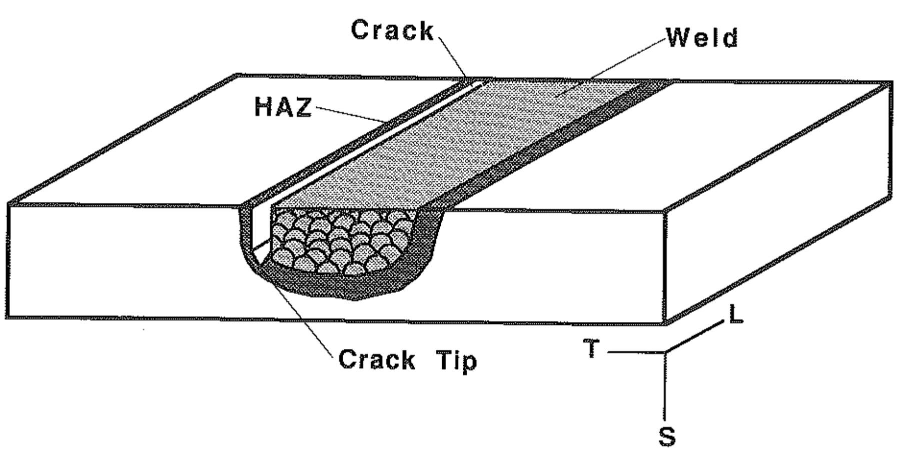

Fig 2 The HAZ-CTOD specimen

Table 2 Specimens tested

Number of specimens of each type and a/W value			
	a/W		
Type	0.1	0.2	0.5
StE 355 steel			
T-CTOD	3	3	3
HAZ-CTOD	3	4	4
ASTM A387 Grade 22 steel			
T-CTOD	2	3	3
HAZ-CTOD	3	3	3

orientation were made with the same cyclic force levels. The StE 355 specimens could not be tested with the available force capacity of 200 kN at their original 60 mm width. They were tested at widths of 40, 20, and 10 mm.

The StE 355 T-CTOD specimens were precracked without special measures to produce straight crack fronts. the T-CTOD specimens were precracked at a maximum cyclic stress intensity factor, K^{max}, of 27 $MPa\sqrt{m}$ and a ratio, R, of minimum to maximum load of 0.1. The HAZ-CTOD specimens were precracked at $R = 0.3$ and $K^{max} = 44\ MPa\sqrt{m}$.

Precompression (7) was used to produce straighter precracks in the A387 steel. To apply the conventional practice of compressing along the weld direction, the T-CTOD specimens were precompressed between 1 and 2 percent along their lengths. The resulting precracks were much less crooked. The T-CTOD specimens were precracked with $R = 0.1$ and $K^{max} = 34\ MPa\sqrt{m}$ and the HAZ-CTOD specimens were precracked with $R = 0.1$ and $K^{max} = 35\ MPa\sqrt{m}$.

All of these K values were in the elastic range and were less than 75 percent of the lowest failure load in the fracture tests. Typically 100 000 cycles were required to grow the fatigue cracks about 1.3 mm.

Satoh has given a set of criteria (8) for the straightness of fatigue precracks in welded specimens; these criteria are intended for precracks with lengths of the order of 15–25 mm, not for the 4 mm cracks of the present case. Satoh considers the quantities a_{min}, a_{max}, the minimum and maximum precrack length, and a_i, and a_j, precrack lengths measured at the quarter- or half-thickness points. He recommends

$$a_{max} - a_{min} \leqslant 0.1\ W$$

$$|a_i - a_j| \leqslant 0.05\ W$$

and

$$a_{min} \geqslant 0.015\ W \text{ or } 0.75 \text{ mm}$$

whichever is greater. Satoh's guidelines are less severe than those of ASTM E 399. Only one of the 18 T-CTOD specimens tested in this project met Satoh's guidelines for fatigue precrack straightness. Twelve of the twenty-one HAZ-CTOD specimens met Satoh's guidelines. The cracks were all approximately the same, but as W decreased the criteria tightened so that the specimens with small W were the ones that failed to meet the criteria.

The problems with fatigue precracks described above are considered to be one of the three major difficulties with the T-CTOD specimen.

Test procedures

After precracking, the specimens were machined to final width and tested. A screw-driven mechanical testing machine with a force capacity of 200 kN was used. The specimens were loaded in three-point-bending with a span between outer loading points of 200 mm, for all values of W. The StE 355 specimens were tested at $-30°C$ in a temperature-control chamber cooled by circulating cold nitrogen vapour. Specimen temperatures were within 0.5°C of $-30°C$ throughout the test. The loading rate was rather low, 0.2 mm/min. Load, crack mouth opening displacement (CMOD), load point displacement (LPD), and direct current potential drop (DCPD) were recorded during the test on x–y plotters and were logged by computer approximately once per second.

Tests were stopped when pop-in was unambiguously detected, or when the travel of the testing machine was exhausted. The criteria for an unambiguous pop-in were the audible pop, a load drop, a displacement increment, and a DCPD increment.

The calculation of CTOD requires a rotation factor r. In these tests r was taken as

$$r = 2\,a/W, \quad a/W < 0.2$$

$$r = 0.4, \quad a/W \geqslant 0.2$$

This approximation is consistent with the results of recent finite element analyses.

Analysis of the data using the J integral was impossible because of weld strength overmatching.

Fractography

The fracture surfaces containing cleavage were sorted into three types: essentially complete cleavage; full width pop-in; and local pop-in. The specimens with essentially complete cleavage had remaining ligaments about 1 mm wide at the sides and 5 mm or less at the back of the fracture surface. The specimens with full width pop-ins had remaining ligaments of 1 mm or less at the sides and crack jumps of 2 mm or more. The local pop-ins were isolated areas of cleavage on the order of 10 mm or less in diameter. Table 3 lists the number of each type of fracture event observed. It was difficult to distinguish between full-width pop-in and essentially complete cleavage in the very narrow specimens ($W = 8$ mm), so their results are marked with asterisks in Table 3.

Table 3 Fracture events

		Number of fracture events observed			
Material type	*W (mm)*	*Local pop-in*	*Full width pop-in*	*Essentially complete cleavage*	*No cleavage*
StE 355					
T-CTOD	40	1	0	2	0
	20	0	0	3	0
	8*	2	0	0	1
HAZ-CTOD	40	0	0	3	0
	20	0	0	4	0
	8*	0	4	0	0
A387 Gr 22					
T-CTOD	40	2	0	0	0
	20	3	0	0	0
	8*	3	0	0	0
HAZ-CTOD	45	0	0	3	0
	23	0	0	3	0
	9*	0	3	0	0

* Difficult to categorize

Scanning electron microscopy (SEM) was used to identify fracture modes and to search for the locations of fracture origins. Based on the fractographic observations, the cracks in the HAZ-CTOD specimens were placed in the most brittle locations. The difficulty of unambiguously locating the fracture origins on the T-CTOD fracture surfaces was the second major difficulty in the present project.

After testing, the HAZ-CTOD specimens were sectioned to determine the precrack's location in the microstructure, Fig. 3. The sectioning procedure was similar to that in (**9**). The section was polished for metallography and etched with nital. The distance between the precrack tip and the outside of the etchable HAZ was measured at four stations within the central 60 percent of the specimen width. Where the precrack was actually within the etchable HAZ, the distance between the crack tip and the outside edge of the HAZ is reported as a negative value.

Results and discussion

The toughness values obtained in the present study are plotted in Figs 4–7. These are all values associated with pop-in or with complete cleavage. Initiation of ductile tearing, which occurred in a few specimens, is ignored.

The toughness data for the T-CTOD specimens in both materials are clearly highly scattered. This indicates that it is too optimistic to hope that the

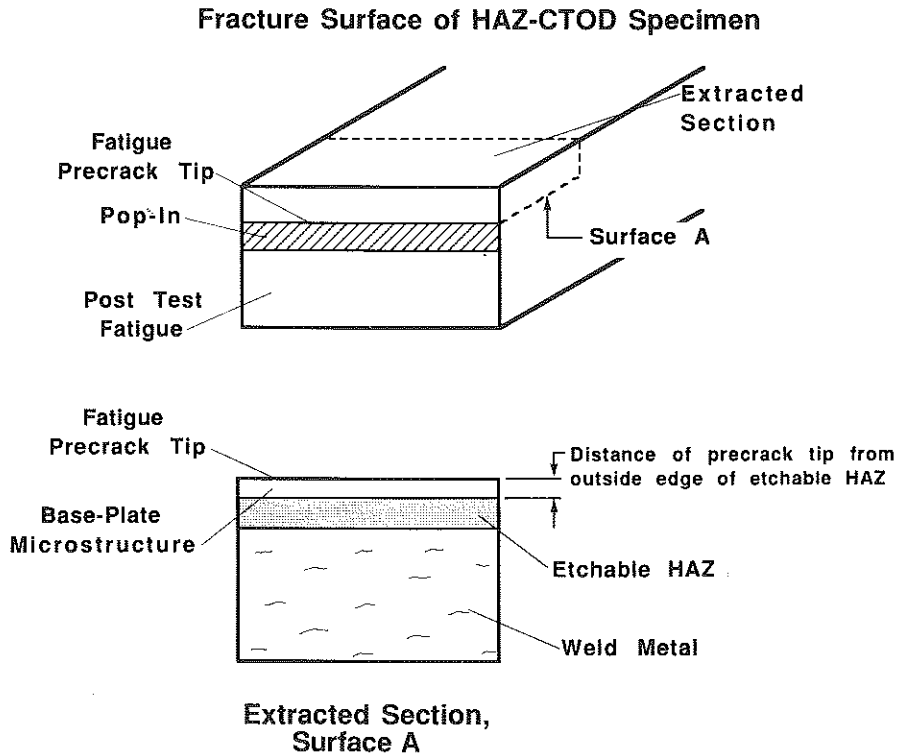

Fig 3 Fractographic procedure used in HAZ-CTOD specimens to locate the fatigue precrack tip with respect to the etchable HAZ

T-CTOD specimen can give a direct and simple evaluation of the lower bound weldment toughness.

The data for the HAZ-CTOD specimens indicate that the location of the crack tip relative to the HAZ was much more important than the relative crack depth, as shown in Figs 8 and 9. For the StE 355, the data are consistent with a maximum in the toughness around the outer edge of the etchable HAZ. Lower toughness values were found 0.8 mm into the HAZ near the fusion line; lowest toughness values are found 0.6 mm outside the HAZ. In the A387 Gr 22 steel, lowest toughness values were found about 0.2 mm outside the etchable HAZ, with higher values within the HAZ and further out in the base metal.

Figures 10 and 11 document the lack of correspondence between the lower-bound toughness data for the T-CTOD and HAZ-CTOD specimens. The figures indicate that the probability that a T-CTOD specimen would have the same toughness as a lower-bound HAZ-CTOD specimen is 1 percent or less. However, the upper bound toughness of the T-CTOD specimens corresponds roughly to the upper bound toughness of the HAZ-CTOD specimens. The solid curves in Figs 10 and 11, calculated after Slatcher **(10)**, indicate that the

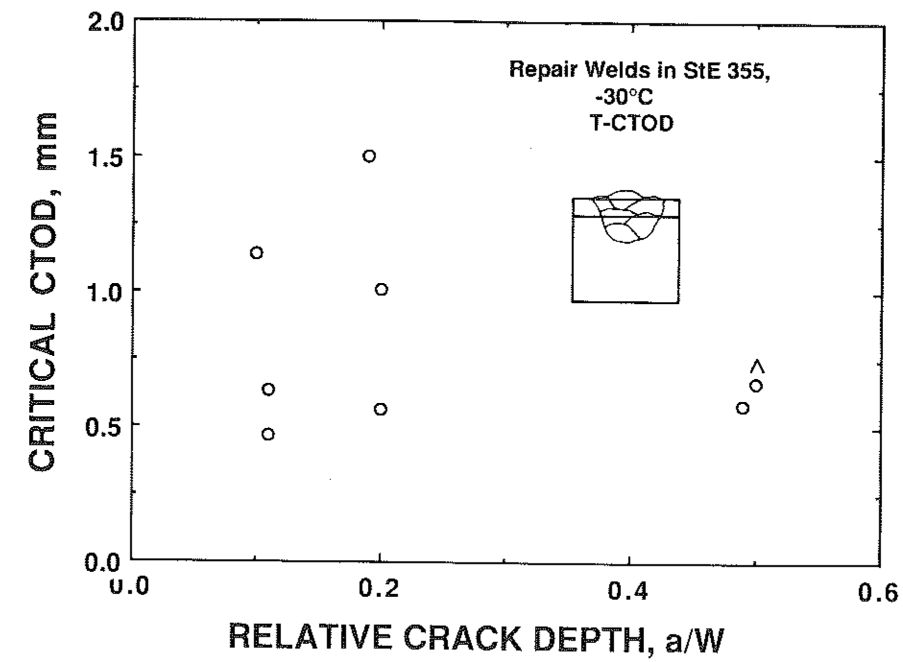

Fig 4 Toughness, critical CTOD, for the specimens of StE 355 plotted against normalised crack depth *a/W*. Here it is held constant, *W* varies

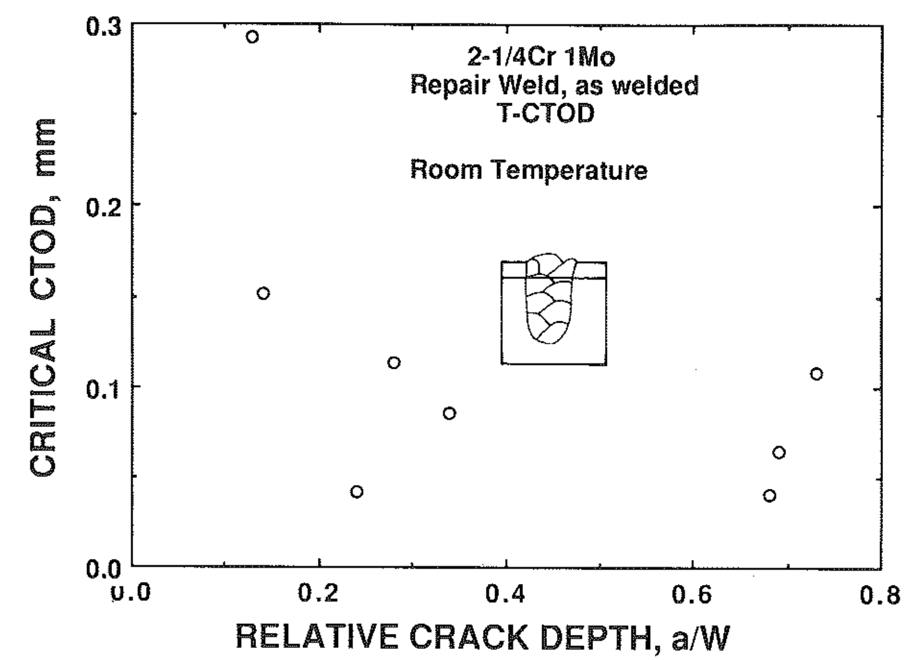

Fig 5 Toughness, critical CTOD, for the specimens of A387 Gr 22 plotted against normalised crack depth *a/W*. Here it is held constant, *W* varies

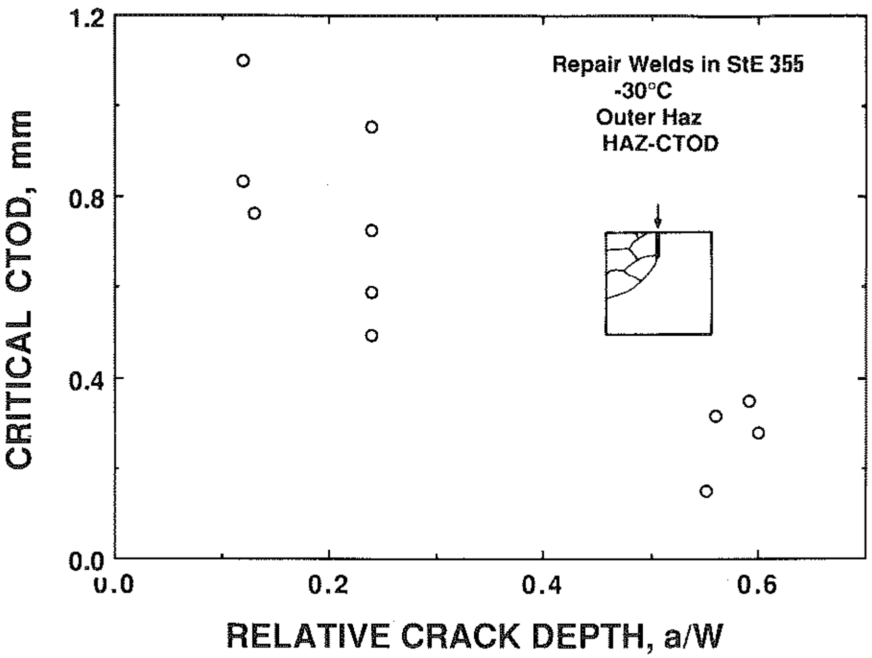

Fig 6 Toughness, critical CTOD, for the HAZ-CTOD specimens of StE 355 plotted against normalised crack depth a/W. Here a is held constant, W varies

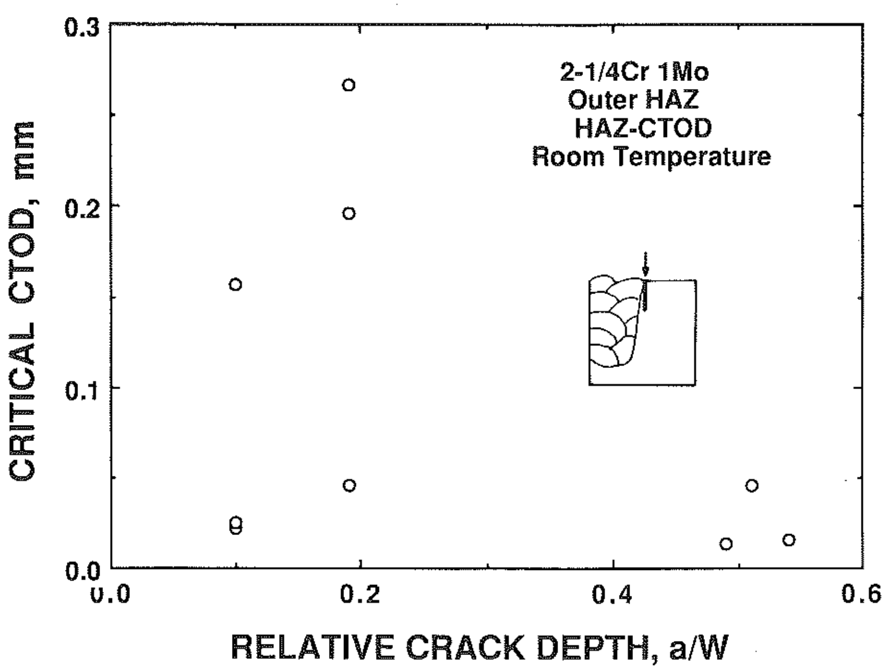

Fig 7 Toughness, critical CTOD, for the HAZ-CTOD specimens of A387 Gr 22 plotted against normalised crack depth a/W. Here a is held constant, W varies

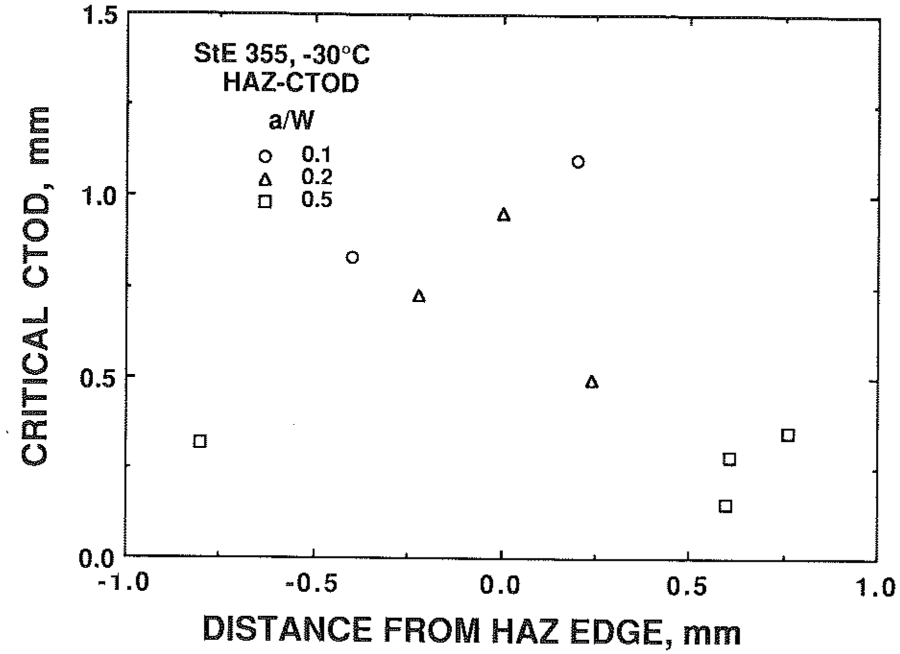

Fig 8 Fracture toughness, critical CTOD, for the StE HAZ-CTOD specimens as a function of the distance from the crack tip outside edge of the etchable HAZ

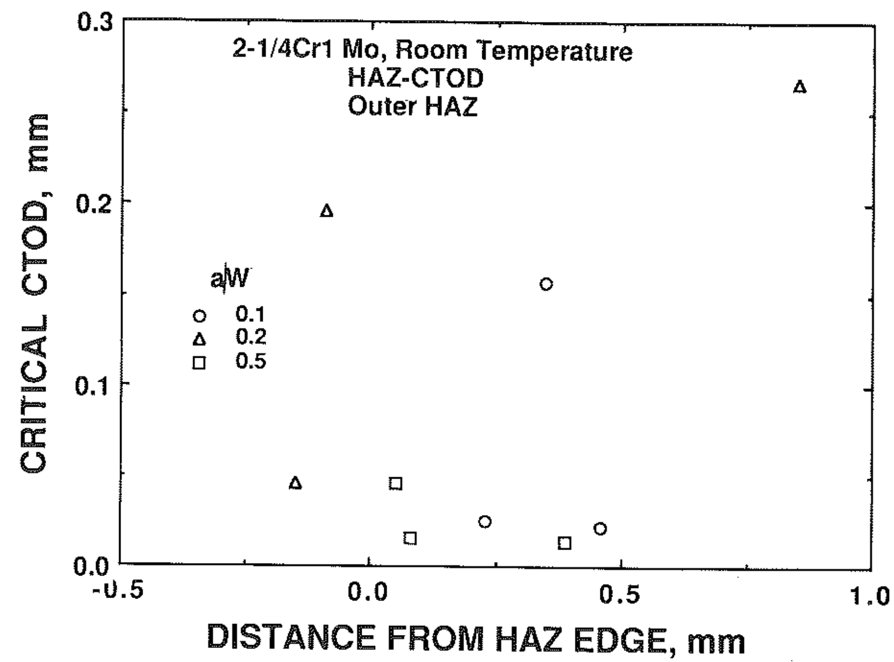

Fig 9 Fracture toughness, critical CTOD, for the A387 Gr 22 HAZ-CTOD specimens as a function of the distance from the crack tip to the outside edge of the etchable HAZ

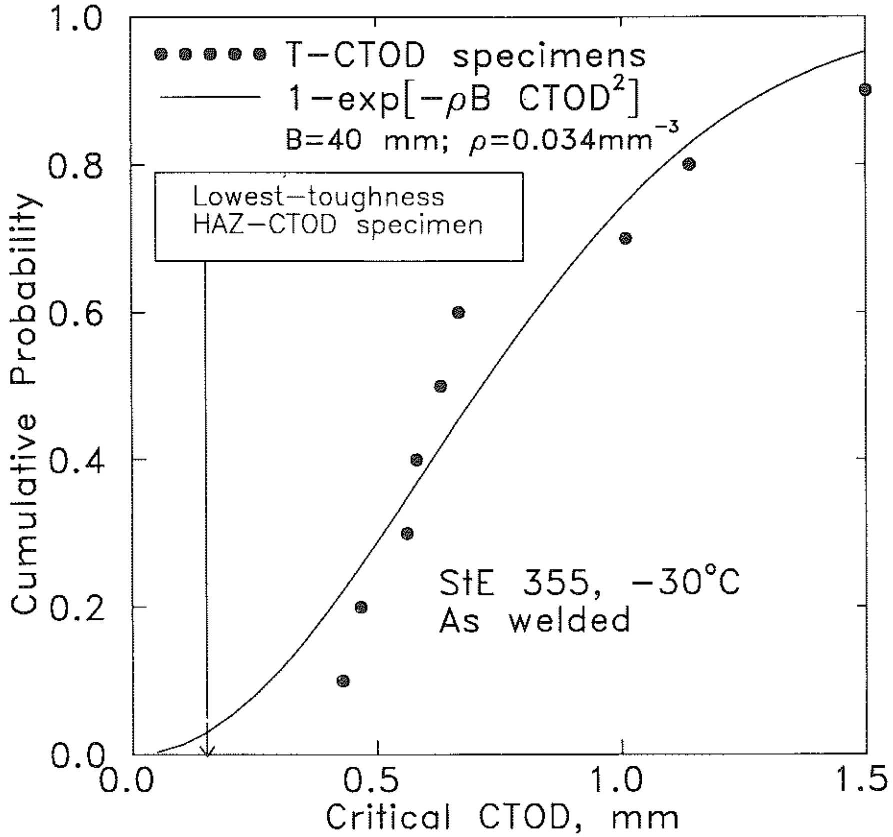

Fig 10 Cumulative probability of fracture toughness, critical CTOD, values for the StE 355 plotted against critical CTOD

T-CTOD specimen data has the scatter expected of fracture toughness results in the ductile-brittle transition.

Conclusions

The main conclusion of this study is that the T-CTOD specimen does not provide a lower-bound fracture toughness value for welds in two ferritic steels; this specimen can indicate approximately where the most brittle zones of a weldment are located. Precracking using normal procedures results in curved crack fronts.

The reference specimen adopted for this study, the HAZ-CTOD specimen, provides valuable information on toughness as a function of crack tip location. Crack tip location effects are believed to have outweighed relative crack depth effects in this study, although the data are insufficient to provide a statistically sound proof of this claim.

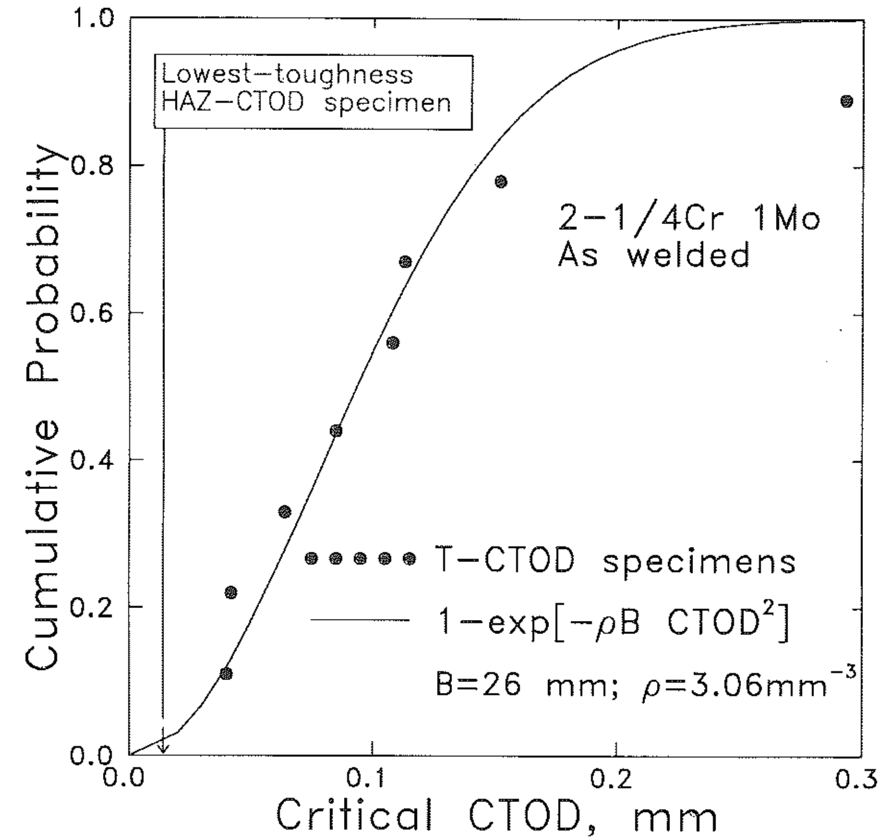

Fig 11 Cumulative probability of fracture toughness, critical CTOD, values for the A387 Gr 22 plotted against critical CTOD

The most brittle zones in the weldments tested were found to be at the outer edge of the etchable HAZ (A387 Gr 22) and 0.6 mm outside the etchable HAZ (StE 355 at −30°C).

Acknowledgements

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