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FRACTURE TOUGHNESS OF HSLA WELDS MADE ON PENSTOCK MATERIAL

LOMNA ŽILAVOST HSLA ZVAROV ZGRAJENIH NA JEKLIH ZA VODNE ZAPORNICE

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Keywords: High Strength low Alloyed Steel, CTOD Fracture Toughness Testing, CTOD-R resistance Curve, Welded joints

Abstract

The presence of different microstructures along the pre-crack fatigue front has a significant effect on the critical crack tip opening displacement (CTOD). This value is the relevant parameter for the safe servicing of welded structures (penstocks). In the case of specimens with the through-thickness notch partly in the weld metal, partly in the heat-affected zone, and partly in the base material, i.e., using the composite notched specimen, the fracture behaviour significantly depends on the portion of the ductile base material, the size, and the distribution of mismatching factor along the vicinity of the crack front.

Povzetek

Prisotnost različnih mikrostruktur na fronti konice utrujenostne razpoke ima pomemben vpliv na odpiranje konice razpoke (CTOD). Ta vrednost je relevantni parameter za varno obratovanje varjenih konstrukcij (vodne zapornice). V primeru preizkušancev z globoko razpoko, kjer fronta konice razpoke zajema del zvara, toplotno vplivanega področja in osnovnega materiala, t.i. kompozitno razpoko v preizkušancih, je lomno obnašanje odvisno od deleža žilavega osnovnega materiala, ter velikosti in porazdelitve faktorja trdnostne neenakosti vzdolž fronte razpoke.

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1 INTRODUCTION

High strength low-alloyed (HSLA) steels are often used as materials of penstocks at hydroelectric power stations for the build-up of multipass welded joints. The welding of HSLA steels to produce under-matched weld joints is a technological challenge for the production of welded structures.

Under-matched welded joints are used for repairing the welding of joint damage during difficult operation conditions or by short-period overloading, *[1]*. They are recommended for preventing hydrogen cracking with preheating, especially for welded joints made of HSLA steels with yield strengths above 700MPa.

Crack tip opening displacement (CTOD) as a fracture toughness parameter is determined as the lowest toughness of different microstructures along the crack front, according to the weakest link model, *[2-5]*. The development of the microstructure in the weld metal and especially in heat-affected zones (HAZ) of multi-pass joints is strongly influenced by welding thermal cycle and base material properties. Metallographically examined microstructures in undermatched joints with homogeneous and heterogeneous welds are primarily those with expected extremely low fracture toughness.

Therefore, the aim of this paper is to analyse the fracture behaviour of HSLA under-matched welded joints made on penstock material, and also to determine the relevant parameters that contribute to higher critical values of fracture toughness, *[6-8]*.

2 EXPERIMENTAL PROCEDURE

High strength low alloyed (HSLA) steel in a quenched and tempered condition, corresponding to the grade HT 80, was used. The Fluxo Cored Arc welding process (FCAW) was used, and two different tubular wires were selected. Three different types of global undermatched welded joints were produced: one homogeneous and two heterogeneous. Homogeneous welded joints were made with pre-heating and post-heating of the base material, entirely with the same consumable. Two different types of heterogeneous welded joints were made using a softer consumable for the soft root layer, one with two and the other with four passes, in order to avoid preheating of the base material and to prevent cold cracking. Defects in the welded joints were detected using the Non-Destructive Method (NDM), *[1]*. Radiography was used, and defects were classified according to the International Standard IIW, *[4]*.

The basic mechanical properties of multi-pass undermatched joints with homogeneous and heterogeneous welds are obtained using round tensile specimens, extracted from the weld metal in the welding direction, from filler passes and the root weld metal region, *[8]*.

In addition to the global strength mismatch between weld metal and base material In the undermatched joint with the homogeneous and heterogeneous welds, a local strength mismatch between the weld metal and HAZ and root weld metal and weld filler metal (filler passes) is also present, which is more pronounced for a joint with a soft root layer. Local strength mismatching is especially pronounced in the thickness direction of undermatched joints with homogeneous and heterogeneous welds, which has been determined by microhardness measurement (the distance between indents was 1 mm). The strength heterogeneity of the aforementioned welded joint is defined by the local mismatching factor ($M=R_{pweld}/R_{pbm}$). To evaluate the weld metal yield strength, the experimental equation ($R_p=3.15HV-168$) is often used, *[1]*, employing microhardness measured values HV.1 in all joint points. In that manner, the strength mismatching factor M in every point of the welded joint is roughly determined.

The fracture toughness of homogeneous and heterogeneous undermatched weld joints was evaluated using standard static CTOD test (Figure 1). The testing temperature was -10ºC, in accordance with the recommendation of OMAE (Offshore Mechanics and Arctic Engineering) association. For CTOD testing, the single specimen method was used. To evaluate the fracture toughness of under-matched welded joints, standard, *[2-4]*, bending specimens (Bx2B, B = 36 mm) with deep (a/W=0.5) notches in the Heat-Affected Zone (HAZ) were used. For all specimens, fatigue pre-cracking was carried out with the GKSS Step-Wise High R ratio method (SHR) procedure. During the CTOD tests, the DC potential drop technique was used for monitoring the stable crack growth. The load line displacement (LLD) was also measured with the reference bar to minimize the effects of possible indentations of the rollers. The CTOD values were calculated in accordance with BS 5762, *[2]*, and also directly measured with a GKSS-developed δ_5 clip gauge, *[5]*, on the specimen's side surfaces at the fatigue crack tip over gage length of 5 mm.

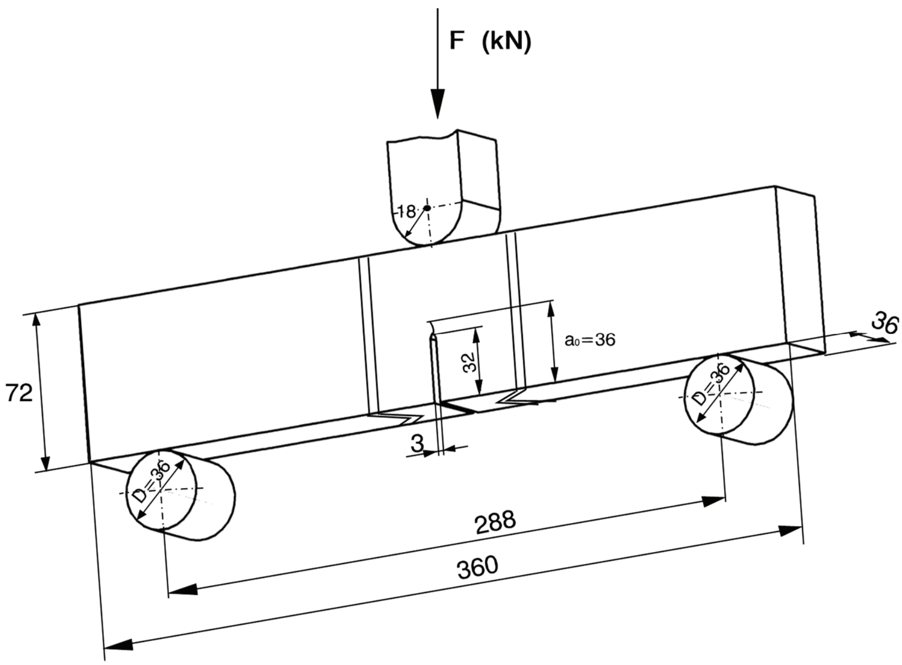
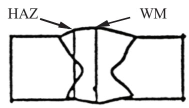
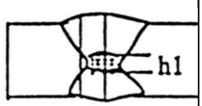


Figure 1: *Shape and dimensions, and loading conditions for bend SENB specimens (B x 2B), made from homogeneous and heterogeneous undermatched weld joints*

For fracture mechanics, suitable standards for the treatment of welded joint- are not available yet, but different procedures exist, *[1, 6-8]*, that recommend different ways of fatigue crack positioning in weld joints. In light of this, different positions and depths (a/W) of fatigue cracks in homogeneous and heterogeneous welds were chosen, as shown in Table 1.

Table 1: *Fatigue crack positioning in SENB specimens (B x 2B) at weld joints*

SENB specimen	Specimen	Fatigue crack position	Crack depth a/W
Bx2B	M		0.5
	D		0.5
	E		0.5

3 RESULTS AND DISCUSSION

HAZ fracture toughness is relatively high, and in the case of homogeneous welds, it is much higher than the base material toughness (Figure 2). One reason for this was the composite fatigue crack front, including narrow HAZ regions with the Coarse Grain (CG) HAZ (Figure 3) of extremely low fracture toughness (Local Brittle Zones), but the remaining part, i.e., most of the fatigue crack front was contained, as were the more robust weld filler metal, base material, and remaining fine-grain HAZ (FG HAZ and Inter Critical (IC) HAZ).

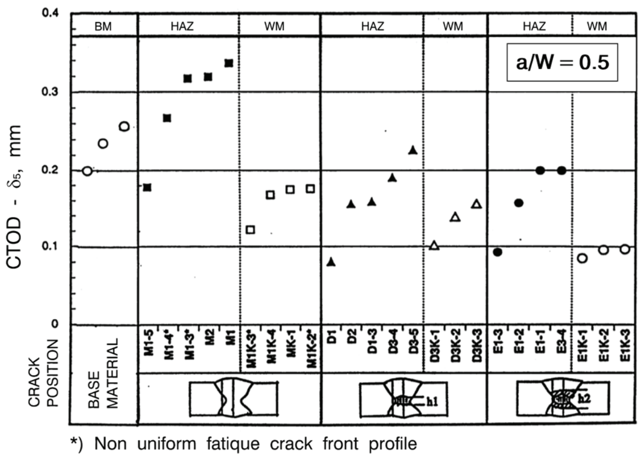


Figure 2: *CTOD (δ_5) fracture toughness values for specimens B x 2B in homogeneous and heterogeneous undermatched weld joints, measured at -10^O C*

The main reason for this was different root welding heat input energy, causing different widths of HAZ in the root region of homogeneous and heterogeneous welds, consequently affecting the initiation of the final brittle fracture of the specimen. Specifically, the distance of fatigue crack tip front from the fusion line was approximately the same (≈ 3.5 mm) for the CTOD specimens with the soft root layer and without it, [*1, 6-8*].

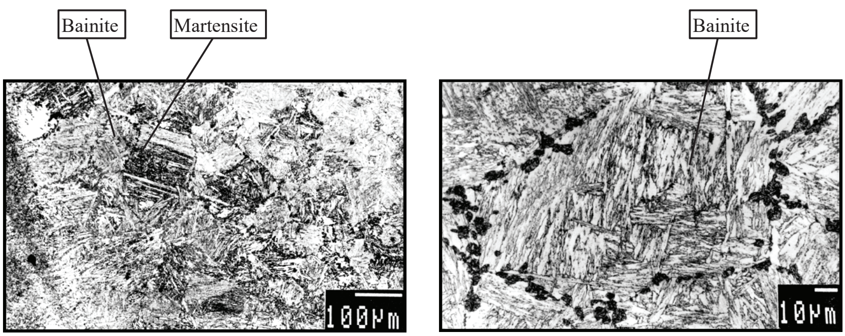


Figure 3: *CG HAZ with bainitic-martensitic microstructure, which was subsequently heated at a temperature between A_{c1} and A_{c3}, i.e., IC CG HAZ b) with distributed brittle M-A constituents along grain boundaries of primary grains (ASTM 4) with directed bainitic microstructure.*

The fatigue crack was sampled CG HAZ of two different widths related to CG HAZ region, which has influenced the value of HAZ fracture toughness of both welds (Figure 4). In CTOD specimens with cracks in HAZ of the homogeneous weld, brittle fracture initiation started in the weld material with the lowest value of mismatch factor M, because of the shielding effect of the overmatched root weld metal. The LBZs were already recorded during CTOD testing of welded joints as pop-ins. After that, an increase in stress intensification followed in HAZ, leading to the final brittle fracture of specimens through the CG HAZ and base material, which provided the least resistance in the specimen centre. The origin of final brittle fracture appeared in tougher fine grain IC HAZ 8 (Figure 4). The crack path deviated to the softer base material, due to the shielding effect of the root overmatched weld metal.

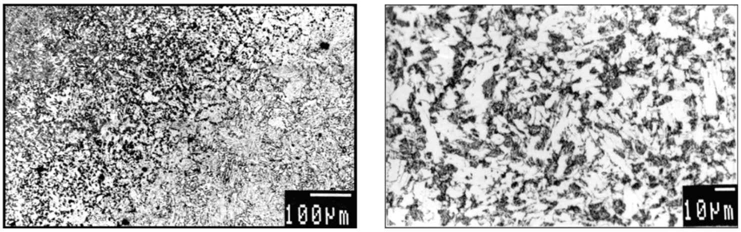


Figure 4: *HAZ, heated at intercritical temperature between A_{c1} in A_{c3} (IC HAZ). At higher magnification, the region of partial transformation to austenite, from which M-A constituents are formed, can be seen.*

In the case of CTOD testing of specimens with soft root layers, the first brittle fractures (LBZs) appeared in IC CG HAZ, which were recorded as small pop-ins. Due to high local strength mismatch between the base material and the soft root layer, the crack propagated towards the region of lower toughness, i.e., towards the fusion line and under-matched weld metal. The Fe_3C carbide was identified as the brittle fracture initiation point at the fracture surface using EDX analysis. The effect of the soft root layer on strain distribution along the fatigue crack front was so pronounced that it caused strain concentration in the soft root layer. Due to its low toughness, this initiated the final specimen fracture in coarse grain IC HAZ and crack path deviation towards the zone of the soft root layer, with a further reduction of toughness level, which would be achieved with higher soft root layer toughness.

The classification of CTOD resistance curves (Figure 5) for specimens with deep cracks in HAZ confirms the abovementioned analysis and conclusions that the HAZ fracture toughness of the homogeneous weld is much higher than the HAZ fracture toughness of the heterogeneous weld. By increasing the soft root layer thickness, the HAZ fracture toughness of the heterogeneous weld joint reduces and becomes lowest for the welded joint with the four-pass soft root layer (Figure 6), as is clear from the classification of CTOD resistance curves in Figure 5.

From the comparison of calculated (δ_{BS}) and measured (δ_5) CTOD values, a good agreement is evident, which is especially important for verifying detailed and directly measured CTOD - δ_5 values, for which one does not need to know the yield strength and the rotation factor as in the case of CTOD - δ_{BS} calculated values (Figure 7).

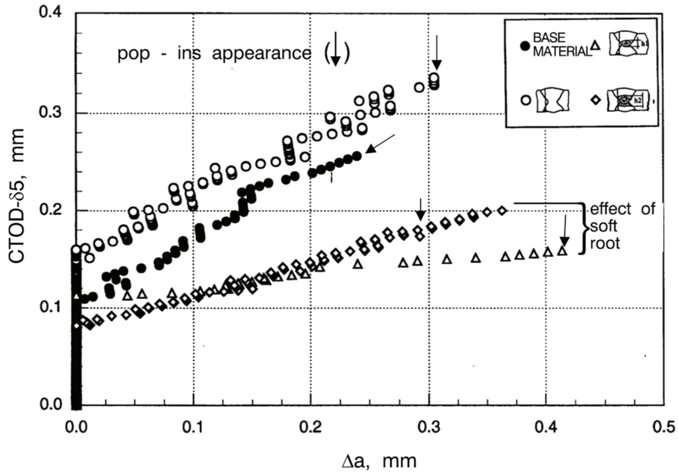


Figure 5: *Resistance curves for specimens (B x 2B) with deep crack (a/W = 0.5) in the HAZ of homogeneous and heterogeneous undermatched weld joints.*

This is essential in cases in which the fatigue crack tip front crosses regions with different strength levels and in which the effect of local strength mismatch at the crack tip is significant, as shown for fracture behaviour of undermatched joints with homogeneous and heterogeneous weld metal. More detailed analysis shows that CTOD-δ_5 values are generally lower than CTOD-δ_{BS} values, thus being more conservative.

As can be seen from Table 1, the fatigue crack was positioned in the HAZ and weld metal of homogeneous and heterogeneous undermatched weld joints. By positioning the fatigue crack in HAZ, a so-called "composite" fatigue crack front crosses the filler passes - HAZ - base material - HAZ - filler passes**.** The distance between the fatigue crack front and the fusion line in the weld root region was approximately 3.5 mm in all specimens B x 2B (Figure 6 - Cross-section A-A). The primary aim of the fractographical investigation was to determine the location of brittle fracture initiation on the fracture surface of specimens B x 2B and to identify the brittle fracture initiation point by using Energy-Dispersive X-ray (EDX) analysis. Microstructures at the brittle fracture initiation point and around it, as well as the nature of the crack path deviation, were evaluated using the fracture surface cross-section through the brittle fracture initiation point. After the metallographic specimen was made, a detailed analysis of welded joint region at the crack tip and along the deviated crack path was done using an optical microscope and scanning electron microscope (SEM). In this manner, critical microstructures at the fatigue crack tip surroundings, where brittle fracture initiated, and microstructure, where it propagated and arrested later, were identified. For fractographical and metallographic analysis, the most representative fractures of specimens B x 2B were chosen, which also appeared in other specimens in an appropriate shape (Figure 6).

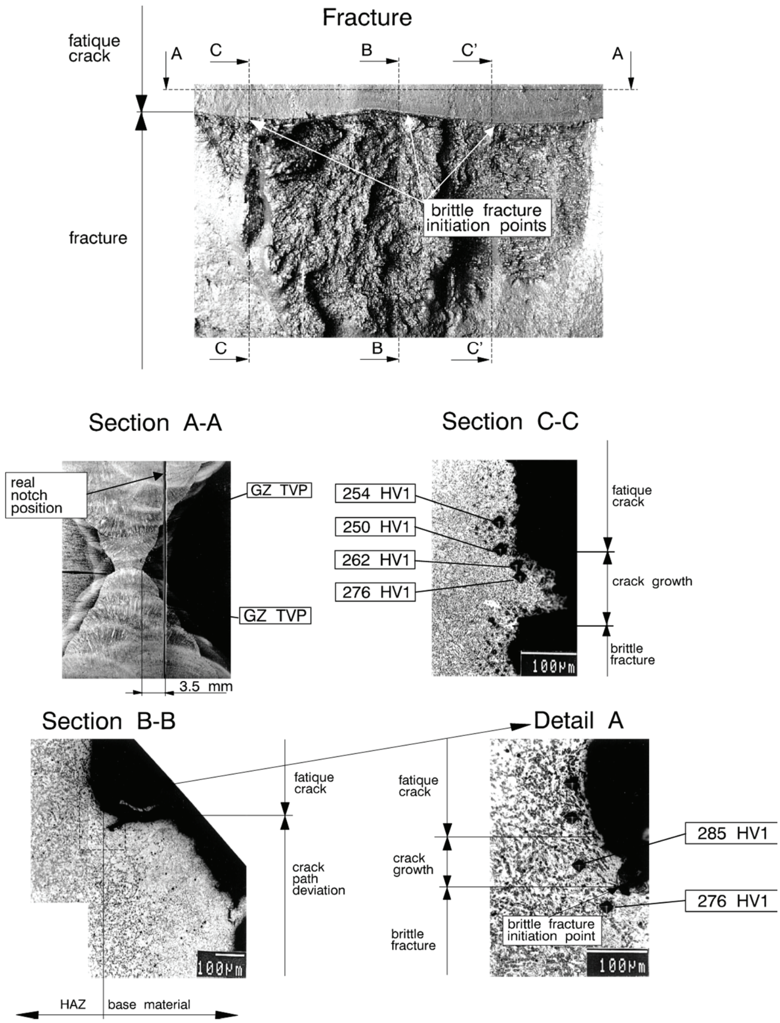


***Figure 6:** Brittle fracture initiation points and crack path deviation on fractured specimen B x 2B with deep cracks in HAZ of* heterogeneous *undermatched weld joint*

Directly measured (δ_5) and calculated CTOD values (δ_{BS}) of fracture toughness for homogeneous and heterogeneous undermatched weld joints are summarized in Figure 7, for Single Edge Notch Bend (SENB) specimens, B x 2B. Different values of the rotational factor were used at the determination of calculated CTOD values (δ_{BS}) for surface cracks introduced in specimens in accordance with different a/W ratios. Rotational factor values r_p, [1], to determine the calculated CTOD - (δ_{BS}) were depended on crack depths (a/W) as follows:

for crack depths a/W = 0.25 - 0.37 » r_p = 0.25

for crack depths a/W = 0.43 - 0.48 » r_p = 0.44

Direct measurement (δ_5 method) and calculation (BS - 5762) of CTOD values from the measured Crack Mouth Opening Displacement (CMOD) values and estimation of δ values (δ_c, δ_u in δ_m) are described in *[1, 6-8]*. Evaluation of pop-in appearance using curves (F - CMOD, δ_5) is described in more detail *in [1]*. The CTOD testing was done at a temperature of -10^O C.

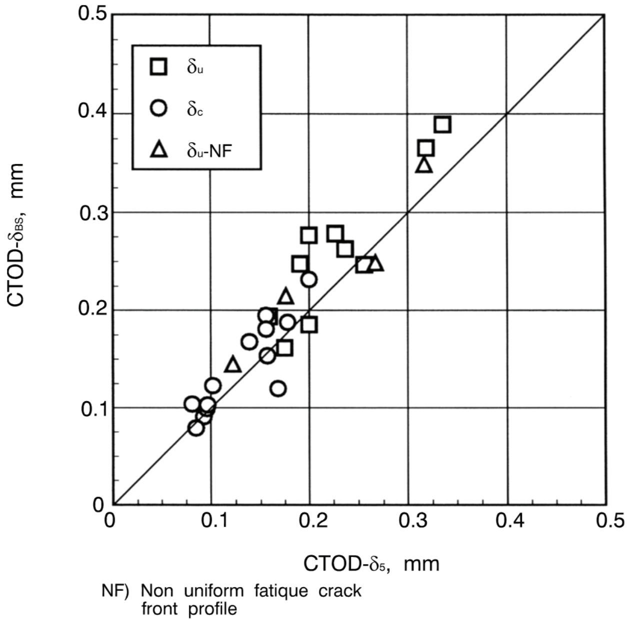


Figure 7: *Comparison of directly measured (δ_5) and calculated (δ_{BS}) CTOD fracture toughness values of specimens B x 2B with deep crack (a/W = 0.5) in homogeneous and heterogeneous undermatched weld joints*

From Figure 7, it is clear that measured (δ_5) and calculated (δ_{BS}) CTOD fracture toughness values match approximately. More detailed analysis indicates that the direct measured method δ_5 gives more conservative CTOD values, *[1]*.

4 CONCLUSIONS

The fracture behaviour of specimens notched partly in the HAZ is strongly affected by microstructure at the crack tip. HAZ toughness improvement has been achieved due to its widening by higher input energy (Q + preheating) in the root region so that one part of the fatigue crack tip front passed through the normalized fine-grained HAZ region. The HAZ fracture toughness of heterogeneous welds is appreciably lower than the HAZ fracture toughness of homogeneous welds due to low ductility of the soft root layer, which has caused the brittle fracture initiation of welded joints by deviating the fracture path from HAZ to the soft root layer. Strength mismatch also has a significant influence on the real values of HAZ fracture toughness. The values obtained in both examples are not the real values for HAZ fracture toughness, because they were influenced by weld root strength properties. Fracture deviation towards the base material (homogeneous weld) overestimates HAZ fracture toughness, whereas fracture deviation towards the soft root layer (heterogeneous weld) underestimates it. Therefore, the determination of HAZ fracture toughness is a complex problem that can be solved by synthetic multi-pass microstructures and their fracture toughness.

Good agreement between calculated (δ_{BS}) and measured (δ_5) CTOD values is evident from the comparison of CTOD results, 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 standard BS 5762. 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 standard BS 5762 for welded joints, which is valid for base material.

The brittle fracture initiation points of the root layer were indicated by EDX analysis as an Mn-Al-Si inclusion or TiCN carbide and they 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. In the opposite case, it could happen that the EDX analysis detects some fictitious brittle fracture initiation point.

Acknowledgements

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