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CTOD TOUGHNESS EVALUATION OF HYPERBARIC REPAIR WELDS MADE UNDER SEVERE CONDITIONS

PROCENA ŽILAVOSTI U HIPERBARIČNIM REPARATURNIM SPOJEVIMA ZAVARENIM U EKSTREMNIM USLOVIMA CTOD METODOM

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- StE steel

Abstract

The CTOD toughness evaluation of repaired weld joints (presence of two weld deposits, complex mechanical heterogeneity and high residual stresses) requires some modifications of commonly used specimen geometry and testing procedure. This paper presents the results of the single edge bend (SENB) specimens with shallow (a/W = 0.16) and deep notches (a/W = 0.3-0.5) extracted from 20 and 30 mm thick multipass submerged arc welded (SAW) joints repaired with hyperbaric (16 bar) welding process at the toe region of the original SAW weld deposits. The results show that an acceptable toughness level can be achieved for hyperbaric repair weld metals deposited at 16 bar (160 m water depth). The repaired single-bevel joint on 30 mm thick StE 445.7 TM steel contained low toughness HAZ (LBZ) regions, whereas another repaired X-joint on 20 mm thick StE 52 steel produced high toughness. The CTOD toughness evaluation (according to BS 5762 standard and CTOD (δ_5) technique) of both plates contained a series of shallow and deep cracked SENB specimens notched (through thickness and surface) at various locations of the repaired welded joints. The directly measured CTOD (δ_5) values are consistent with the calculated CTOD BS5762 values. An effect of weld metal overmatching on through thickness shallow cracked SENB specimen results was observed as these specimens can produce low CTOD values despite their lower crack tip constraint.

Ključne reči
- određivanje žilavosti CTOD metodom
- hiperbarični reparaturni spoj
- EPP postupak
- StE čelik

Izvod

Ocena žilavosti preko CTOD kod reparaturno zavarenog spoja (u prisustvu dva sloja, složene mehaničke heterogenosti i visokih zaostalih napona) zahteva određene modifikacije uobičajene geometrije epruveta i postupka ispitivanja. U ovom radu su prikazani rezultati ispitivanja epruvete za savijanje (SENB) sa plitkim (a/W = 0,16) i dubokim zarezom (a/W = 0,3-0,5) iz spojeva zavarenih EPP postupkom u više prolaza, debljine 20 i 30 mm, repariranih hiperbaričnim zavarivanjem (16 bar) u oblasti ivice prvobitno zavarenog spoja. Rezultati su pokazali da se prihvatljiv nivo žilavosti može postići hiperbaričnim reparaturnim zavarivanjem pri pritisku od 16 bar (dubina vode 160 m). Reparirani HV spoj u čeliku StE 445.7 TM debljine 30 mm sadržao je oblasti ZUT niske žilavosti (LBZ), dok se u drugom repariranom X spoju čelika StE 52 od 20 mm javila visoka žilavost. Ocena žilavosti CTOD metodom (u skladu sa standardom BS 5762 i tehnikom CTOD (δ_5)) za obe ploče se sastojala od ispitivanja serije SENB epruveta sa plitkim i dubokim zarezima i prslinom (površinskom i u pravcu debljine) na različitim mestima reparaturnih zavarenih spojeva. Direktno izmerene vrednosti CTOD (δ_5) su pokazale dobro slaganje sa vrednostima određenim CTOD BS5762 metodom. Uticaj overmečinga zavarenog spoja na rezultate ispitivanja SENB epruveta sa plitkom prslinom u pravcu debljine se ogledao u niskim vrednostima CTOD, uprkos manjem ograničenju vrha prsline.

INTRODUCTION

The shallow defects or cracks at the toe or root regions of the weld joints of offshore structures sometimes have to be repaired under harsh service conditions with wet or dry hyperbaric welding processes. Generally, the volume and depth of the deposited repair welds are smaller compared to the defected original weld. The CTOD toughness evaluation of these complex welded joints (presence of two weld deposits and higher residual stresses) certainly requires some modifications of commonly used specimen geometry and testing procedure.

However, the CTOD test standards BS 5762:1979 /1/, ASTM E 1290-91 /2/ and EGF P1-90 procedure /3/ recommend to use deep cracked ($a/W = 0.5$) SENB specimens. Fracture toughness data determined on such specimens are bound to lead to the use of conservative toughness data on material selection, welding qualification and defect assessment procedures. Yet, particularly in repair welded joints, defects are often found to be in the form of shallow toe or root cracks. Obviously, the significance of such defects may thus be assessed in an unduly conservative manner, especially if very low toughness values are used. Also, having two weld deposits, which can often cause remarkable mismatched properties in the thickness direction of the repaired joints, further complicates the fracture mechanics testing and analysis of results. A direct application of fracture toughness testing practice of unrepaired original welds to repaired joints is not a straightforward task, since repair welding can produce additional local brittle zones (LBZ) to be tested. Hence the use of a shallow cracked specimen, in addition to the standard specimen geometry, is essential to characterize repair welded joints.

Various studies have already shown that the elastic-plastic fracture toughness values at crack initiation (δ_i or J_i) can be higher on shallow cracked specimens than on deep cracked ones, /4-10/. It is known that the CTOD formula used in testing standards is based on the plastic hinge model of bend specimens. The value of plastic rotation factor r_p significantly affects the calculated CTOD values. A considerable decrease of the notch depth (a/W) can cause a shift of the plastic hinge point location $(W - a)r_p$ in the unnotched ligament ahead of the crack tip. Hence, the determination of r_p values for shallow cracked specimens plays an important role in CTOD testing, particularly of shallow notched weld specimens where material heterogeneity (mismatching) should particularly be taken into account. Several studies revealed that the plastic rotation factor, r_p, can have a higher value than 0.4 for deep notched homogeneous specimens and a much lower value for shallow notched specimens /4-6, 9-12/. In fact, the new ASTM E-1290-91 standard /2/ uses the r_p values of 0.44 for SENB, and 0.46 and 0.47 values for CT specimens ($r_p = 0.47$ for $0.45 \leq a/W \leq 0.50$ or $r_p = 0.46$ for $0.50 \leq a/W \leq 0.55$) which is higher than the one used in the BS 5762 standard.

In this sense, the specimen size or geometry dependent fracture toughness data have caused increasing interest in elastic-plastic toughness testing procedures. The CTOD or J testing of the repair welded joints and their heat affected zones (HAZs) further complicate the issue due to their micro- and macro-heterogeneities. Therefore it has become necessary to conduct CTOD or J testing of repair weldments extensively to understand the difficulties and applicability of the present testing procedures.

The present study is the extension of previous research /13/, and therefore, focuses on CTOD toughness testing in multipass structural steel welds repaired by hyperbaric (160 m water depth simulation) welding procedure to determine the effects of the original weld groove preparation, weld joint micro- and macro-heterogeneities and crack depth/location in the CTOD testing procedure.

EXPERIMENTAL PROCEDURE

Multipass submerged arc welds (SAW) are prepared on 20 and 30 mm thick StE 52 and low carbon HSLA pipeline steel StE 445.7 TM plates in half-K and X grooves respectively, under atmospheric condition. The repair weld grooves are machined as shown in Fig. 1. The repair welds are deposited in flat position by using the GMA welding procedure under 16 bar pressure (160 m water depth) in the welding chamber of the Bundeswehrhoch-schule Hamburg. The heat inputs are 2.7 kJ/mm and 1.8 kJ/mm for SAW and GMA welding respectively. For the original weld (SAW) and hyperbaric repair weld deposits, consumables are selected to obtain overmatching weld metals with respect to their respective base metal yield strengths as shown in Table 1.

Three-point bend SENB specimens ($B\times B$, B =28 mm and 18 mm) are extracted from the original SAW and repair welded 30 mm and 20 mm thick plates with various notch locations and notch lengths as shown in Tables 3a and 3b.

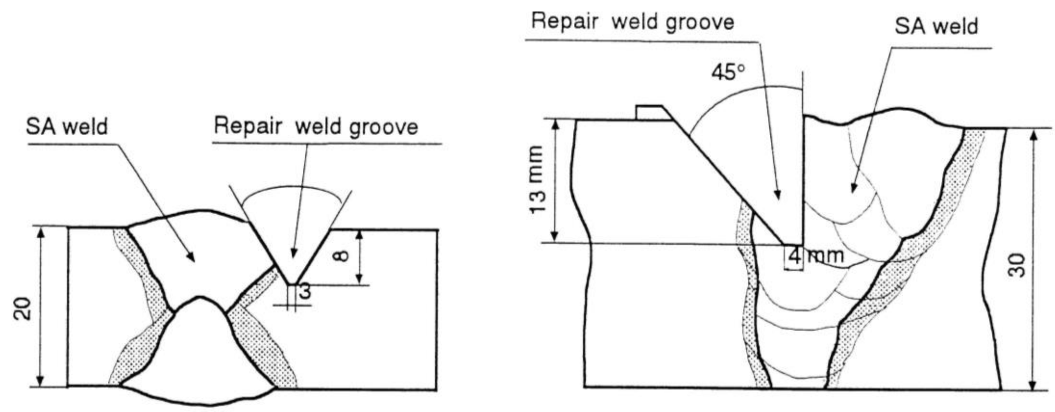


Figure 1. Repair weld groove preparation.

Table 1. Base material and weld metal mechanical properties.

Material	Yield stress, MPa	Tensile strength, MPa	Elongation (%)	Mismatching factor M
Base material, 30 mm	388	550	29.7	-
SAW weld metal (1 bar)	582	701	23.4	1.50
Repair weld metal (16 bar-dry)	630	704	24.7	1.62
Base material, 20 mm	368	557	28	-
SAW weld metal (1 bar)	570	686	22	1.55
Repair weld metal (16 bar-dry)	603	747	24.3	1.64

The specimens are prepared with a/W ratio of 0.16, 0.3, 0.4 and 0.5, and subsequently fatigue precracked. These extensive notch locations and configurations are selected in order to screen potentially embrittled zones of these complex welded joints and to compare the shallow and deep notched specimen toughness results. All CTOD tests are conducted at –10°C. The CTOD values are calculated in accordance with BS 5762 (δ_{BS}) and also directly measured with the GKSS developed δ_5 clip gages (d_5) on the specimen side surface at the fatigue crack tip over the gauge length of 5 mm /14-15/. Since there is a very good agreement between the two CTOD measurements, /16/, it is thought that δ_5 values can be substituted into the δ_{BS} formula to determine the plastic rotation factor, r_p, experimentally for deep and shallow notched bend specimens:

$$\text{CTOD}_{\text{BS}} = \frac{K^2(1-\nu^2)}{2\sigma_y E} + \frac{r_p(W-a)V_p}{r_p(W-a)+a+z} = \delta_5 \qquad (1)$$

From Eq.(1), the plastic rotation factor r_p can be obtained as:

$$r_p = \frac{a+z}{W-a} \cdot \frac{2\sigma_y E\delta_5 - K^2(1-\nu^2)}{2\sigma_y E(V_p-\delta_5)+K^2(1-\nu^2)} \qquad (2)$$

The rotation factors obtained in this manner for various shallow ($a/W \cong 0.1$) and deep notched ($a/W \cong 0.3$-0.5) specimens produced values of about 0.2 and 0.45 respectively, /16/. It is clear that these r_p values were found under the equal condition of the CTOD_{BS} and CTOD (δ_5) values. The plastic rotation factor determined for shallow and deep cracked specimens in other studies /7, 10/ also showed the value of about 0.2 for shallow cracked ($a/W \cong 0.1$) specimens. By following up this approach and various other results developed at the GKSS, the r_p value of 0.25 is used for 28 mm thick specimens to calculate the δ_{BS} for shallow cracked specimens ($a/W = 0.16$).

RESULTS AND DISCUSSION

Micro-hardness survey

Figures 2a and 2b show the micro-hardness paths (a-f) for 30 mm (a-g) and 20 mm thick welds. This hardness survey was made to determine the hardness distribution across the microstructural critical zones recognised by metallographic examination. The inter- critically coarse grained heat affected zone (ICCGHAZ) region of the SAW weld is found to be the most brittle zone of this joint as shown in Fig. 2a. This zone is also depicted as the most critical microstructure in other studies, /21-22/. Figure 3a presents the distributions obtained from paths *a* and *b* of 30 mm thick plate which indicates the hardness increase at the root pass of the repair weld (*RW b*) and root-HAZ compared to its cup passes (*RW a*). For the 20 mm thick plate, the hardness distribution obtained from path *f* is given in Fig. 3b. The characteristic maximal hardness values obtained in thickness direction (paths *d*, *e* and *f* for 30 mm thick plate and *e*, *f* and *g* for 20 mm thick plate) and corresponding calculated yield stresses, /23/, for these peak hardness values are given in Table 2. Obviously, the mismatching factor, *M*, shows differences compared to the global *M* values in Table 1, with locally varying mechanical properties which are depicted by hardness measurements. Hence, this complex mechanical heterogeneity at the vicinity of the crack tip will certainly influence the characteristics of crack initiation and growth.

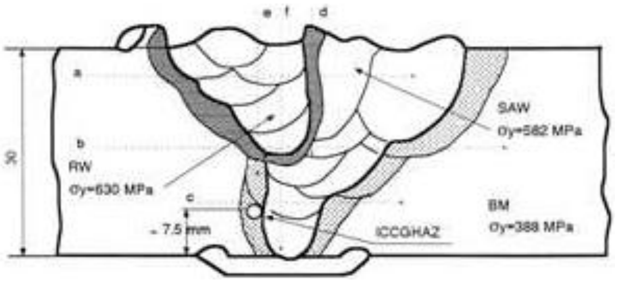


Figure 2a. Hardness measurement directions and yield strengths of the base- and weld metal.

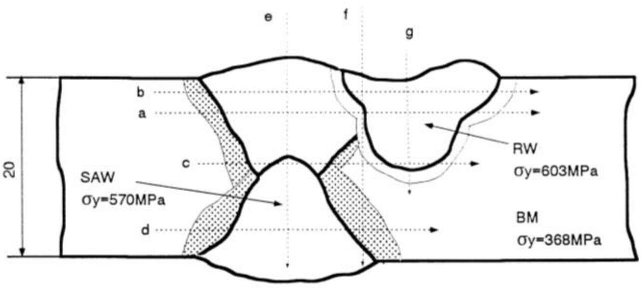


Figure 2b. Hardness measurement directions and yield strengths of base- and weld metal.

CTOD evaluation

Present CTOD testing standards have originally been prepared for testing homogeneous materials. Therefore, the selection of a yield strength value (in the elastic part of the CTOD formula) for testing welded joints presents some difficulties. It is general practice to use the average of the base- and weld metal yield strength for HAZ notched specimens. However, with this practice, the effects and contribution of the base- and weld metals on the crack tip plastic zone development and consequently, on the toughness values are assumed to be equal. This solution is an over-simplification of the problem, particularly for mismatched joints.

Figure 4 schematically shows the difficulty of the yield stress selection for the HAZ/fusion line notched specimens of mismatched welds due to the presence of a mechanical property gradient.

The BS 4515 standard /24/ prescribes recommendations and acceptance criteria for Charpy and CTOD testing of hyperbaric repair welds. According to this standard, the CTOD tests should be conducted with deep notched specimens extracted from notch positions 1b, 3 and 4a (see Table 3). However, this standard does not give any guidance with respect to the mechanical heterogeneity (mismatching) of the crack tip vicinity and respective selection of yield stress. For the thickness and yield strength of 30 mm thick steel plate used in this study, the minimum permissible CTOD value according to this standard is 0.12 mm.

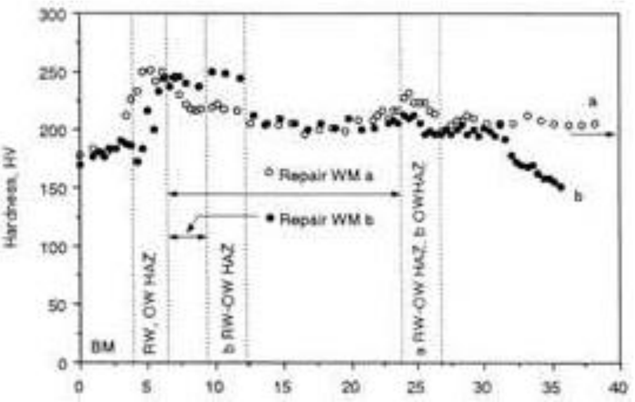


Figure 3a. Hardness distribution for paths *a* and *b*. See Fig. 4a.

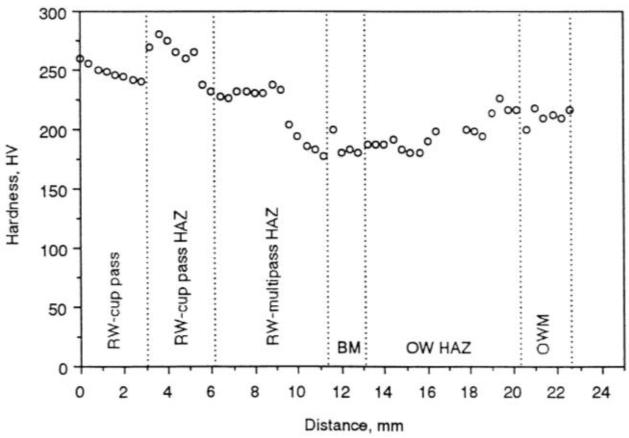


Figure 3b. Hardness distribution for path *f*. See Fig. 4b.

Table 2. Weld metal yield stresses in thickness direction, calculated from max. hardness values.

Plate-30 mm	HV Micro-hardness measurement, direction *f*	Yield stress-calculated* (MPa)	Mismatching factor *M*
RW-cup pass	204	474	1.28
RW-root pass	238	582	1.58
RW-OW HAZ	250	620	1.69
OW	214	506	1.37
Plate-20 mm	HV Micro-hardness measure. direction *f*	Yield stress-calculated*	Mismatching factor M
RW-cup pass	260	651	1.77
RW-OW HAZ, cup pass	280	714	1.94
RW-OW HAZ, multi pass	238	582	1.58
OW-HAZ	226	544	1.48
OW	218	519	1.41
BM	170	367.5	-

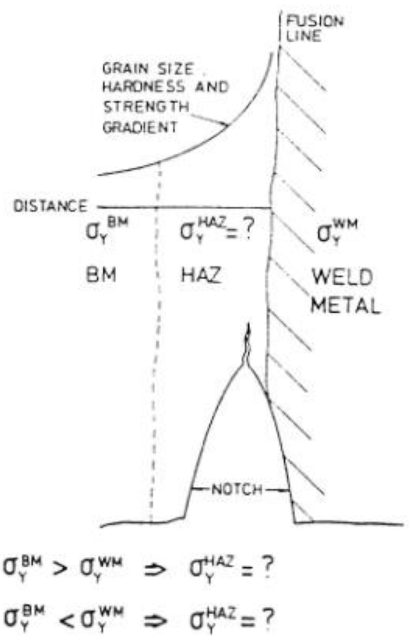


Figure 4. The problem of yield stress selection for HAZ notched specimens.

CTOD testing of 30 mm thick repair welded joint

Various yield strength values used (in relation to the notch position) in the calculation of CTOD values according to the BS 5762 formula are given in Table 3. The so-called ‘equivalent yield strength’ value is obtained by the average material combination at the vicinity of the crack tip, for example, for notch position 4*a* and 4*b* (see Table 3):

$$\sigma_y = \frac{\sigma_y^{RW} + \sigma_y^{OW} + \sigma_y^{BM}}{3}$$

The purpose of this exercise is to include the approximate effect of strength mismatching of the crack tip vicinity into the CTOD toughness determination. Two weld metals and one base metal mechanical properties in varying combinations are used with respect to the notch positions. The effect of yield stress selection on values can be seen in Table 4 in which two specimen results are presented. Five yield stress levels are used to calculate the CTOD (BS) values. For these notch positions, a significant contribution of the soft (high toughness) base metal side on the plastic zone development at the crack tip can be expected. Apparently, if the yield stress of the base metal is used, the CTOD (BS) results are getting closer to CTOD (δ_5) values. These results indicate the potential advantage of directly measured CTOD (δ_5) values, since they do not need to be calculated by using some yield strength values. The direct application of the CTOD (δ_5) technique on shallow and deep notched specimens without any plastic rotation factor correction offers another advantage of this technique. The comparison of two CTOD values obtained according to the BS 5762 standard and CTOD (δ_5) procedure for deep and shallow notched specimens extracted from 30 mm thick plate is shown in Fig. 8.

Table 4. CTOD (BS)-CTOD(δ_5) comparison for a/W = 0.16 and 0.5 specimens.

	CTOD (BS)-Pos. 4b	a/W = 0.16	CTOD (BS)-Pos. 4a	a/W = 0.5
	Specimen 10.12	Specimen 11.2	Specimen 10.2	Specimen 10.7
1. σ_y = 388, BM	0.096	0.018	0.139	0.054
2. σ_y = 582, OW	0.081	0.013	0.122	0.041
1. σ_y = 630, RW	0.079	0.012	0.120	0.039
1. σ_y = 606 av.*	0.080	0.012	0.121	0.040
1. σ_y = 533 av.**	0.082	0.013	0.123	0.041
CTOD (δ_5)	0.092	0.025	0.159	0.061

* 1/2 (RW+OW) ** 1/3 (RW+OW+BM)

The CTOD(BS) results are plotted in Fig. 5 with respective notch positions. Large differences in toughness results between shallow and deep (a/W = 0.5) through thickness notched weld metal specimens (see notch positions 1a and 1b in Table 3) can be observed due to the differences in constraint. However, a similar observation could not be made so clearly on surface cracked repair weld metal specimens (positions 2a and 2b) with a/W ratios of 0.4 and 0.16, respectively. Shallow cracked specimens (position 2b) showed only slightly higher toughness values than the test pieces of position 2a in which crack tip plastic zone developments can easily extend into the softer base metal (388 MPa) compared to the shallow cracked specimen in which crack tip plastic zone development predominantly remains within the high strength (630 MPa) hyperbaric weld metal (see Table 3).

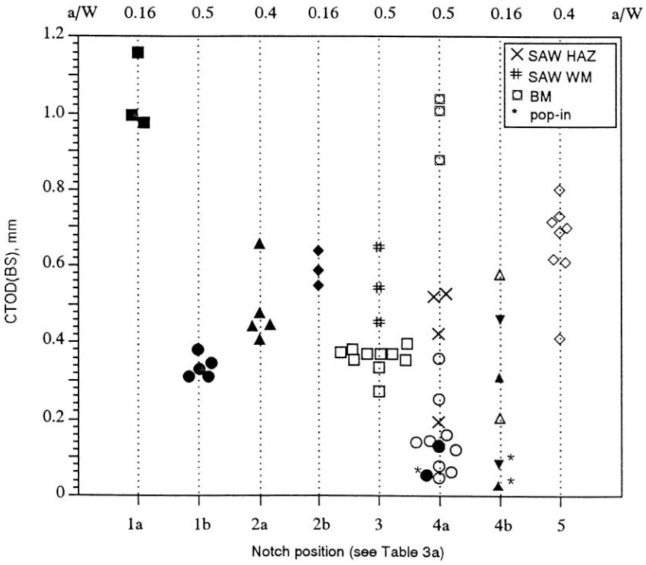


Figure 5. The CTOD (BS) values for all notch positions on 30 mm thick plate showing the effects of notch position and a/W ratio.

Clearly, the lowest toughness data (lower than the permissible CTOD value of 0.12 mm) is obtained for specimens having notches at position 4a. In this notch position, the fatigue crack is sectioning the repair weld metal and HAZ of the SAW deposit, Table 3. The shallow cracked specimens with this notch position 4b also produced low pop-in toughness values comparable to the deep notched results. Obviously, this notch position is sampling the most critical regions of the repaired weld joint.

Contrary to the expectations, test results obtained from notch position 3 indicate that the repair HAZ region developed within the original SAW weld metal has higher toughness properties than the regions sampled by position 4a, Fig. 5. Therefore, extensive microstructural examination was conducted to determine the location of cleavage crack initiation for these two notch positions. Typical fracture surfaces of deep and shallow notched specimens for positions 4a and 4b are shown in Figs. 6a and 6b. For both cases, brittle fracture initiated at the ICCGHAZ region of the original SAW weld (schematically shown in Fig. 2a). Ductile crack initiation and growth is observed at the repair weld metal side of the specimens.

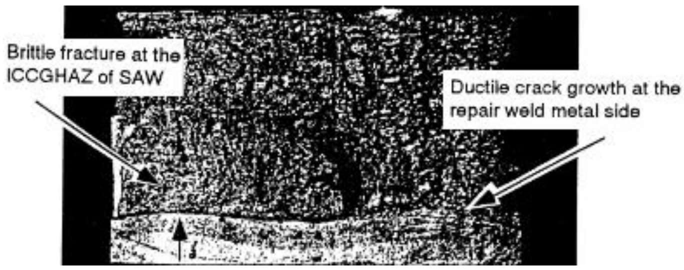


Figure 6a. Fracture surface *f* specimen (position 4a, a/W = 0.5) showing the brittle and ductile fracture path corresponding to the original weld HAZ and repair weld, respectively.

Figure 6b. Fracture surface of the specimen (position 4b, a/W = 0.16) showing at the right side a ductile crack growth occurred at the repair weld metal and brittle fracture at CGHAZ of the SAW joint.

The metallographic examination of the ICCGHAZ on sectioned specimens revealed the embrittled grain boundary microstructure shown in Fig. 7.

Figure 7. ICCGHAZ microstructure at the brittle fracture initiation point (see Fig. 8), optical micrograph (500×).

It is interesting to note that the ICCGHAZ of the SAW weld metal showed this low toughness behaviour only in specimens with repair weld deposits. The CTOD results of the unrepaired SAW HAZ specimens are included in Fig. 8 at notch position 4a. These specimens showed higher values compared to the position 4a results obtained from repaired joints, Fig. 7, notch position 4a. This may imply that the repair weld caused further embrittlement of the CGHAZ of the original SAW weld and hence low toughness values were only obtained after repair weld deposition.

The effect of large strength differences (mismatching) along the crack front in the thickness direction may also play a role in low toughness results. The highly overmatched repair weld metal (630 MPa) protects the crack tip portion which samples the repair weld metal from applied deformation and hence forces the other part of the crack front neighbouring the low strength base metal (388 MPa) to accommodate the applied deformation. This asymmetric strength distribution along the crack front of the position 4a and 4b specimens can enhance the attainment of the critical stress for cleavage crack initiation at the ICCGHAZ region of the original SAW weld metal. Due to this negative effect of the overmatching repair weld metal, the shallow cracked specimens (notch position 4b) also showed low CTOD results, despite their lower crack tip constraint (if one considers the crack depth only).

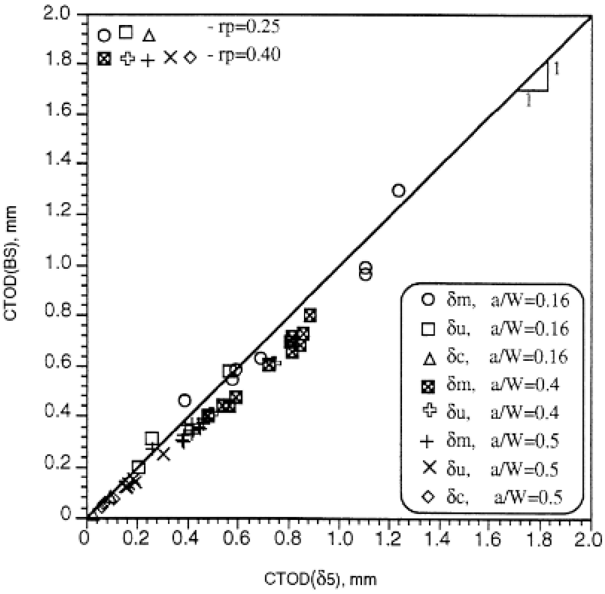
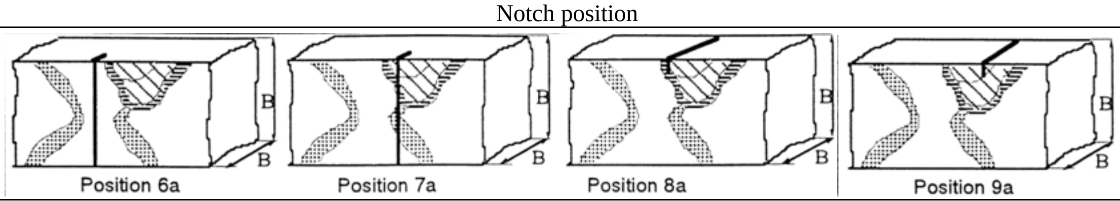
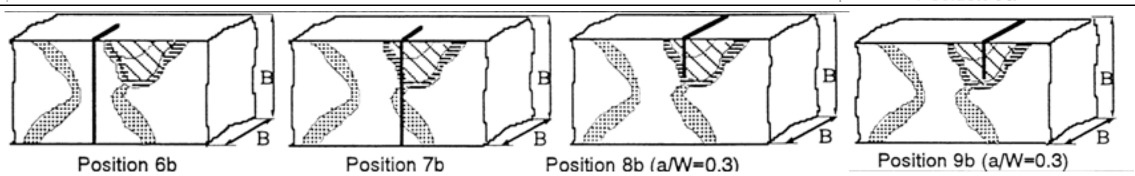


Figure 8. Relationship between δ_{BS} and δ_5 for shallow and deep notched specimens for 30 mm thick plates showing close agreement.

The intersection of two HAZs of two weld deposits (notch position 5, Table 3) is tested by using surface notched specimens with $a/W = 0.4$. The results are shown in Fig. 7 which indicates a high toughness level compared to the through thickness notched 4a and 4b specimens. Figure 7 further indicates a certain similarity of the surface notched specimen results, positions 2b and 5. It is believed that the higher toughness values of position 5 are again obtained under the positive influence of the neighbouring soft base metal (which readily provides some crack tip relaxation due to the plastic zone development at the undermatched base metal side). Evidently, these high CTOD results are being influenced by a high base metal toughness level included in Fig. 7 at position 4a.

Table 3. Various notch positions for repair welded joint, 20 mm thick plates.

a/W	Notch position
0.16	
0.3 & 0.5	

It can be concluded that the mechanical heterogeneity along the crack front (in this case the presence of overmatching hyperbaric weld metal) can significantly influence the CTOD values due to the asymmetric distribution of the applied deformation along the crack front. It is apparent that the present toughness values obtained from such complex welded joints will always reflect the effect of the strength mismatching of the crack tip vicinity. Therefore, such data should be called 'apparent toughness' rather than the material parameter 'intrinsic toughness' of the microstructure at the crack tip. There is still a need to define the effect of mismatching on the crack tip stress state (constraint) and on toughness, since mismatching significantly changes the fracture initiation behaviour and crack path direction.

CTOD evaluation for 20 mm thick repair welded joint

The hyperbaric repair weld under 16 bar pressure is carried at the toe region of the symmetrical double-V grooved SAW welded joint. In this case microstructural examination prior to the CTOD tests did not reveal any embrittled low toughness HAZ region. Deep and shallow notched SENB specimens are extracted as shown in Table 3. The CTOD values are obtained from these specimens shown in Fig. 9. The effect of notch depth on CTOD values is visible for notch positions 6 and 7 both having through thickness shallow (a/W = 0.16) and deep notched (a/W = 0.5) specimens. Both deep notched specimens produced the same level of low toughness results although notch position 6b is sectioning purely SAW weld metal (see Table 3). Because of low yield strength effect on CTOD (BS) (see for example Table 4) results, yield strength value of 570 MPa is used for CTOD (BS) calculations for all SENB specimen locations presented in Table 3. Nevertheless, this repaired joint generally produced rather good toughness levels for all its regions (no CTOD value below 0.2 mm). Even specimens with notch position 7b which partly covers HAZs at mid thickness (see Table 3) produced acceptable values. The comparison of two CTOD values obtained according to the BS 5762 standard and CTOD (δ_5) procedure for deep and shallow notched specimens extracted from 20 mm thick plate is shown in Fig. 10.

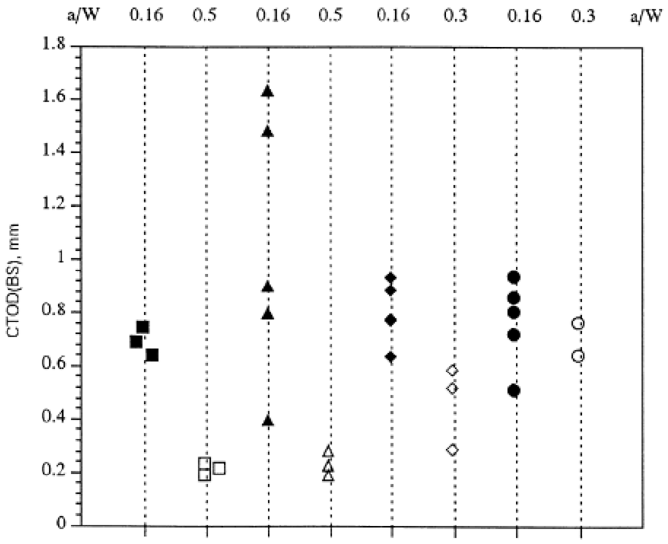


Figure 9. CTOD (BS) values for all notch positions on 20 mm thick plate (T = –10°C) showing effects of notch position and a/W ratio.

It can be concluded that despite unsymmetrical distribution of the applied deformation along the crack front (due to through thickness direction high mechanical M ratio), slow crack growth after crack initiation has appeared in all tested specimens and the apparent toughness is high.

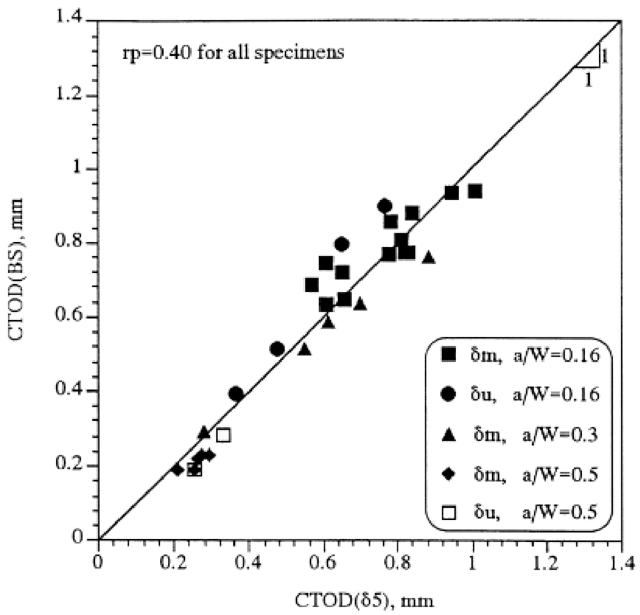


Figure 10. Relationship between δ_{BS} and δ_5 for shallow and deep notched specimens for 20 mm thick plates showing also close agreement.

CONCLUSIONS

A characterization of the multipass SAW welded joint repaired with hyperbaric MAG welding process at 16 bar pressure (160 m water depth) is carried out by microstructural examination and testing of shallow and deep notched CTOD specimens. The CTOD is determined according to the BS 5762 standard and the CTOD procedure. The analyses of the experimental results led to conclusions as follows.

Prior to the extraction of CTOD test pieces and notching, detailed microstructural examination of the repaired joint is recommended to establish the most critical zones, since repair weld deposition with a different welding process can produce additional local brittle zones. A hardness survey of the repaired joint may help to identify such zones. Various notch configurations are essential for full toughness characterization of the joint.

The hyperbaric repair weld metals have shown good CTOD toughness levels. This indicates that the hyperbaric welding process used in this study for water depth of 160 m can provide weld metals with toughness levels equal to the original defective weld deposit. The most critical zone (HAZ of the original SAW weld joint of 30 mm thick plates) is depicted by through thickness shallow and deep notched specimens (position 4a and 4b) under the influence of the overmatched repair weld deposit. Prior to the repair the same HAZ region did not produce low toughness results. Shallow cracked specimens in this case produced similar CTOD results compared to deep notched ones.

The CTOD measurements are consistent with the calculated CTOD values according to the BS 5762 standard for both deep and shallow cracked specimens (a/W = 0.16) if the r_p value of 0.25 is used in the latter. The application of the CTOD technique on the shallow and deep notched specimens extracted from repair welded joints offers a simple and quick toughness estimation technique.

CTOD fracture toughness testing of repair welds with shallow notched specimens (a/W = 0.16) gives generally geometry dependent toughness values.

It seems that most important factors for complex repair welded joint fracture toughness evaluation are: original welded joint design, geometry of the repair weld, crack tip sampling of the ICCGHAZ / UCGHAZ microstructures and heterogeneous crack tip constraint distribution.

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