JET Volume 6 (2013), 51 - 60

Issue 1, February 2013

Journal of Energy Technology

http://www.fe.um.si/en/jet/e-jet.html

FRACTURE EVALUATION OF ENERGY COMPONENTS WITH LOCAL BRITTLE ZONES

VREDNOTENJE LOMA V ENERGETSKIH KOMPONENTAH Z LOKALNIMI KRHKIMI PODROČJI

Zdravko Praunseis[ℜ]

Keywords: fracture, energy components, sectioning technique brittle zones

Abstract

The fracture toughness in the testing of multi-pass welds and heat-affected zones is remarkably sensitive to the microstructures in the vicinity of the crack tip of test specimen. Therefore, the introduction of the pre-crack to the weld and heat-affected zone specimen should be done most carefully. However, since there is an uncertainty of the crack tip position in fatigue pre-cracking, it becomes common to section near the fatigue pre-crack front after testing is complete, and to examine the cross section in order to identify the position in weld and heat-affected zone microstructures, the so-called local brittle zones. Concerning this sectioning technique, the precise experimental procedure is specified in this article.

Povzetek

Lomna žilavost večvarkovnih zvarov in toplotno vplivanih področjih je odvisna od vrste mikrostrukture na konici razpoke v preizkušancu. Zato je nujna natančna postavitev utrujenostne razpoke v zvar in toplotno vplivano področje preizkušanca. Postavitev utrujenostne razpoke ni natančno določena v nobeni proceduri, je pa postala praksa, da se

[ℜ] 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, SI-8270 Krško, Slovenia, E-mail address: zdravko.praunseis@uni-mb.si

----

razrez preizkušancev izvrši v neposredni bližini utrujenostne razpoke in sicer tako, da prerez omogoča natančno določitev lokacije utrujenostne razpoke v zvaru in toplotno vplivanem področju ter pripadajoče mikrostrukture, tako imenovanih lokalno krhkih področij. V članku je natančno opisana eksperimentalna procedura za razrez in ocenitev preizkušancev.

1 INTRODUCTION

The crack tip opening displacement (CTOD) test has been become a common method of measuring the fracture toughness of steel weldments. Nevertheless, the commonly used fracture mechanics testing standards, including the CTOD testing standards, such as BS 5762, [1], assume the use of metals with high degrees of homogeneity, although not explicitly emphasised. As already mentioned, 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 been established outside 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 weldments 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 [2-4]. Therefore, in the common fracture toughness specimen, attention is carefully paid to realise 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 reproducibility, in the current standards it is required that as straight a crack front as possible be achieved, [5].

2 NOTCHING AND SECTIONING PROCEDURE TECHNIQUE

In order to achieve a uniform fatigue crack shape that meets the standard requirements, some treatments, i.e. residual stress-relieving treatment, have to be applied for notched specimens of welded joints. A different method for relieving residual stresses is to impose a local plastic strain on the region suffering from residual stresses; the following techniques [2–5] 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 sides hole method.

Table 1 gives a summary of the relative merits of the three methods of them. In the Recommended Procedure proposed by The Welding Institute, [6, 7], the mechanical relief of residual stresses by local compression, in which a plastic strain of 1% of the specimen thickness, is recommended. According to the institute, "the use of reverse bending prior to fatigue pre-cracking as a means of redistributing welding stresses is not recommended." 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 pre-cracking has been found to be successful in obtaining acceptable crack front profiles."

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

Advantages	Disadvantages
LOCAL COMPRESSION.	
-method well published -method been in use since 1975 -uses normal fatigue pre-cracking procedures	-requires extra operation -requires high capacity compression rig and tools -toughness may be conservative for some materials -specimen must be flat
REVERSE 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 pre-crack 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 confusion and to realize reproducibility, the condition of the fatigue pre-cracking loading must also 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 the 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 inter-critical coarse grain (IC) and subcritical coarse grain (SC) HAZ areas. Fatigue-crack sampling calculations are made by examining enlarged photographs (3–6 times magnification) of the CTOD cross sections.

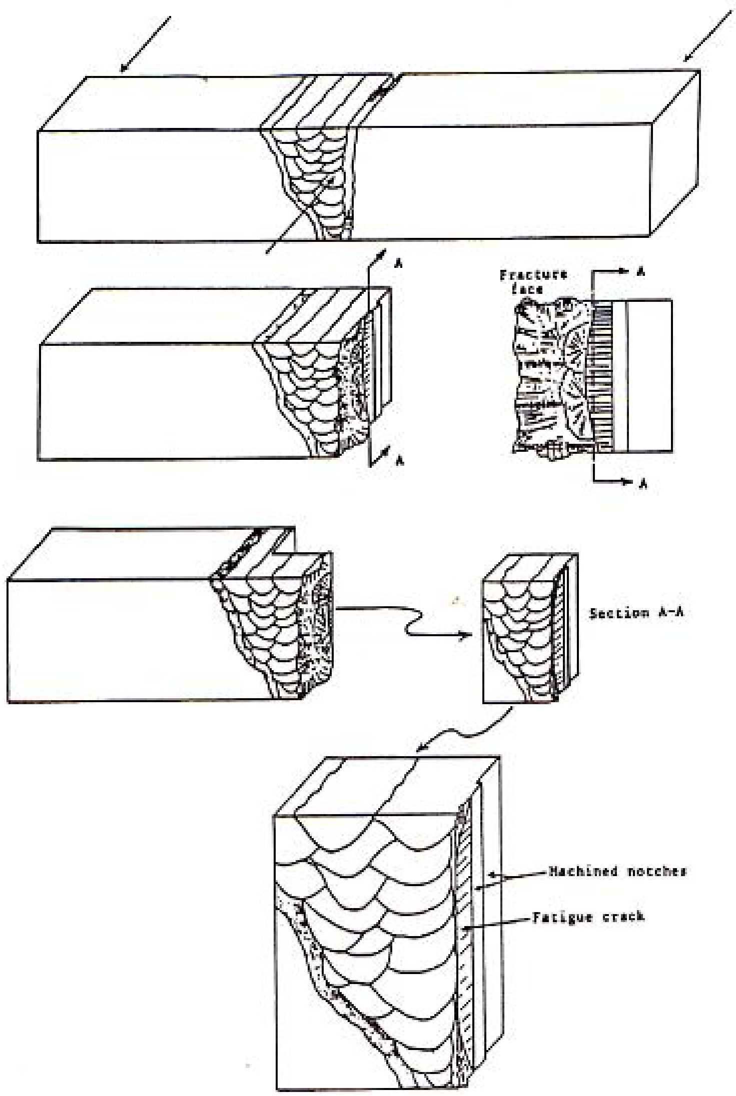

Figure 1: *Sectioning both halves of a HAZ CTOD specimen to calculate CGHAZ percentage*

By using both halves of the broken CTOD specimen and the 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.

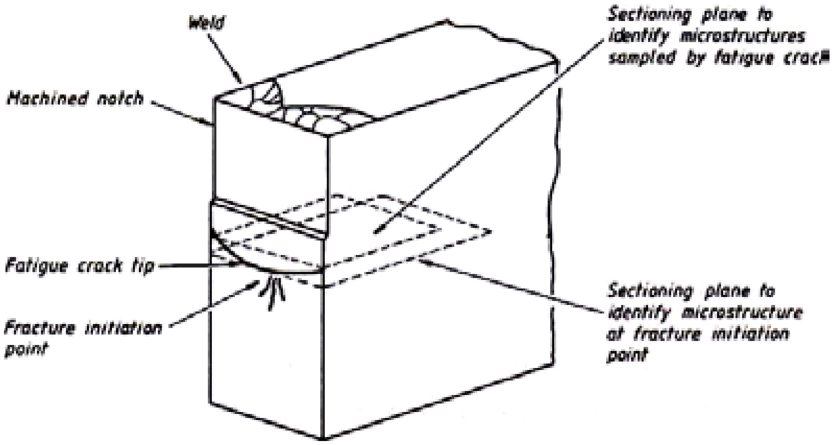

Figure 2: *Example of sections taken from a HAZ, through-thickness-notched CTOD specimen to identify microstructures sampled by fatigue crack and at the fracture initiation point.*

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, where 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.

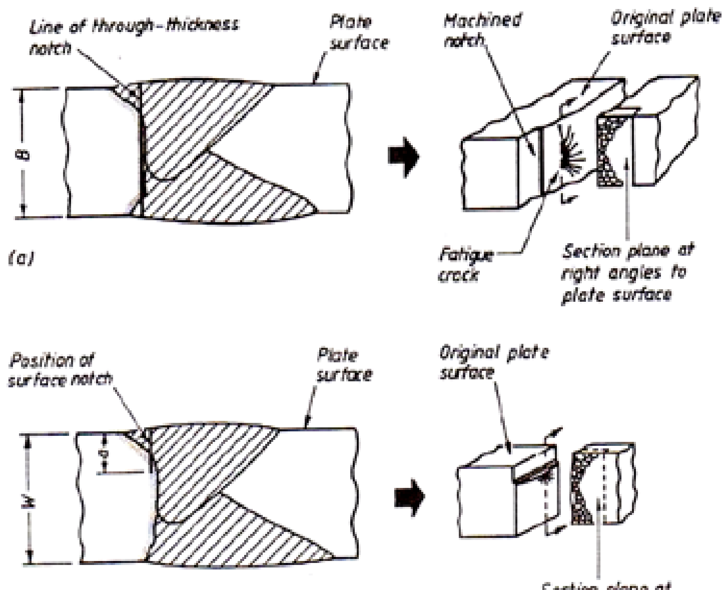

Figure 3: *Example of sectioning techniques for: a) through-thickness notched, and b) surface notched specimens*

It is recommended that similar sectioning procedures are applied to all tests (HAZs and weld metals) carried out to measure the fracture toughness associated with known cracks, [5]. It is generally agreed that there is an 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. A practical example, [5], of the sectioning procedure is shown in Figure 4 and Figure 5.

3 DISCUSSION OF RESULTS

The cause for differences, [2–4], of HAZ fracture toughness (Fig. 4) was the effect of the root weld metal strength mismatch (overmatched root of homogeneous weld and under-matched soft root layer of heterogeneous weld) on the deviating nature of stable crack growth and on the initiation of the specimens' final brittle fractures. Specifically, in CTOD specimens with homogeneous and heterogeneous welds, the whole fatigue crack tip front was located in CG HAZ (Fig. 4 - Cross-section G-G, Detail A and B), as also indicated with the high values of micro-hardnesses (≈ 340 HV1). All specimens with homogeneous welds reached CTOD values δu after initial stable crack growth (Fig.4 - Fracture). Owing to the root overmatched weld metal and its shielding effect, the stable crack growth path deviated towards the base material (Fig.4 - Cross-section P-P), so that the crack tip front first crossed the brittle part of CG HAZ (appearance of a small pop-in); then, the tougher fine grain (FG) HAZ followed by the final specimen fracture in IC HAZ (Fig.4 - Detail A). The influence of root overmatched weld metal (shielding effect) of the under-matched homogeneous weld on a deviation of fracture path was (in this example) as expressed as for the specimens with so-called composite fatigue crack front (a/W=0.5) in HAZ, where the crack growth path also turned toward the softer base material. Soon after the start of the loading, local brittle zones (LBZ) in the form of pop-ins appeared in the HAZ-notched CTOD specimens taken from heterogeneous weld, because the crack tip reached the region of low toughness - IC CG HAZ (Fig. 4). The presence of expressive local strength mismatches at narrow CG HAZ and the global mismatching effect of the softer under-matched root layer has caused deviations of stable crack growth paths to the regions of low toughness, fusion lines and under-matched weld metals (Fig. 4 - Cross-section G-G and Detail A). The specimen brittle fracture appeared in the bainitic microstructures (Fig.4 - Detail C) of weld filler metal. The brittle fracture initiation point was indicated on the specimen fracture surface (Fig. 4 - Fracture) by EDX analysis as a carbide Fe_3C, [5]

The CTOD - $\delta 5$ values, [5], for through-thickness notched specimens (Fig. 5) in the heterogeneous weld indicate a reduction of the fracture toughness with an increase of soft root volume, i.e. for soft root passes thickness h > 8mm. In the aforementioned CTOD specimens, the brittle fracture occurred in the soft root layer centre (Fig. 5 – Fracture surface) without previous origin, at the position where the mismatch factor was the lowest, as well as hardness, 161 HV1 (Fig. 5 - Detail A), being a consequence of very low toughness of soft root layer. The main cause for the low soft root layer toughness was a change of the microstructure of the all-weld metal obtained by the welding wire, which was exposed to different alloying mechanisms during welding in the root region. Specifically, the all-weld metal microstructure of soft root weld metal was bainitic, having high toughness, but because of the aforementioned reasons its microstructure was changed to inconvenient ferritic microstructures (Fig. 5 – Section L-L and Detail A), causing low toughness of the soft root layer.

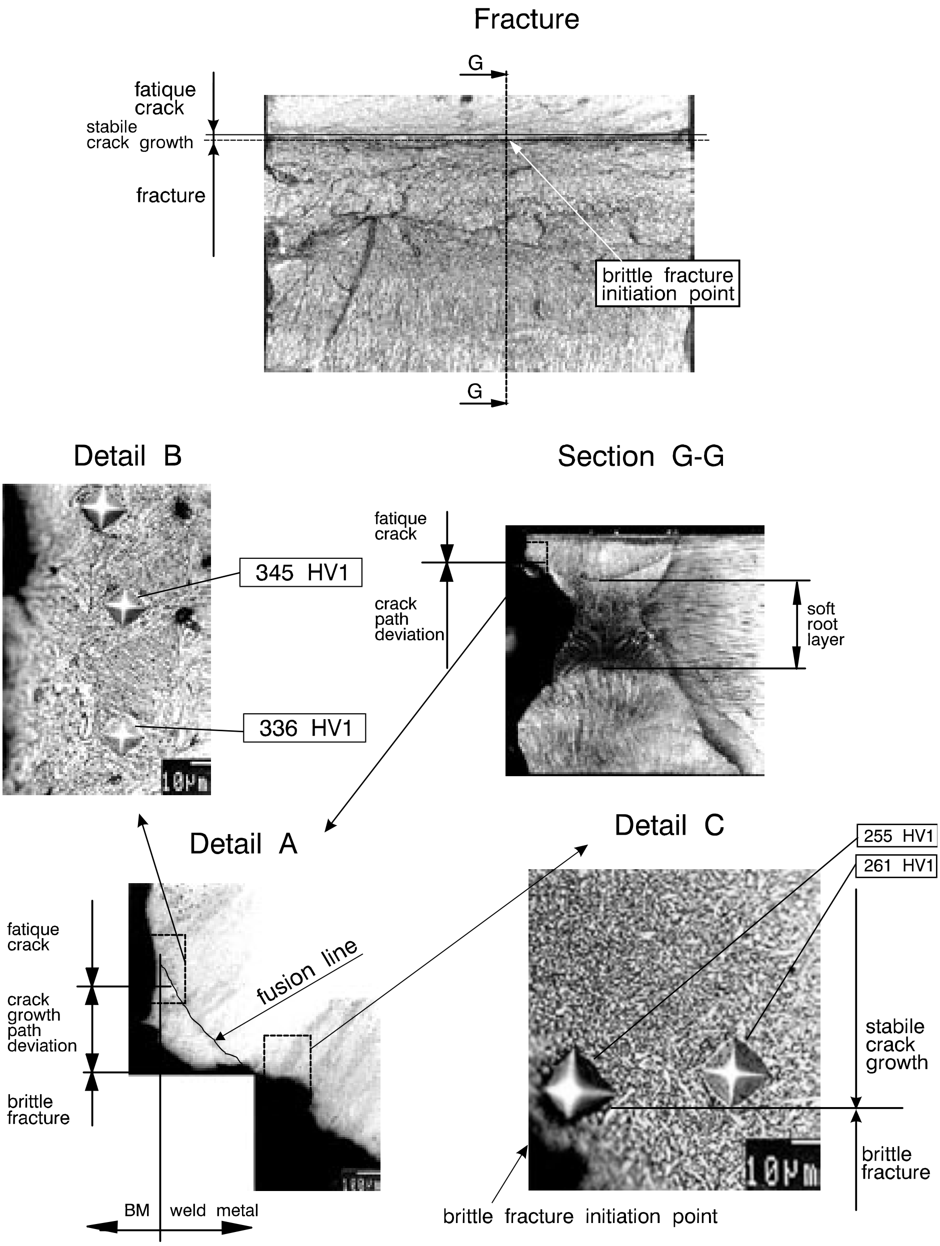

Figure 4: *Position of surface (a/W = 0.254) fatigue crack in CG HAZ and crack path deviation in specimen with heterogeneous weld joint*

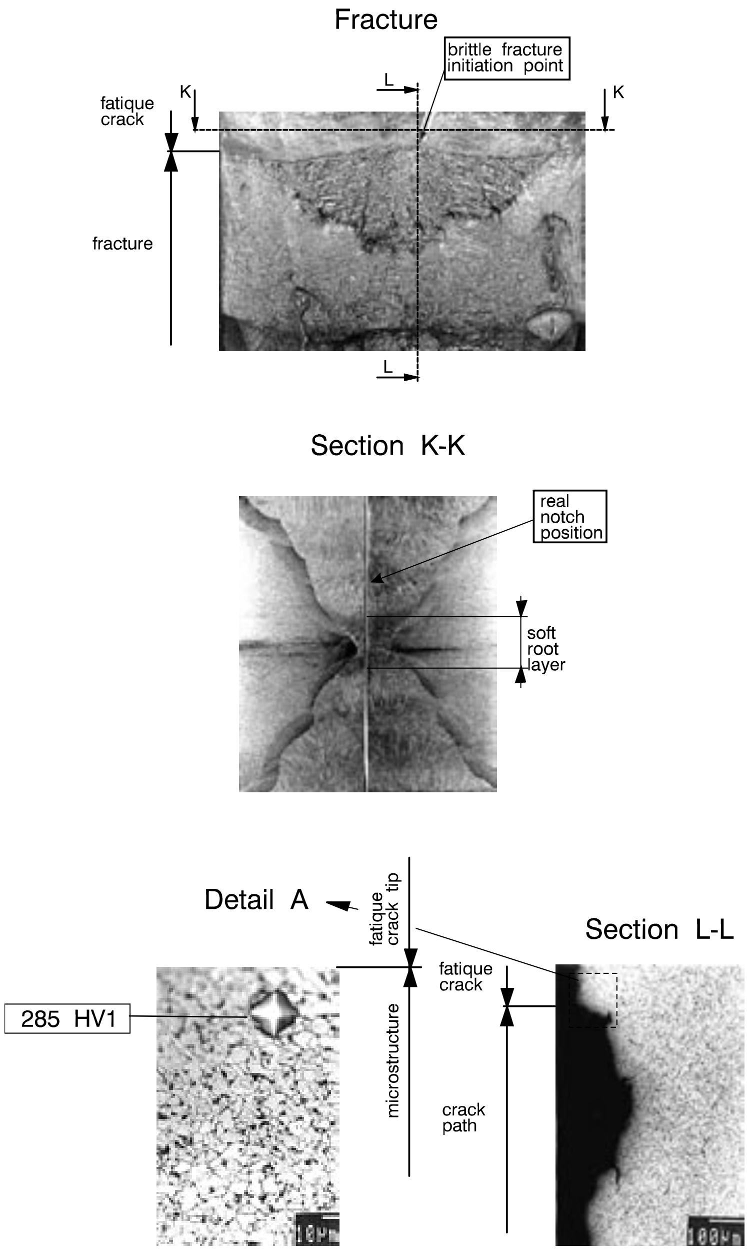

Figure 5: *Fracture and microstructure at the vicinity of brittle fracture initiation point of through-thickness notched specimen in heterogeneous weld*

----

4 CONCLUSIONS

The crack tip opening displacement (CTOD) test has been become a common method of measuring the fracture toughness of steel weldments. The fracture toughness in the multi-pass welds and heat-affected zones testing is remarkably sensitive to the microstructures in the vicinity of the crack tip of the test specimen. In the common fracture toughness test, the use of a notch sharpened by a pre-crack 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. After CTOD test is conducted, both halves (or the half-containing the weld metal) of the broken specimen are sectioned and metallurgically examined. Detailed fractography is necessary to determine the microstructure at that fracture initiation point and hence locate the position from which the section has to be taken.

Acknowledgements

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

References

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

[2] **Praunseis, Z., Toyoda, M., Sundararajan, T.**: *Fracture behaviours of fracture toughness testing specimens with metallurgical heterogeneity along crack front*. Steel res., Sep. 2000, 71, no 9,

[3] **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., 2001, vol. 16, 2

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

[5] **Praunseis, Z.:** *The influence of Strength Under-matched Weld Metal containing Heterogeneous Regions on Fracture Properties of HSLA Steel Weld Joint* (Dissertation in English). Faculty of Mechanical Engineering, University of Maribor, Slovenia, 1998

[6] 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.

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