JET Volume 6 (2013), p.p. 25 - 34
Issue 3, August 2013
http://www.fe.um.si/en/jet.html

APPLICATION AND TESTING OF STEELS FOR THE ENERGY PROCESS INDUSTRY

UPORABA IN PREIZKUŠANJE JEKEL ZA ENERGETSKO PROCESNO INDUSTRIJO

Zdravko Praunseis[ℜ], Jurij Avsec, Renato Strojko, Sonja Novak

Keywords: energy steels, process industry, fracture CTOD tests

Abstract

The aim of this paper is to analyse the fracture behaviour of high-strength low-alloyed steels for application in the energy process industry, and also to determine the relevant parameters that contribute to higher critical values of fracture toughness. For all testing of the steel specimens, fatigue pre-cracking was carried out using the GKSS Step-Wise High R ratio method (SHR) procedure. During the Crack Tip Opening Displacement (CTOD), the DC potential drop technique was used for monitoring the stable crack growth. The load line displacement (LLD) was also measured with a reference bar to minimize the effects of possible indentations of the rollers. The CTOD values were calculated in accordance with the BS 5762 standard and also directly measured via the GKSS-developed δ_5 clip gauge on the specimen side surfaces at a fatigue crack tip-over gauge length of 5 mm.

Povzetek

Namen članka je analiza lomnega obnašanja modernih visokotrdnostnih drobno zrnatih jekel za uporabo v energetski procesni industriji in določitev relavantnega parametra za merjenje izmerjenih vrednosti lomne žilavosti. V vse jeklene preizkušance je predhodno nameščena utrujenostna razpoka izdelana po metodi SHR, ki je bila razvita v centru GKSS. Med merjenjem vrednosti konice odpiranja razpoke (CTOD) je uporabljena metoda padca potenciala (DC) za

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

----

določitev stabilne rasti razpoke. Izmerjen je tudi pomik v smeri sile (LLD) s posebno merilno naprava, ki zazna pomike podpornih valjčkov med preizkušanjem. Odpiranje konice razpoke (CTOD) je izračunano po angleškem standardu BS 5762 in neposredno izmerjeno z metodo GKSS, ki uporablja posebno merilno napravo montirano na konico utrujenostne razpoke z začetnim razmikom 5mm.

1 INTRODUCTION

With High-Strength Low-Alloyed Steels (HSLA) and their welded joints, the thermal and strain cycles during welding inevitably bring about metallurgical, mechanical and other heterogeneities. Fig. 1 and Fig. 2 show a summarised illustration of effects of various characteristics on fracture joint performance and/or fracture transition behaviors. Almost all of these factors result in the deterioration of the fracture performance of welded joints, [1,8].

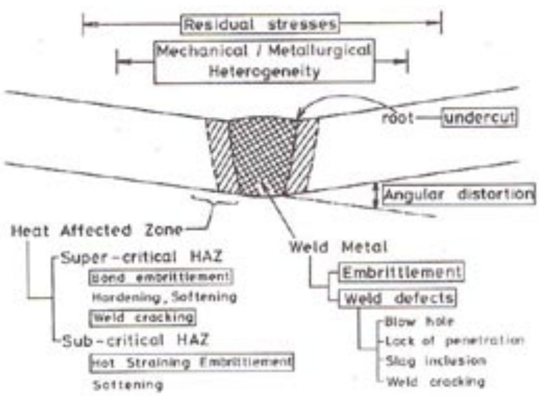

Figure 1: *Mechanical characteristics of energy steel welds*

Microstructures in welded joints of structural steels can be roughly divided as follows with regard to the change of material characteristics: (1) welded metal, (2) fusion line, (3) supercritical HAZ, and (4) subcritical HAZ. There are two main controlling factors that dominate the fracture performance of welded joint: factors controlling (a) fracture toughness and (b) deformation behavior under loading. Although the fracture performance of welds is affected by various factors and their complex combined incidence, the following two controlling factors of brittle fracture strength of welds are essential: (I) the embrittlement in HAZ and the weld metal in the vicinity of pre-existing defects, and (II) inhomogeneity in strength, such as hardening and softening in HAZ and matching between the weld metal and base metal. The various factors control the embrittlement in welds. Mechanical heterogeneity is also a result of the same kind of controlling factors, [6,7]. In particular, as mentioned above, the embrittlement results in problems with the existence of local brittle zones (LBZs) in multi-pass welds.

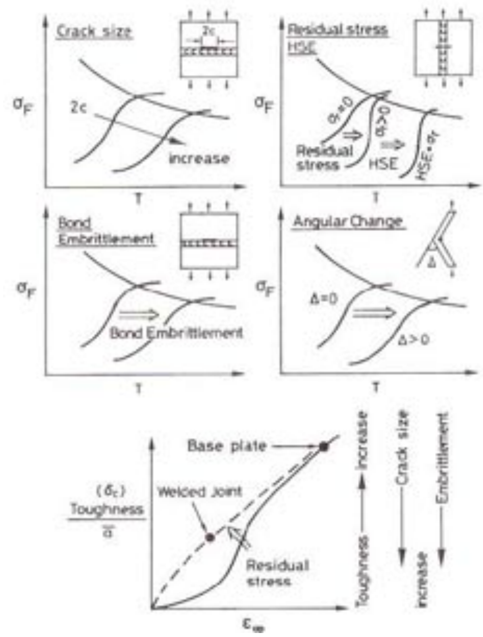

Figure 2: *Summary of various controlling factors on fracture performance of energy steel welds.*

2 EXPERIMENTAL PROCEDURE

The crack tip opening displacement (CTOD) test was developed in the U.K. during the 1960s. The first draft for the methods for CTOD testing were prepared as British Standard DD19 (1972). The CTOD test specimen (Fig. 3) contained a fatigue-pre-cracked notch and was loaded in a three-point bending to fracture.

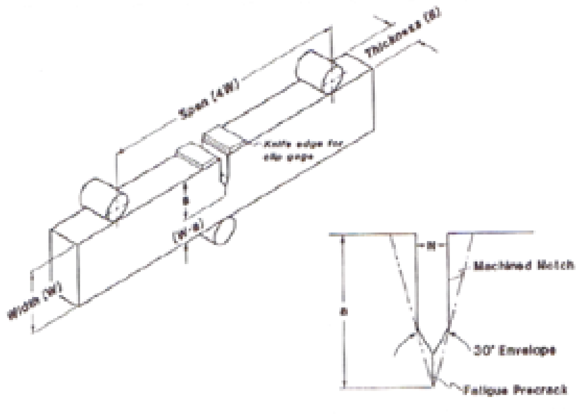

Figure 3: *Three-point bending CTOD test specimen.*

The critical CTOD was obtained via the clip-gauge displacement *Vg* measured across the notch mouth by using a certain converting equation. In 1979, the above testing method was specified as BS 5762 [2]: British Standard Methods for Crack Opening Displacement (COD) Testing (1979). In the current British Standard, the CTOD be calculated from the new equation as follows:

$$\delta = \frac{K^2}{2\sigma_Y E'} + \frac{0.4(W-a)\,V_p}{0.4W + 0.6a + z} \quad (2.1)$$

where the first term is the elastic component of CTOD, the second term is the plastic component, and *Vp* is the plastic component of the clip-gauge displacement. The stress intensity factor for the elastic CTOD calculation is obtained from the following relationship.

$$K = YP / BW^{1/2} \quad (2.2)$$

where *P* is the applied load, and *Y* is the stress intensity coefficient given as a function of the crack length-to-width ratio.

In this standard, the type of critical CTOD was clearly defined according to the nature of the observed fracture event. The four kinds critical CTOD, i.e. δ_c, δ_u, δ_m and δ_i, are measured (Fig. 4). At low temperatures, the steel fails by cleavage and δ_c is measured empirically.

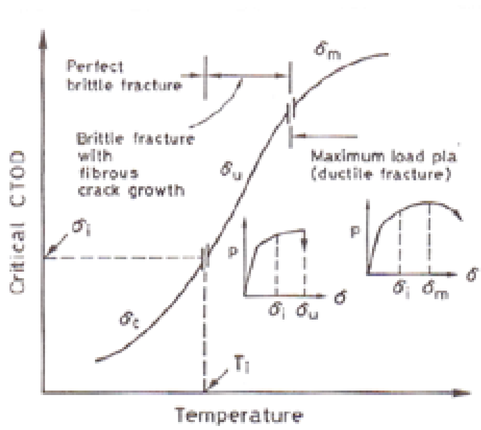

Figure 4: *Definition of critical CTODs in BS 5762.*

As the test temperature increases, cleavage becomes less favorable and the fracture toughness increases. The fracture mode changes to microvoid coalescence, and the crack grows in a stable manner. δ_i is defined as the value of CTOD at the onset of tearing. At temperatures slightly above the fracture mode change, stable tearing can be followed by unstable cleavage. In this case, the critical measure is δ_u at the instability point. On the upper level of toughness, the steel reaches a point of plastic collapse when the work-hardening cannot keep pace with the decrease in ligament area caused by stable crack growth. δ_m is then measured at the point of maximum load in a bend test.

The fracture toughness of heterogeneous regions of HSLA steels was evaluated using a standard static Crack Tip Opening Displacement (CTOD) test at the Geesthacht Research Center [5]. All

----

CTOD tests were conducted using Zwick (20t) and Schenk (100t) testing machines. Specimen loading was carried out with constant crosshead speed v = 0.5 mm/min. The test temperature was -10°C, following the recommendation of the OMAE (Offshore Mechanics and Artic Engineering) association. For CTOD testing, the single specimen method was used. To evaluate the fracture toughness of under-matched welded joints, standard bending specimens, [2-4] with deep (a/W = 0.5) and shallow (a/W = 0.25 - 0.4) notches in the weld metal and HAZ were used, [1,6,7]. For all specimens, fatigue pre-cracking was carried out with the Step-Wise High R ratio method (SHR) procedure, [5]. During the CTOD tests, the potential drop technique was used for monitoring stable crack growth, [1]. The load line displacement (LLD) was also measured with a reference bar to minimise the effects of possible indentations of the rollers. The CTOD values were calculated in accordance with BS 5762, [2], and also directly measured using a clip gauge on the specimen side surfaces at the fatigue crack tip over a gauge length of 5 mm, [5].

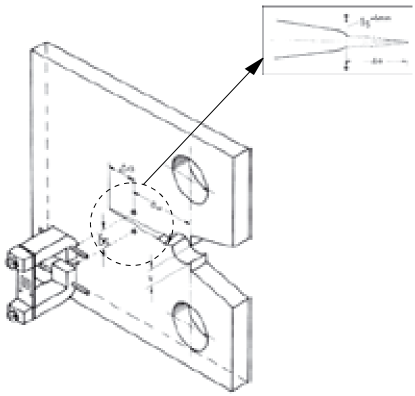

Figure 5: *Direct measurement of CTOD values at crack tip of fracture mechanics specimen*

For fracture mechanics, standards for the treatment of welded joints suitable are not yet available, but different procedures exist, [1, 6-8], recommending different ways of fatigue crack positioning in weld joints. Different positions and depths (a/W) of fatigue cracks in welds were chosen, taking this into account.

3 RESULTS AND DISCUSSION

The basic values of the yield strength and tensile strength of the tested steels were obtained from engineering stress (R) - strain (e) diagrams. It is known that engineering material curves cannot be used for the analysis of material deformation characteristics or for finite element calculations in the range of high plastic deformations.

For this purpose, the true stress-strain curve (Fig. 6) was used, which is described by the power law expression, [1]:

$$\sigma = \sigma_0 \mathrm{e}^{\mathrm{n}} \tag{3.1}$$

where σ_0 is the fictitious yield strength and n is the strain-hardening exponent.

$$n = \frac{\log \dfrac{R_m(1+A_{gt})}{R_{p0,2}}}{\log \dfrac{\ln(1+A_{gt})}{e_{0,2}}} \tag{3.2}$$

where R_m is the ultimate tensile strength, A_{gt} is the engineering extension at the maximum tensile load, $R_{p0,2}$ is the yield strength equivalent to 0.2 percent of proof stress and $e_{0,2}$ is the engineering extension.

$$e_{0,2} = \frac{R_{p0,2}}{E} + 0,002 \tag{3.3}$$

where: E is Young's module.

Finally, the fictitious yield strength σ_0 was calculated by:

$$\sigma_0 = R_{p0,2} 10^{\frac{n}{n-1}\log\frac{E_{e0,2}}{R_{p0,2}}} \tag{3.4}$$

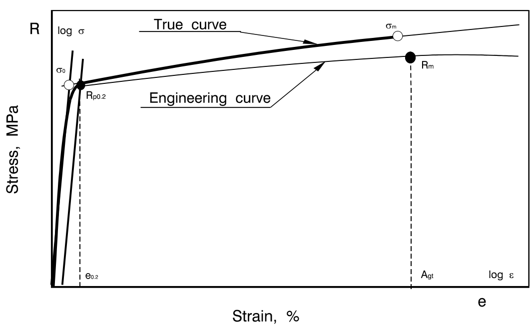

***Figure 6:** Engineering and true stress - strain curves for uniaxial tension*

During CTOD testing of fracture mechanics samples, the appearance of pop-ins at the propagating crack tip was expected. These moments are detected by force-displacement relationship (Fig. 7), which are evaluated according to the standard, [4], depending on their size (decrease of force and sudden increase of displacement). The maximal CTOD toughness was measured in the samples with the crack tip.

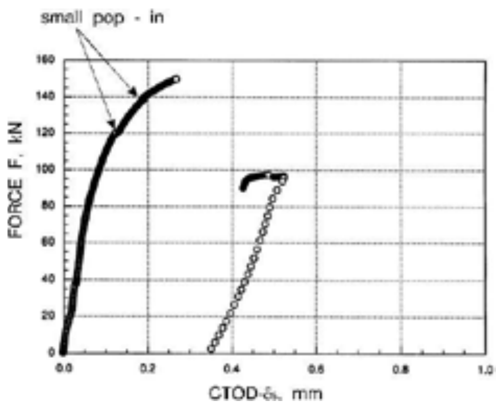

Figure 7: *Appearance of local brittle zones during CTOD testing and final fracture of fracture mechanics specimen*

The basic aim of the fractographical investigation was to determine the location of brittle fracture initiation on the fracture surface of CTOD test samples and to identify the brittle fracture initiation point by using Energy Disperse X-ray (EDX) analysis. Microstructures at the brittle fracture initiation point and around it, as well as crack path deviation nature, were evaluated using the fracture surface cross-section method [1,8] through the brittle fracture initiation point. A detailed analysis of material at the crack tip region and along deviated crack path was made with an optical microscope and scanning electron microscope. In this way, the critical microstructure (local brittle zones) at the fatigue crack tip surroundings, where the brittle fracture was initiated, and the microstructure, where it propagated later, were identified. For fractographical and metallographical analysis, the most representative fractures of CTOD test samples were chosen, which also appeared in other samples in appropriate shapes.

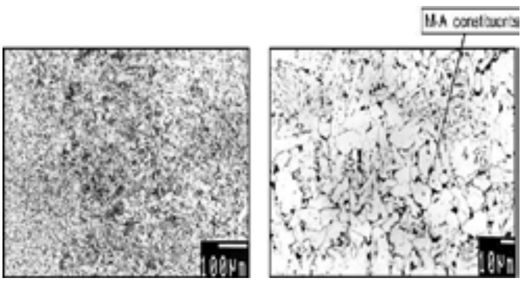

Figure 8: *Ferritic microstructure with distributed brittle M-A constituents along ferrite grain boundaries*

In the case of CTOD testing of specimens with the crack tip located in the thickness direction, the lowest CTOD test value was measured due to the appearance of the first brittle fracture in the mainly ferritic microstructure with carbides (Fe_3C), precipitated at the grain boundary (Fig. 8, Fig. 9 and Fig. 11) and appearance of brittle fracture initiation point, i.e. Al-Si-Mn inclusions (Fig. 10).

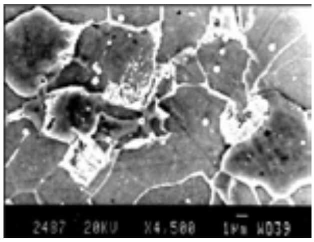

Figure 9: *Mainly ferritic microstructure with carbides (Fe_3C) precipitated at the grain boundary*

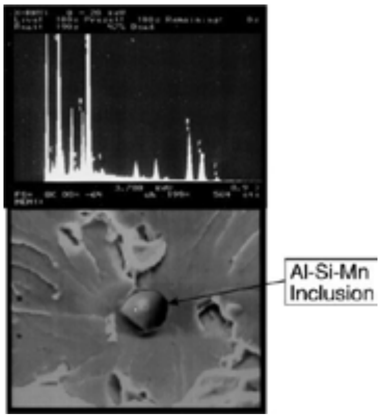

Figure 10: *Appearance and EDX analysis of brittle fracture initiation point, i.e. Al-Si-Mn inclusion*

It should be noticed that for correct identification of the brittle fracture initiation point, it is of the utmost importance to apply EDX analysis to both fracture surfaces. Otherwise, it could happen that the EDX analysis mistakenly detects a false brittle fracture initiation point.

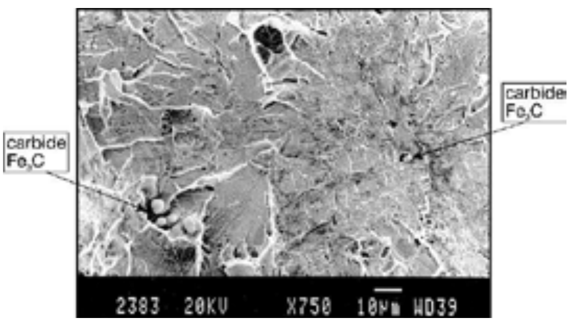

Figure 11: *Identification of brittle fracture initiation point as Fe_3C on the fracture surface of CTOD test sample*

----

4 CONCLUSIONS

1. In the heterogeneous regions of HSLA steel welded joints, microstructures change from that of the base metals because of the weld thermal/strain cycles. This change brings about the variation of mechanical properties such as yield strength, ultimate tensile strength, strain hardenability and elongation; in particular, they take place even in the macroscopic scale.

2. It can be understood from the basic experiments that fracture initiation in materials with a local brittle zone in the vicinity of crack tip is controlled by the fracture toughness of the embrittled region, and that the size of the local brittle zones along the crack front play a decisive role in the scatter of fracture toughness.

3. The brittle fracture initiation points of welds were indicated as a Mn-Al-Si inclusion or TiCN carbide (according to EDX analysis), and are found just below the blunting line, which is in agreement with the brittle fracture model theory. It should be noted that for correct identification of a brittle fracture initiation point it is of utmost importance to apply EDX analysis to both fracture surfaces. Otherwise, it could happen that the EDX analysis mistakenly detects a false brittle fracture initiation point.

4. Good agreement between calculated (δ_{BS}) and measured (δ_5) CTOD values is obvious from the comparison of CTOD values, verifying the method of direct measurement of CTOD, for which the material property data (e.g. yield strength) is not necessary, in contrast to the calculated CTOD values according to the BS 5762 standard. This argument favours using direct measurement δ_5 at the crack tip in welded joints with local and global strength mismatching, and precludes the application of the BS 5762 standard for welded joints, which is valid for the base material.

Acknowledgements

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

References

[1] **Z. Praunseis:** *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

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

[7] **Z**. **Praunseis**, **T. Sundararajan, M. Toyoda, M. Ohata:** *The influence of soft root on fracture behaviors of high-strength, low-alloyed (HSLA) steel weldments*. Mater. manuf. process., 2001, vol. 16, 2

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