Journal of Energy Technology

JET Volume 8 (2015) p.p. 11-22
Issue 4, December 2015
Typology of article 1.01
www.fe.um.si/en/jet.html

DETERMINATION OF LOCAL BRITTLE ZONES AT THE CRACK FRONT IN THE HAZ OF WELDED JOINT

DOLOČITEV KRHKIH PODROČIJ NA FRONTI RAZPOKE V TVP ZVARNEGA SPOJA

Zdravko Praunseis℞, Marko Mlakar[1], Sonja Novak[2]

Keywords: steel welds, heat-affected zone, fracture toughness, crack front

Abstract

Welded joints are the weakest link in the construction of steel structures. The brittlest part of a multi-pass welded joint is the heat-affected zone, where brittle fractures of the structure often appear.

In this article, examination of the whole heat-affected zone of high strength multipass X welded joints was performed. All microstructures and the local brittle zones' sizes at the crack tip front were precisely determined.

Povzetek

Zvarni spoji so pri gradnji energetskih komponent najšibkejši člen jeklene konstrukcije. Najbolj krhko področje večvarkovnega zvarnega spoja je toplotno vplivano področje, kjer se najpogosteje pojavi krhki zlom konstrukcije.

℞ Corresponding author: Zdravko Praunseis, PhD, Faculty of Energy Technology, University of Maribor, Tel.: +386 31 743 753, Fax: +386 7 620 2222, Mailing address: Hočevarjev trg 1, Krško, Slovenia, E-mail address: zdravko.praunseis@um.si

[1] University of Maribor, Faculty of Energy Technology, Hočevarjev trg 1, Krško, Slovenia
[2] University of Maribor, Faculty of Energy Technology, Department Velenje, Koroška 62a, Velenje, Slovenia

V članku je obravnavano celotno toplotno vplivano področje visokotrdnostnega večvarkovnega X zvarnega spoja. Natančno so določene vse krhke mikrostrukture in velikosti lokalno krhki področij ob fronti utrujenostne razpoke.

1 INTRODUCTION

The crack tip opening displacement (CTOD) test has become a common method of measuring the fracture toughness of steel welds. Nevertheless, the commonly used fracture mechanics testing standards, including the CTOD testing standard such as BS 5762, *[2]*, assume the use of metals with a high degree of homogeneity, although this is not explicitly stressed. As already mentioned, in reality, welded joints have typical macroscopic heterogeneity and residual stresses as a result of welding. In order to clarify the applicability of the common testing methods, a basis of knowledge taking the above heterogeneity into account must be established in addition to the standards. Recently, some activities have been conducted for establishing the CTOD testing procedure of steel welds, and some recommended practices/guidelines for CTOD tests of welds have been published.

It is widely understood that the fracture toughness is considerably affected by the shape of the crack front of the fracture toughness specimen, *[6-8]*. Therefore, in the common fracture toughness specimen, attention is carefully paid to realize a straight crack front perpendicular to the plate surface. However, in the welded joint, it is sometimes very difficult to obtain a straight crack front of the fatigue pre-crack due to the existence of weld residual stresses. In order to avoid the confusion due to the irregularity of the crack front and to realize the reproducibility, the current standards require that as a straight crack front as possible be achieved, *[1]*.

2 SECTIONING PROCEDURE TECHNIQUE

In order to achieve a uniform fatigue crack shape which meets the standard requirements, some treatments, i.e. residual stress relieving treatment, have to be applied to notched specimens of welded joints. A different method for relieving residual stresses is to impose a local plastic strain to the region suffering from residual stresses; the following techniques, *[1, 6-8]*, are currently in use,

- Local compression
- Reverse bending
- The use of a high R-ratio in the cycle and step-wise high R-ratio method
- Both side holes method.

Table 1 gives the summary of the relative merits of the three methods. In the Recommended Procedure proposed by The Welding Institute *[8]*, the mechanical relieving residual stresses by local compression, where a plastic strain of 1% of the specimen thickness, is recommended. Moreover, "the use of reverse bending prior to fatigue precracking as a means of redistributing welding stresses is not recommended", *[8].* Moreover, "the effect of a high R- ratio on the fracture toughness is not well understood and so until more work has been completed on this technique its use is not generally recommended." However, for very thick section welds, "the use of high R-ratios during fatigue precracking has been found to be successful in obtaining acceptable crack front profiles", *[8].*

***Table 1**: Characteristics of materials used in stress relieving*

Advantages	Disadvantages
LOCAL COMPRESSION	
– method well published – method in use since 1975 – uses normal fatigue precracking procedures	– requires extra operation – requires high capacity compression rig and tools – toughness may be conservative for some materials – specimen must be flat
REVERS BENDING	
– special equipment not needed – conservative toughness measurements expected – uses conventional fatigue pre-cracking procedures	– requires extra operation – toughness may be significantly lower – little information published
USE OF HIGH R-RATIO	
– no extra operation needed – no extra equipment needed	– required loads and R-ratios in conflict with limits of current standards – little information published – non-conservative assessments of toughness are expected

In the common fracture toughness test, the use of a notch sharpened by a precrack produced by fatigue loading of the test piece is generally required in order to simulate sharp macroscopic defects in the structure and to provide a conservative assessment of toughness. In order to avoid the confusion and to realize the reproducibility, the condition of the fatigue precracking loading must be kept within limits.

After the CTOD test is conducted, both halves (or the half containing the weld metal) of the broken specimen are sectioned and metallurgically examined. The cut into the fracture face is taken just behind but within 2.5 mm, of the fatigue-crack front. The cross section may contain a portion of the fracture surface near one or both surfaces due to fatigue-crack front curvature. Each such portion is not wider than 10% of the specimen thickness. For CTOD specimens that are notched to sample the coarse grain (CG) regions, quantification is as shown in Fig. 1, where the linear fraction of the CGHAZ region sampled by the fatigue crack is calculated. A similar procedure is used for the intercritical coarse grain (IC) and subcritical coarse grain (SC) HAZ areas. Fatigue-crack sampling calculations are made by examining enlarged photographs (3 to 6 times magnification) of the CTOD cross sections.

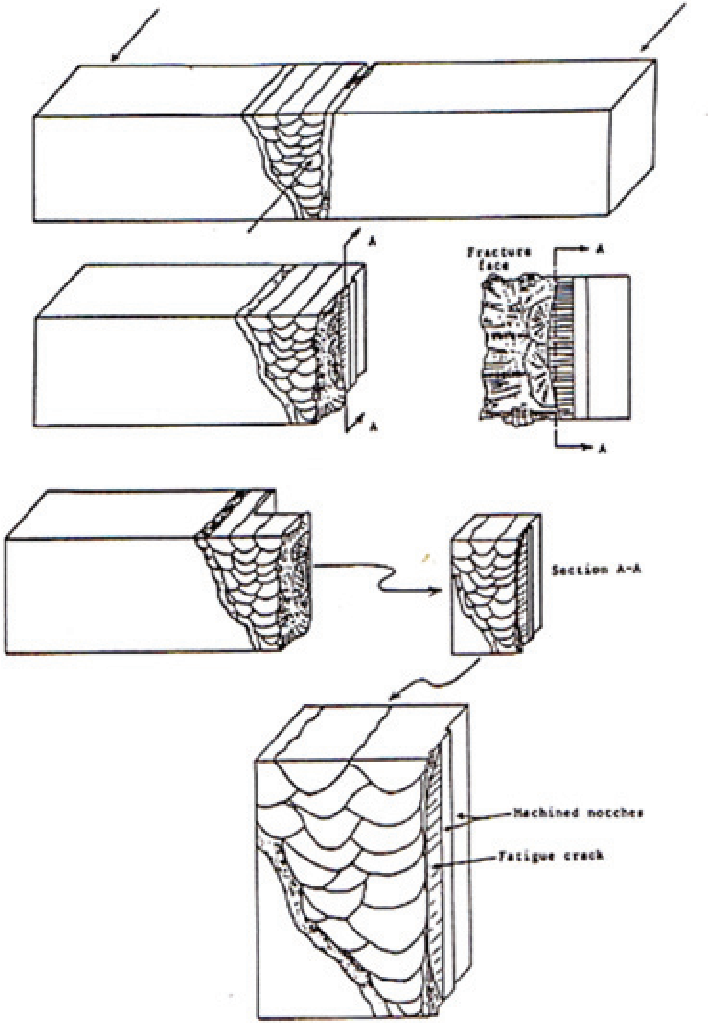

Figure 1: *Sectioning both halves of an HAZ CTOD specimen to calculate CGHAZ percentage*

By using both halves of the broken CTOD specimen and enlarged photographs, fatigue-crack sampling calculations can be made with reasonable accuracy without microscopic examination. Each HAZ specimen should be sectioned to determine the regions of microstructure sampled by the fatigue crack.

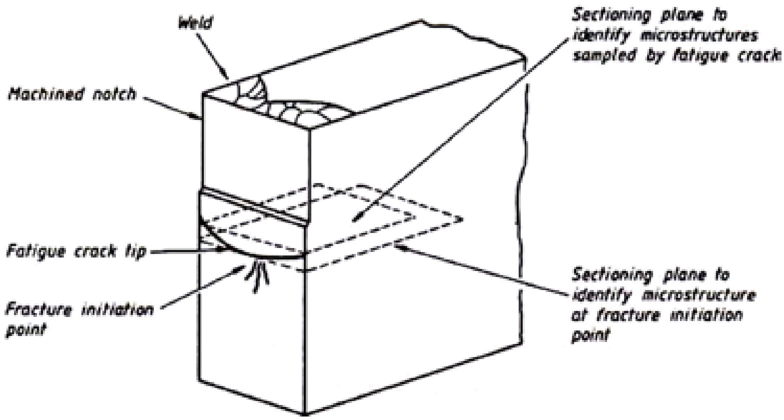

Figure 2: *Example of sections taken from an HAZ, through-thickness notched CTOD specimen to identify microstructures sampled by fatigue crack and at the fracture initiation point*

In the case of through-thickness notched specimens, this is best achieved by sectioning at a small distance behind the fatigue crack tip, so as to include as much of the fatigue crack front as possible (Fig. 2). With surface notched specimens, a similar approach could be used. However, when the region being sampled is small and/or the fatigue crack front is bowed, misleading results may be obtained. For this situation, a better approach is to section as shown in Fig. 3(b), and if necessary, take a series of sections.

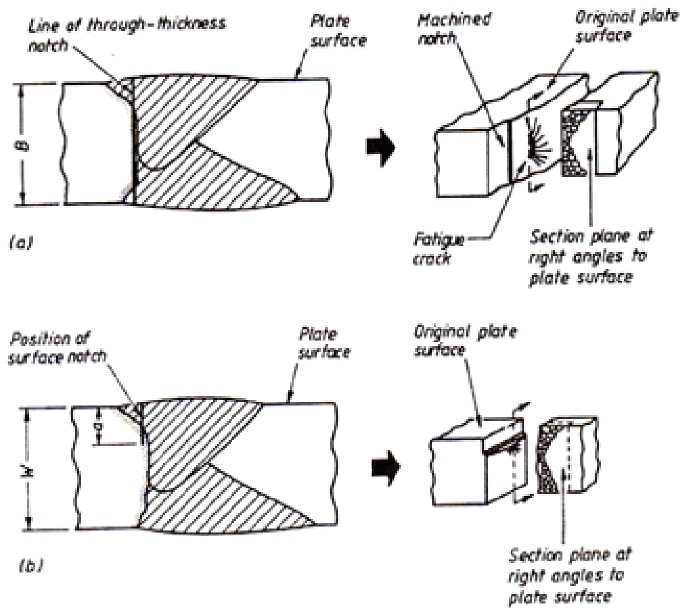

Figure 3: *Example of sectioning techniques for a) through-thickness notched, and -b) surface notched specimens*

It is recommended that similar sectioning procedures be applied to all tests (HAZs and weld metals) carried out to measure the fracture toughness associated with known cracks, *[1]*. By agreement, there is the additional requirement to establish the microstructure at the fracture initiation point; detailed fractography is necessary to determine the microstructure at that point and hence locate the position from which the section has to be taken.

3 EXPERIMENTAL PROCEDURE

Three different types of welded joints were tested for a comparison of mutual mechanical properties. The mechanical properties of the welds made on HSLA steel grade HT50 and HT80 and mild steel were evaluated using standard tensile, *[6]*, Charpy, *[7]*, and CTOD (Crack Tip Opening Displacement) tests, *[8]*. The HAZ specimens were taken from the welded steel plates in the rolling, thickness, and width directions.

The differences in microstructures among material regions influence the mechanical properties, *[6-8]*. Thus, systematic experimental determination of material mechanical properties including fractographical and metallographic investigation of fracture surfaces is necessary.

The chemical composition of the HSLA steel grade HT50 and HT80 and mild steel, with plate thicknesses of 40 mm are given in Table 2. All testing HAZ specimens were taken from the steel plates in the rolling direction (A), the thickness direction (B), and the width direction (C).

The yield strength and tensile strength were obtained using round bar tensile specimens, as shown in Fig. 4. Tensile testing was done at room temperature (20 ºC).

Table 2: *Chemical composition of the HSLA steel grade HT50 and HT80 and mild steel*

Composition (%)	HT50	HT80	Mild steel
C	0.12	0.16	0.28
Si	0.55	0.68	0.52
Mn	0.67	0.75	0.71
P	0.015	0.020	0.011
S	0.002	0.003	0.007
Cr	0.70	0.79	0.05
Ni	0.07	0.09	0.01
Mo	0.042	0.032	0.013
Cu	0.19	0.24	0.62
Al	0.001	0.002	0.001

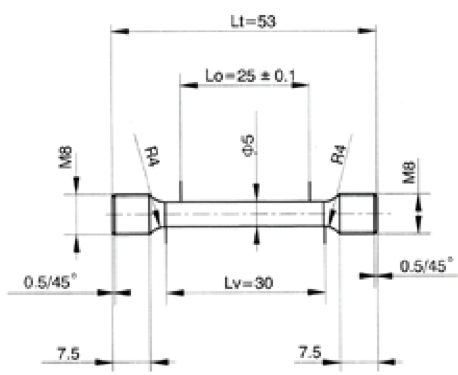

Figure 4: *Tensile round bar specimen B 5 × 25*

Charpy - V testing was used to determine the impact toughness of steel plates. The shape and dimensions of a standard Charpy - V specimen, mechanically notched, are shown in Fig. 5. Testing was performed at -10 ºC. For every test temperature, three specimens were fractured.

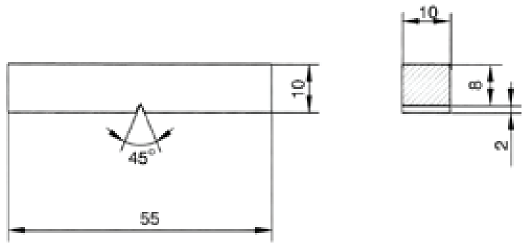

Figure 5: *Shape and dimensions of Charpy – V notch specimen*

CTOD fracture toughness of the welds made on HSLA steel grade HT50 and HT80 and mild steel was evaluated using standard static CTOD test, [4-5]. Specimen loading was carried out with constant crosshead speed v = 0.5 mm/min. The test temperature was -10 ºC according to the recommendation of the OMAE (Offshore Mechanics and Artic Engineering) association. For CTOD testing, the single specimen method was used, *[8]*. To evaluate the fracture toughness of steels, standard fracture mechanics tensile specimens with shallow notches were used, as shown in Fig. 6.

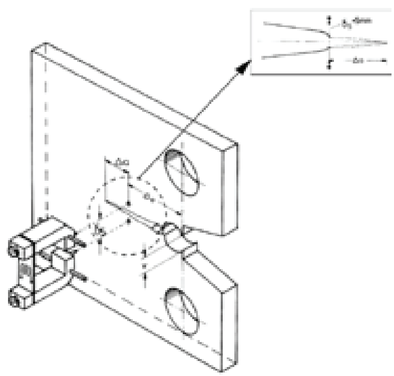

Figure 6: *Direct measurement of CTOD values at the crack tip of fracture mechanics specimen*

For all specimens, the fatigue precracking was carried out with the Step-Wise High R ratio (SHR) method procedure, *[4]*. During the CTOD tests the potential drop technique was used for monitoring stable crack growth, *[5]*. The CTOD values were directly measured with a special clip gauge, *[5]*, on the specimen side surfaces at the fatigue crack tip over a gauge length of 5 mm (see Fig. 6).

4 DISCUSSION OF RESULTS

Mechanical properties of welds made on HSLA steel HT80 and HT50 and mild steel plate in the rolling direction (A), thickness direction (B) and the width direction (C) are presented in Table 3. The basic values of yield strain and tensile strain of testing steels, given in Table 3, were obtained from engineering stress (R) - strain (e) diagrams. It is known that engineering material curves cannot be used for analysis of material deformation characteristics and finite element calculations in the range of high plastic deformations.

Average Charpy-V testing values of three fractured specimens are represented in Table 3.

Table 3: *Mechanical properties of welds made on HSLA steel HT80 and HT50 and mild steel plate in the rolling direction (A), thickness direction (B) and width direction (C)*

Weld-Steel grade	Measured direction	Yield strain (MPa)	Tensile strain (MPa)	CTOD (mm)	Charpy V (J) at –10 ºC
HT50	A	542	591	0.390	47, 68, 71 Av=62
HT80	A	693	830	0.401	69, 78, 64 Av=70
Mild steel	A	452	497	0.423	42, 55, 62 Av=53
HT50	B	501	562	0.240	39, 41, 55 Av=45
HT80	B	657	799	0.253	53, 68, 66 Av=62
Mild steel	B	439	471	0.231	39, 44, 61 Av=48
HT50	C	531	587	0.416	42, 76, 69 Av=62
HT80	C	665	811	0.478	67, 71, 63 Av=67
Mild steel	C	447	478	0.443	40, 51, 65 Av=52

The lowest Charpy toughness was measured in the HAZ specimens taken from the steel plates in the thickness direction (B). The cause for low toughness was the appearance of inconvenient ferritic microstructures with distributed brittle martensite-austenite (M-A) constituents (Fig. 7).

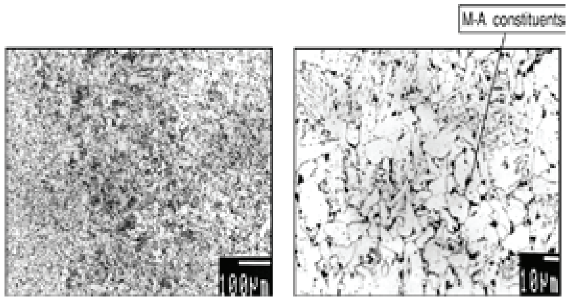

Figure 7: *Ferritic microstructure with distributed brittle M-A constituents along ferrite grain boundaries of HAZ specimen*

The Charpy toughness of HAZ specimens taken from the steel plates in the rolling direction (A) is approximately equal to the Charpy toughness of HAZ specimens taken from the steel plates in the width direction (C).

Directly measured CTOD values of HAZ fracture toughness for each type of steels are summarized in Table 3. The maximal CTOD toughness was measured in the HAZ specimens with the crack tip located in the width direction (C).

In the case of CTOD testing of HAZ specimens with the crack tip located in the thickness direction (B), the lowest CTOD was measured due to the appearance of the first brittle fracture in the mainly ferritic microstructure with carbides (Fe3C), precipitated at the grain boundary (Fig. 8) and the appearance of brittle fracture initiation point, i.e. Al-Si-Mn inclusions (Fig. 9). For the correct identification of a brittle fracture initiation point, it is of utmost importance to apply Energy Disperse X-ray (EDX) analysis to both fracture surfaces. In the opposite case, it could happen that the EDX analysis detects some fictitious brittle fracture initiation point.

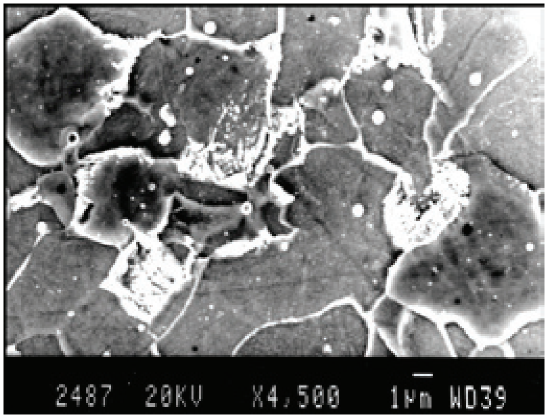

Figure 8: *Mainly ferritic microstructure with carbides (Fe_3C) precipitated at the HAZ grain boundary*

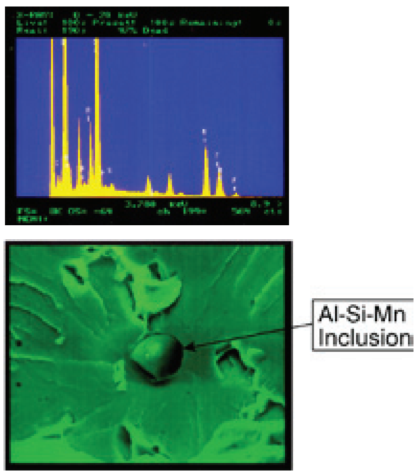

Figure 9: *Appearance and EDX analysis of brittle fracture initiation point, i.e. Al-Si-Mn inclusion in the HAZ specimen*

5 CONCLUSION

Exact evaluation of real material mechanical properties is essential for the safe servicing of energy components. The presence of different HAZ microstructures along pre-crack fatigue fronts has significant effects on the critical crack tip opening displacement (CTOD). This value is the relevant parameter for the safe servicing of modern energy components. The mechanical properties of welds made on of HSLA steels grade HT50 and HT80 and mild steel are the lowest in the thickness direction of the steel plate due to the appearance of carbides (Fe3C) and Al-Si-Mn inclusions in the ferritic microstructure. The mechanical properties of welds made on HSLA steels grade HT50 and HT80 and mild steel are approximately equal in the rolling and in the width directions of the steel plates.

References

[1] **Mlakar, M.:** *Determination of local brittle zones at the crack front in the HAZ of welded joint. Master Thesis,* Faculty of Energy Technology, University of Maribor, Slovenia, 2015

[2] BS 5762, *Methods for crack opening displacement (COD) testing*, The British Standards Institution, London 1979

[3] ASTM E 1152-87, *Standard test method for determining J-R curves*, Annual Book of ASTM Standards, Vol. 03.01, American Society for Testing and Materials, Philadelphia, 1990

[4] ASTM E 1290-91, *Standard test method for crack-tip opening displacement (CTOD) fracture toughness measurement,* American Society for Testing and Materials, Philadelphia, 1991

[5] GKSS Forschungszentrum Geesthacht GMBH, *GKSS-Displacement Gauge Systems for Applications in Fracture Mechanic*

[6] **Praunseis, Z., Toyoda, M., Sundararajan, T.**: *Fracture behaviours of fracture toughness testing specimens with metallurgical heterogeneity along crack front*. Steel res., 71, Vol. 9, Sep. 2000

[7] **Praunseis, Z**., **Sundararajan, T., Toyoda, M., Ohata, M.:** *The influence of soft root on fracture behaviors of high-strength, low-alloyed (HSLA) steel weldments*. Mater. manuf. process., Vol. 16, 2001

[8] **Toyoda, M.:** Fracture toughness evaluation of steel welds, Book of Mechanics, Osaka University, 1989

Acknowledgements

The authors wish to acknowledge the financial support of the Slovenian Foundation of Science and Technology and the Japanese Promotion of Science.