EFFECT OF NOTCH TIP LOCATION IN CTOD TESTING OF THE HEAT AFFECTED ZONE OF STEEL WELDMENTS

C. Thaulow*, M. Hauge*, A.J. Paauw+, M. Toyoda† and F. Minami†

For offshore steel weldments most low toughness results are experienced when the notch is located close to the fusion line of the weld, with subsequent initiation of a brittle fracture from the embrittled coarse grained zone of the HAZ. The HAZ/fusion line is also the preferred location of planar defects in the weldment. Hence, in order to characterize and evaluate the fracture toughness and acceptance criteria for a typical offshore steel weldment, focus must be directed towards the HAZ/fusion line region. The paper examines the relationships between the mechanical properties of the zones in the weldment and the notch location, on the fracture toughness. If the weld metal overmatches the base material by more than 5-10 % in strength, it is recommended to have a cross fusion line type of notch, hitting both weld metal and CGHAZ.

1. INTRODUCTION

In the fracture mechanics testing of steel weldments, low fracture toughness is frequently experienced. The low toughness is caused by the interaction between the notch tip and an embrittled microstructural constituent, so-called Local Brittle Zone (LBZ).

Most existing fracture mechanics testing standards were developed for parent metals with a high degree of homogeneity. However, fracture mechanics testing of weldments is inherently more complicated, and a range of parameters must be defined in order to standardize the testing procedure. A testing standard for welds has not yet been issued, but experiences gained during the testing of welds has been documented in various recommendations (Dawes et al (1), API (2), Nordtest (3), Toyoda and Thaulow (4)).

* University of Trondheim, Norway
+ Aker Engineering, Oslo, Norway
† Osaka University, Japan

An additional important feature for the fracture mechanics testing of weldments, is that the large scatter often observed is not only due to the existence and distribution of LBZ but also depends on the global and local distribution of mechanical properties, eg. material stress-strain behaviour. Accordingly, the investigation of the fracture behaviour of weldments has been extended to include the influence of mechanical properties, and the term WELDING MECHANICS has been introduced to cover this direction of research, (Toyoda, Thaulow and Blauel (5)).

The present paper discusses one important variable in fracture mechanics testing of weldments; the location of the fatigue precrack.

2. LOCATION OF FATIGUE PRECRACK DURING CTOD TESTING OF WELDS

The positioning of the fatigue precrack with respect to the region containing LBZ, is one of the dominating parameters during CTOD testing of the heat affected zone (HAZ). Traditionally, one aims at sampling as large a portion of the embrittled zones as possible, hence a major part of the crack tip will usually be on the HAZ/base metal side of the fusion line.

Weld thermal simulation testing of various structural steel qualities has shown that there is a toughness gradient within the coarse grained zone of the HAZ, with the lowest toughness adjacent to the fusion line, Fig.1. A common procedure applied in laboratories is to locate the notch so as to sample a maximum amount of the coarse grained zone, without hitting weld metal. The aim is to avoid brittle fracture initiation from weld metal which is not subject of testing. This notching procedure causes a part of the crack tip to be located at some distance from the fusion line, e.g. in a region with higher toughness. Recent research has, however, shown that lower fracture toughness values are obtained when the crack tip is located adjacent to the fusion line, even if the fatigue precrack samples slightly the weld metal along the crack front. Especially in the case of weld metal yield strength overmatch, this tendency is apparent because weld metal overmatch will increase the constraint in the CGHAZ near the fusion line.

The effect of notch position on measured CTOD values has been reviewed by Hauge (6). In one case, it was found that in only one of 15 CTOD tests, all with fracture initiation in CGHAZ, the crack tip was located entirely in the CGHAZ. In two tests, the crack tip was located at the fusion line and in the remaining 12 tests a part of the crack front was located in the weld metal, see, for instance, Fig.2.

3. WIDE PLATE TESTING

To further clarify the influence of precrack location, six wide plates were tested in four point bending at -10°C, see Fig.3. The plates were submerged arc welded, with a heat input of 4 MJ/m. The weld metal was slightly overmatched, 550 MPa yield strength, compared with the base material yield strength of 500 MPa. The weld metal overmatch is also reflected in the hardness distribution, shown in Fig.4. A surface notch with a zig-zag pattern was electro discharged machined and extended by fatigue loading to a depth of 20mm and a length of 200 mm.

A high degree of plasticity was obtained before the onset of a final unstable fracture in four cases, and brittle fracture without preceeding ductile crack growth was experienced in the remaining two plates, as summarized in Table 1.

The evaluation of the notch location and the area of brittle fracture initiation confirmed the observations from the above referred CTOD tests. The two low CMOD values were obtained when the fatigue crack crossed the fusion line and the crack tip was located on the weld metal side of the fusion line, close to an area with a coarse grained HAZ, Fig.5.

In addition, 6 B*2B CTOD specimens were cut from the end of the 6 wide plates.

The distance of the notch from the fusion line was slightly varied for each specimen, see Fig. 6. All six specimens exhibited brittle fracture initiation in the coarse grained HAZ close to the fusion line, and the crack propagated along the fusion line in the coarse grained HAZ. The lowest CTOD values were experienced with the notch positined on the fusion line or close to the fusion line on the weld metal side, Fig.6. The member of tests are very limited, but the results are donfirming the observations made by Hauge (8), Thaulow et al (12) and Minami et al (13).

4. DETAILED EXAMINATION OF THE NOTCH POSITION

The effect of notch position is one of the variables examined in an ongoing Norwegian-Japanese research project on the application of high strength steels for offshore purposes. For a number of CTOD test specimens, detailed sectioning and metallographic examinations have been carried out, see Fig.7. The initial distance from the fatigue crack tip to the fusion line and the subsequent length and direction of ductile crack growth before the onset of an unstable fracture, have been determined.

One example from CTOD testing of a weldment with a weld metal yield strength overmatch close to 30% and a plate thickness of 50 mm, is shown in Fig.8. The distance from the fatigue crack tip to the fusion line, and the subsequent ductile crack growth before the onset of the brittle fracture, are indicated in the figure. Two of the specimens with relatively low CTOD values, whose fatigue crack originally positioned in the weld metal, revealed limited ductile crack growth towards the fusion line/coarse grained zone before the onset of the final fracture. But, on the contrary, two other specimens, initially positioned in the coarse grained zone, also revealed limited ductile crack growth towards the fusion line.

Alternatively, similar CTOD tests performed on the same steel, but with a minor change in the welding procedure, were examined according to the procedure outlined in Fig.9. The distance from the fusion line to the fatigue crack tip, d, has been measured at five positions and divided by the width, w, of each corresponding CGHAZ. The result is presented as an average "distance" from the fusion line vs. the CTOD value, d/w, Fig.10. Again, low HAZ CTOD values have been determined when the notch was located on the weld metal side of the fusion line.

It should be noted that the effect of notch positioning will depend on both the actual CGHAZ toughness and the strength mismatching condition. In the case of moderate or high toughness of the CGHAZ, weld metal overmatch can result in increased CTOD values due to the deviation of the crack path towards the base metal. (Kocak et al (7), Thaulow and Paauw (8)). For this case, the plastic strain will accumulate to a larger extent in the softer areas of the HAZ and in the base material, before the critical stress can be attained at the CGHAZ.

On the other hand, in the case of a low CGHAZ toughness, the weld metal overmatch will favour the conditions to obtain lower bound CTOD values. This is due to the elevation of the local stress in the CGHAZ/fusion line region caused by the constraint effect of the overmatch weld metal. This result has been confirmed by other studies. (Aihara (9), Toyoda et al. (10), Thaulow et al. (11)).

CONCLUSION

During fracture mechanics testing of steel HAZ, it is recommended that the target notch position, in order to obtain lower bound values, is to sample the areas of coarse grained- and reheated coarse grained HAZ at the fusion line. In order to hit the maximum length of the coarse grained HAZ at the fusion line, the fatigue precrack will also partly sample weld metal. If the weld metal overmatches the base material by more than 5-10 % in strength, it is recommended to have a cross fusion line type of notch in order to obtain lower bound fracture toughness, provided that the weld metal itself has sound toughness.

ACKNOWLEDGEMENT

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TABLE 1 Summary of the results from the wide plate testing of butt weldments with a heat input of 4 MJ/m. The zig-zag surface notch was located at the fusion boundary.

Heat treatment	Load at fracture kN	$CMOD_{-10°C}$ mm	Remark
AW	1069	4.1	u brittle fracture
	825	0.58	c brittle fracture
	1081	2.4	u brittle fracture
PWHT	675	0.30	c brittle fracture
	1065	3.4	u brittle fracture
	1169	6.0	u brittle fracture

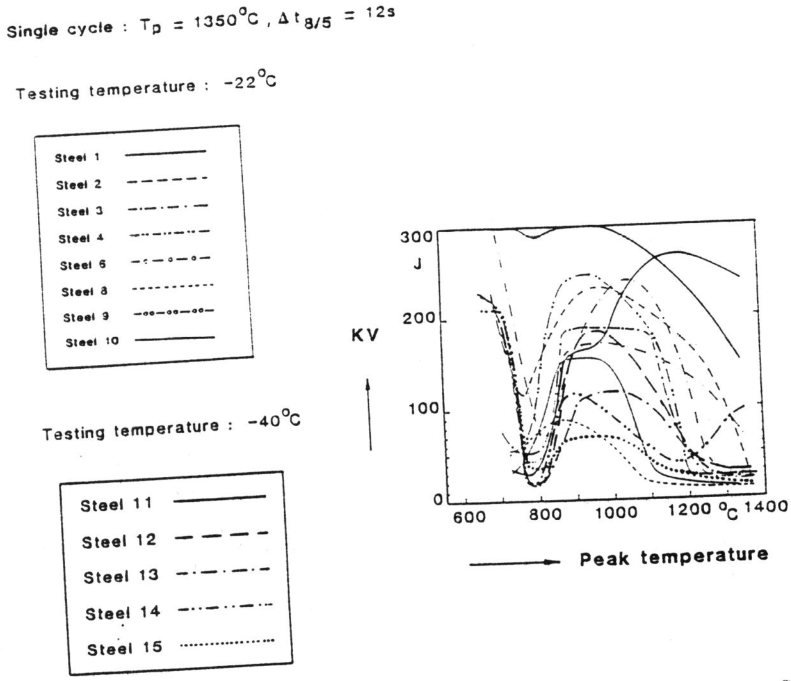
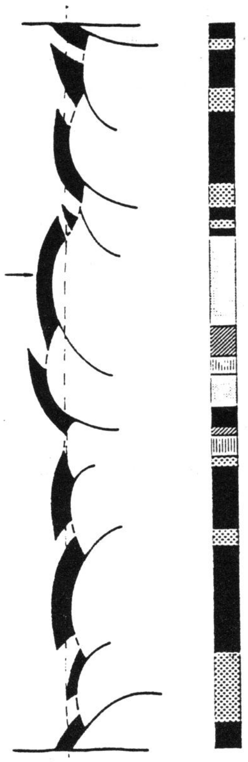
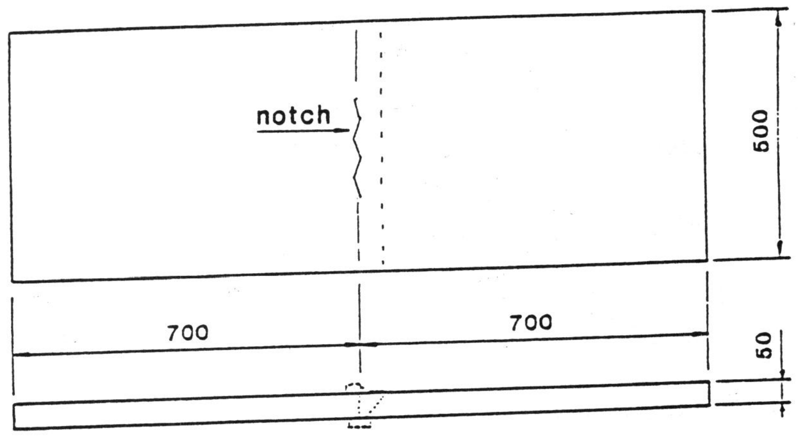


Figure 1 Charpy weld thermal simulation testing of 15 offshore steels.

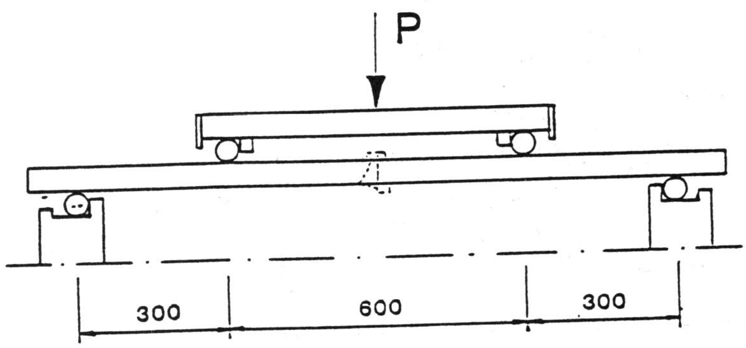


Microstructure	Code	Indication
Primary weld metal	PWM	
Coarse grained weld metal	CGWM	
Fine grained weld metal	FGWM	
Base material	BM	
Coarse grained HAZ	CGHAZ	
Fine grained HAZ	FGHAZ	
Intercritical HAZ	ICHAZ	

Figure 2 CTOD notch location in a HAZ of a steel weldment. The point of crack initiation and the distribution of microstructure along the notch tip are indicated.

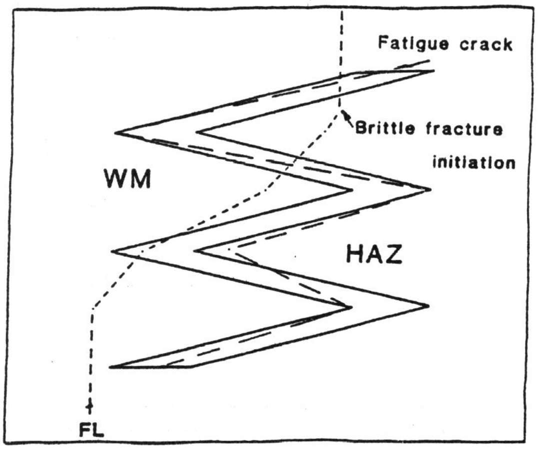


Wide plate test-specimen



Four point bending fixture for the wide plate specimen

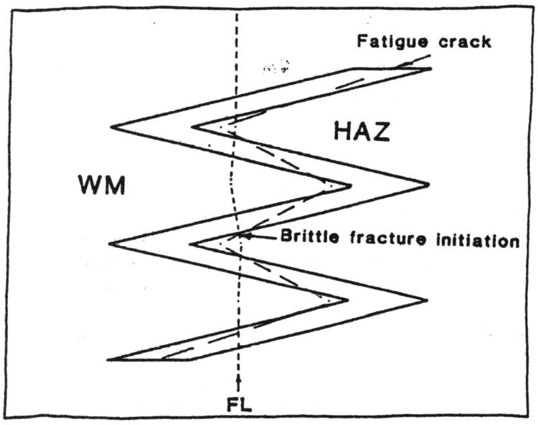
Figure 3 Four point bending wide plate test.



CMOD$_{-10^\circ C}$ = 3.4 mm

(u)

Crack tip location : **Large distance between the fatigue crack-tip and the coarse grained HAZ.**



CMOD$_{-10^\circ C}$ - 0.30 mm

(c)

Crack tip location : **Optimal location of the fatigue crack-tip i.e. close to the coarse grained HAZ sligtly on the weld metal side of the fusion boundary.**

Figure 5 The location of the brittle fracture initiation in a four point bending wide plate specimen.

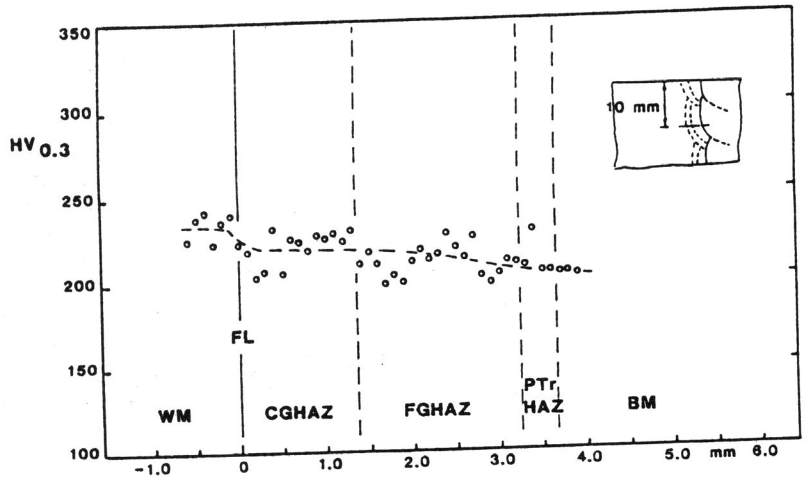


Figure 4 The hardness distribution in a SAW butt-weldment

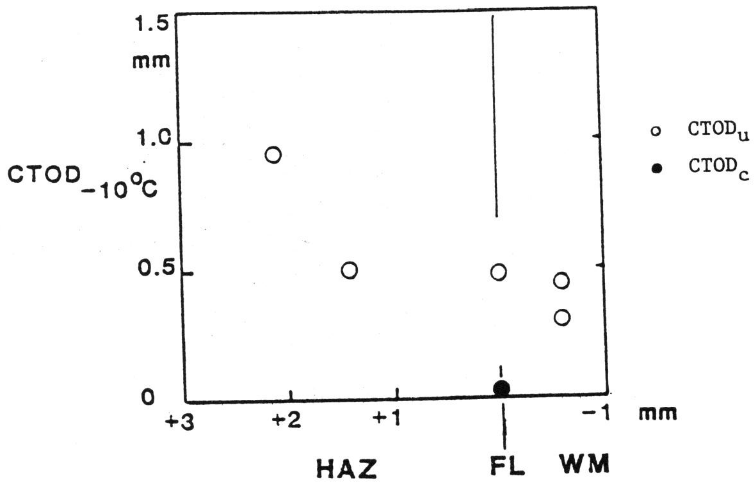
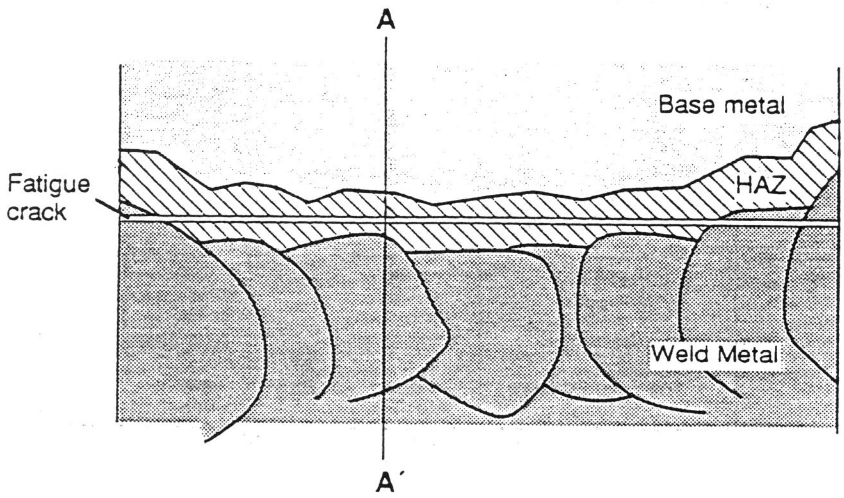
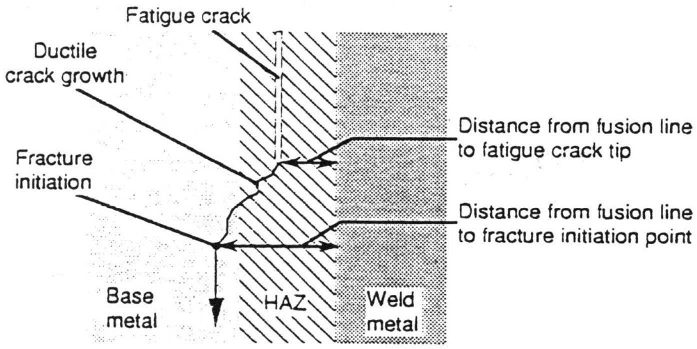


Figure 6 CTOD test results from Bx2B specimens with notch positioning close to the fusion line. In all cases the point of fracture initiation was located in the CGHAZ, close to the fusion line.





A-A´ section

Figure 7 CTOD specimen sectioned through the fatigue crack and through the point of fracture initiation.

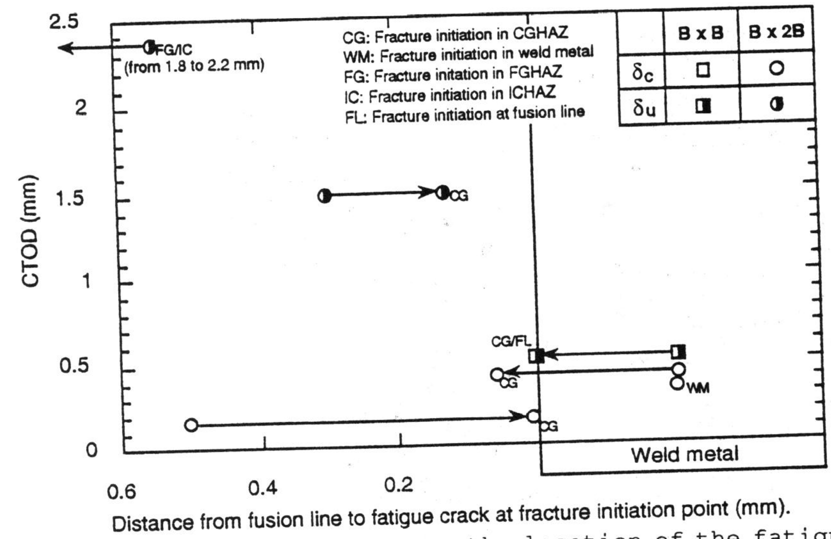
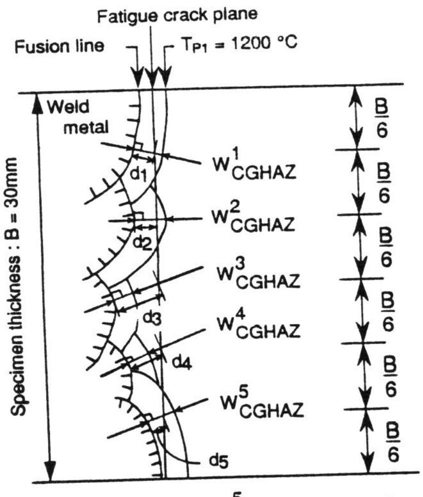


Figure 8 Relationship between the location of the fatigue crack tip and the point of fracture initiation on the CTOD record. Both the initial location of the fatigue precrack and the position at the onset of the brittle fracture are indicated. The arrows show the direction of the ductile crack growth.



$$\bar{d}/\overline{W}_{CGHAZ} = \frac{1}{5}\sum_{i=1}^{5}\left[d_i/W^i_{CGHAZ}\right]$$

Figure 9 Measurement of the CGHAZ width and the distance from the fusion line to the fatigue crack plane.

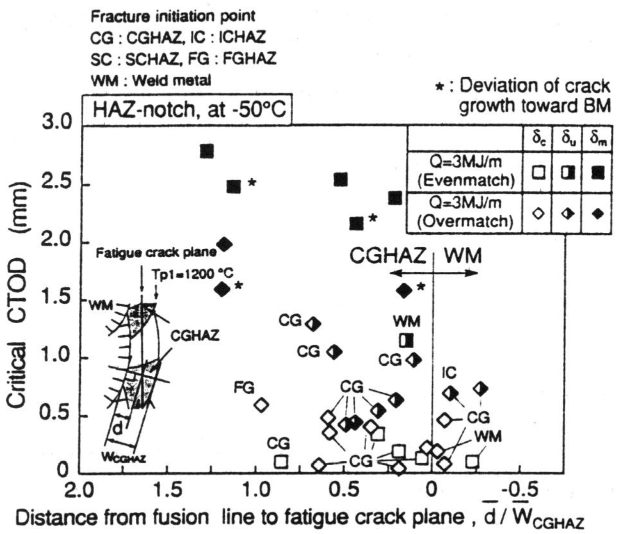


Figure 10 Influence of notch position on CTOD results of specimens notched in the HAZ