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THE FRACTURE BEHAVIOUR OF GLOBAL /LOCAL MIS-MATCHED WELD JOINTS PROVIDED ON HSLA STEELS

POJAV LOMA V GLOBALNO/LOKALNO TRDNOSTNO NEENAKIH ZVARNIH SPOJIH, IZVEDENIH NA VISOKOTRDNOSTNIH JEKLIH

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The fracture behaviour of thick-section high-strength steel weldments that contain soft root passes has been studied. Two different weld consumables with different strength-mismatch (1>M>1) and fracture-toughness properties in the WM have significantly increased the complexity of the mismatch effect and the failure behaviour of weld joints, depending upon the crack location and the thickness of the soft root layer. The aim was to explain the effect of strength heterogeneity between the BM and the WM, and between different regions in the WM (global/local mismatching). R-curves of the WM and the HAZ regions were also discussed. The conclusion is that the application of a welding procedure with a two-pass soft root layer introduced for the purpose of reducing or even omitting preheating, can be recommended for mismatched weld joints on HT80 steel. Nevertheless, the alloying from BM and the tempering effect of the subsequent weld passes have to be taken into account. They can cause a reduction in the root-region ductility and affect the local mismatch in the WM and the HAZ. The deterioration when providing a soft root layer can probably be reduced by choosing a particular consumable and a proper welding procedure. The final conclusion is that the application of a mismatched weld joint with a soft root layer can be recommended only if high root toughness can be provided.

Key words: toughness, ductility, fracture toughness, mismatch effect, soft root layer, weld joints, high-strength steel

Raziskovan je bil pojav loma v zvarnih spojih, izvedenih na visokotrdnostnem jeklu, ki so vsebovali mehke korenske varke. Dva različna dodajna materiala z različno trdnostno neenakostjo (1>M>1) in lomno žilavostnimi lastnostmi v strjenem zvaru sta izrazito povišala kompleksnost vpliva trdnostne neenakosti in pojave loma v zvarnih spojih. Navedeni vpliv je bil odvisen od položaja razpoke in debeline mehkega korenskega sloja. Namen je bil raziskati vpliv trdnostne heterogenosti med osnovnim materialom in strjenim zvarom in med različnimi področji v strjenem zvaru (globalna/lokalna trdnostna neenakost). Poleg tega so bile obravnavane odpornostne krivulje področij v strjenem zvaru in toplotno vplivanem področju. Zaključek je, da je uporaba varilne tehnologije z dvovarkovnim mehkim slojem, ki je vnesen zaradi znižanja ali celo preprečitve predgrevanja, priporočljiva za trdnostno neenake zvarne spoje pri jeklih tipa HT80. Pri tem pa je treba upoštevati nalegiranje, ki izhaja iz osnovnega materiala, in vpliv popuščanja od naslednjih varkov. To lahko povzroči zmanjšanje duktilnosti v področju korena in vpliva na lokalno trdnostno neenakost v osnovnem materialu in toplotno vplivanem področju. Poslabšanje lastnosti z uporabo mehkega korenskega sloja je verjetno lahko znižati z uporabo ustreznega dodajnega materiala in izbrano varilno tehnologijo. Sklepamo, da je uporaba trdnostno neenakega zvarnega spoja z mehkim korenskim slojem priporočljiva le, če je korenska žilavost visoka.

Ključne besede: žilavost, duktilnost, lomna žilavost, trdnostna neenakost, mehki korenski sloj, zvarni spoj, visokotrdnostno jeklo

1 INTRODUCTION

Substantial differences in the strength properties (mismatch) of the base material (BM), the weld metal (WM) and the heat affected zone (HAZ) are found in the weld joints of high-strength-steel constructions. It is common practice in various engineering constructions to deposit WM which has a higher strength (over-matching) than the steel. In this case, the higher strength of the WM compared to the BM can provide the best weld-joint performance by shielding short cracks or other planar faults from the applied strains. It is however, rather difficult to deposit WM with a strength level which over-matches the high-strength micro-alloyed or low-alloy steel, and simultaneously fulfils the codes which prescribe the level of impact toughness.

Sometimes due to the weldability limitation (sensitivity to coarse-grained HAZ-CGHAZ cold cracking for instance) the deposition of WM which has a lower strength (under-matching) is used with the aim of reducing or even eliminating the preheating. On the other hand, the fused part of the BM can effect, because of its additional alloying, the degree of weld under-matching which can be shifted towards the properties of the BM. Nevertheless, higher under-matched WM with lower toughness can be a potential danger for structural integrity. As a result it is necessary to have a higher level of toughness than that of the BM. It is known, however, that a fused-weld impact-toughness energy of over 50 J at -10 °C, or lower, is difficult to attain for Q+T steels with a yield strength above 700 MPa.

The failure behaviour of such a mechanically heterogeneous weld joint has to be influenced by the strength levels of the neighbouring zones associated with the existent defect. Both the strength and toughness of the defective weld region will control the brhaviour of the welded structure.

The aim of this research work was to estimate the CTOD fracture toughness using standard procedures [1,2,3,8] of over- and under-matched X-grooved multi-pass weld joints. Deeply notched standard SENB specimens (a/W=0.5), with the notch positioned at the centre line of the WM, in the through-thickness direction were used. We also wanted to take into account the effect of the weld width (2H) on the CTOD behaviour. The weld width varies across the thickness due to the X weld groove preparation and is the shortest at the root region.

We intended to prove that if the weld width (2H) is shorter than the uncracked ligament, W-a, than the local brittle zone (LBZ) can be forced to appear early and the standard procedure for estimating J_{IC} and δ_c remains inaccurate [4]. In order to determine the fracture toughness of the HAZ, steps were taken to hit the fusion boundary by notching the CG- or ICCGHAZ at two points to receive a so-called "composite notch". Since the plastic deformation associated with the crack tip is not symmetrical in this case, the reduction of the HAZ toughness for over-matched weld joints as a result of increasing constraint due to the restriction in plastic deformation on the WM side was expected [5]. Due to plastic deformation on the WM side for the under-matched weld joints an apparent increase in the HAZ toughness is expected, but only in the case when the WM is tough enough and its strain hardening takes place.

Special treatment is needed during fatigue-crack preparation on a CTOD specimen taken from the weldments. If one uses the prescribed procedures (valid for uniform materials) [6,7,8], then the crack-tip front will not be straight. This phenomenon is caused by the residual stresses distributed in the specimen, through-thickness and heterogeneous hardness distribution along the crack tip [9,10]. To overcome this problem the modified version of High R-ratio, the so-called "Step Wise High R-ratio (SHR) method", is used [1,11]. This method was improved recently by introducing the model of straight-fatigue-front prediction, which takes into account the magnitude and distribution of the residual stresses intensity factor at two levels and thus the maximum force for the pre-crack loading calculation. With this model the prediction of the equilibrium stage of fatigue-crack propagation is possible by finding the optimum fatigue- loading regime[12]. So, using this improved method, and taking into account the highest value of the WM yield stress, straight crack-tip fronts can be achieved for the as-welded specimen. Using the a procedure in BS 7448, Part 2, such as Local compression as an alternative method, was shown to be inappropriate for global/local mismatched weld joints with a soft root layer.

A series of Charpy impact toughness specimens taken from different weld-joint regions, and BM and a series of SENB specimens extracted from thick steel weldments prepared for welding by using X-groove, were made of under- and over-matched WMs. The CTOD values on the SENB specimens which were perpendicularly notched and prefatigued in the WM and the HAZ, achieving the ratio a/W=0.5, are presented and the fracture behaviour of over- and under-matched weld joints with and without a soft root layer are compared .

The differences in the mechanical properties among the different weld regions affected the strain distribution around the crack tip during the fracture-toughness tests and consequently affected the measured CTOD fracture toughness values of the under- and over-matched weld joints.

2 TESTING PROCEDURES AND RESULTS

2.1 Welding Procedures

High-strength-low alloyed (HSLA) steel in a quenched and tempered condition, corresponding to grade HT 80, was used. For the welding of steel plates the FCAW procedure, and two tubular wires were selected so as to produce weld joints in over- and under-matched conditions. In **Tables 1 and 2** the mechanical properties and the chemical compositions of the BM and the measured mechanical properties and the chemical compositions of the all-weld metals for the selected consumables are given. The strength mismatched factors M (M=WM yield stress/BM yield stress) were 0.76 for under- and 1.08 for over-matched weld joints. **Table 3** shows the welding procedure and all the welding data used. In **Table 4** the changes of the chemical composition among the cap and root regions of the homogeneous WM and the WM of the soft root layer for an under-matched and over-matched weld joint are presented. **Figure 1a and Figure 1b** show a cross-section of the multi-pass homogeneous weld joint and the weld joint with the soft root layer for on over-matched weld joint.

2.2 Testing of mechanical properties

Mechanical properties were determined with specimens taken from welded plates, as shown in **Figure 2**. Only the results of testing the CTOD Bx2B specimens are presented. In **Table 5** the mechanical properties obtained with full-thickness flat tensile specimen testing of over- and under-matched weld joints are shown. It can be seen that all the flat over-matched specimens failed in the BM and did not show any of the effects expected from a soft root layer. In the under-matched specimen the effect of the soft root layer was pronounced because it failed in the WM, while the under-matched specimen of the homogeneous weld joint failed in the BM. The mechanical properties of the WM obtained with round tensile bars for different WM regions are shown in **Table 6**. It can be recognisis clear that the under- and

Table 1: Mechanical properties of base metals and all weld metals for under- and over-matched weld joints
Tabela 1: Mehanske lastnosti osnovnega materiala in čistega strjenega zvara v zvarnih spojih z nižjo in višjo mejo tečenja od osnovnega materiala

Designation	Y.S (MPa)	U.T.S. (MPa)	Elongation (%)	Charpy imp. toughness (J)	Designed mis-match factor $M=\sigma_{yWM}/\sigma_{yBM}$
HT 80 used for um weld joit	693	830	19.6	79, 78, 64 at -10 °C	-
HT 80 used for om weld joint	711	838	19.6	158, 130, 158 at -50 °C	
Filler wire WM 3-B370	403	466	32	100, 215,145 at -40 °C	0.58 um, 0.56 om
Filler wire WM 2-B 575	542	591	23	47, 70, 71 at -40 °C	0.78 um, 0.76 om
Filler wire WM 1-B 800	770	845	16	59,55, 60 at -40 °C	1.11 um, 1.08 om

Table 2: Composition of materials and all-weld metals (wt%)
Tabela 2: Sestava materialov in čistih strjenih zvarov (mas.%)

Chemical composition	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al
HT 80 um	0.10	0.68	0.75	0.020	0.003	0.79	0.09	0.032	0.24	0.037
HT 80 om	0.09	0.27	0.25	0.015	0.004	1.12	2.63	0.25	-	0.020
Filler wire B370	0.05	0.25	0.61	0.011	0,008	0.06	0.07	0.03	-	-
Filler wire B 575	0.05	0.04	1.52	0.011	0.008	0.08	1.45	0.66	-	-
Filler wire B 800	0.06	0.35	1.43	0.009	0.008	0.86	3.01	0.56	-	-

HT 80um-base material used for under-matched, HT 80om-base material used for over-matched weld joints

Table 3: Welding procedure
Tabela 3: Postopek varjenja

FCAW Welding procedure (80%Ar+20%)				
	Under-matched weld joint		Over-matched weld joint	
Filer consumable, root pass/other passes	B575/B575 Hom. joint	B370/ B575 Heter. joint	B800/B800 Hom. joint	B575/B800 Heter. joint
Preheat temp. °C	120	-	102/113	-
Heat input kJ/cm	16.5/16-23	10.1/16-23	18.14/19.63	18.06/18.78
Calculated Δt8/5, s	9.5/10.7	7.1/10.3	9.70/10.17	10.18/11.39
Measured Δt8/5, s	8.9/9.2	6.7/8.6	9.08/9.78	7.11/9.32
Interpass temperature	135/135	50/135	135	50/135
Postheating temperature, 200 °C/2 hours	200	-/-	200	-/-
Number of passes	2/14	2/16	2/14	2/17

over-matched weld properties that were designed were not achieved in the two homogeneous weld joints. This might be due to the weld pool alloying from the molten surrounding, the local quenching during cooling, or tempering as a consequence of additional weld bead deposition. The alloying effect is more pronounced in the root region of the under-matched weld joints than in the cup region. This is the reason why the WM under-matching properties in the through thickness did not appear. For the over-matched weld joints the designed mismatch properties were also exceeded. The alloying effect in the root region is actually less pronounced, but the absence of tempering effects in the cup region results in an increase in strength. The use of a lower strength filler consumable to produce a softer root layer produced a real under-matched condition in the designed under-matched weld joint, whilst the soft root layer in the designed over-matched weld joint did not provide the desired under-matched properties.

2.3 Hardness measurements

The WM hardness measurements on both the under- and over-matched weld joints, and the yield stress calculation using the formula σ_{yw}= 3.15HV-168 [1,13], give even higher mismatch differences than the tensile-test

Table 4: Chemical composition of under- and over-matched weld metals of homogeneous and heterogeneous (soft root layer) weld joints
Tabela 4: Kemijska sestava homogenih in heterogenih zvarnih spojev (mehki korenski sloj) z nižjo in višjo mejo tečenja od osnovnega materiala

Chemical composition	Composition (wt%)									
	Under-matched weld joint									
	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al
WM - cap	0.04	0.44	1.48	0.010	0.009	0.12	1.63	0.49	0.12	
WM - root	0.10	0.33	0.89	0.013	0.008	0.73	1.11	0.42	0.13	
WM - soft root layer	0.12	0.41	0.78	0.015	0.006	0.40	0.10	0.17	0.16	
	Over-matched weld joint									
WM - cap	0.07	0.36	1.27	0.008	0.015	0.86	2.21	0.47	-	0.004
WM - root	0.08	0.32	0.78	0.012	0.013	0.99	2.50	0.35	-	0.014
WM - soft root layer	0.08	0.40	1.12	0.007	0.013	0.49	1.75	0.44	-	-

Table 5: Mechanical properties of full-thickness flat tensile specimens
Tabela 5: Mehanske lastnosti ploščatih preizkušancev iz celotne debeline

Weld joint type	Rm (MPa)	RA(%)	Failure mode
om-homog.w.j.	862	18.0	BM
om-soft root w.j	849	19.5	BM
um-homog.w.j.	804	22.6	BM
um-soft rot w.j.	792	20.5	WM

Table 6: Mechanical properties of under- and over-matched weld joints of homogeneous and heterogeneous (soft root layer) weld joints
Tabela 6: Mehanske lastnosti homogenih in heterogenih zvarnih spojev (mehki korenski sloj) z nižjo in višjo mejo tečenja od osnovnega materiala

Designation	Y.S. (MPa)	U.T.S. (MPa)	Elongation (%)	Charpy (J) at -10 °C	DesignedM	Achieved M
Under-matched weld joint - filler material B575						
WM - cap	687	804	22.3	110, 104, 102	0.76	0.99
WM - root	730	803	21.8	72, 38, 50	0.76	1.05
Under-matched weld joint - soft root filler material B370 + B575						
WM - soft root layer	567	625	19.7	35,17,34	0.56	0.81
Over-matched weld joint - filler material B 800						
WM - cap	861	951	11.7	56, 46, 66	1.08	1.21
WM - root	807	905	15.3	55, 56, 55	1.08	1.14
Over-matchedweld joint - soft root filler material B575 +B800						
WM - soft root layer	769	818	17	71	0.76	1.08 0.82-0.96*

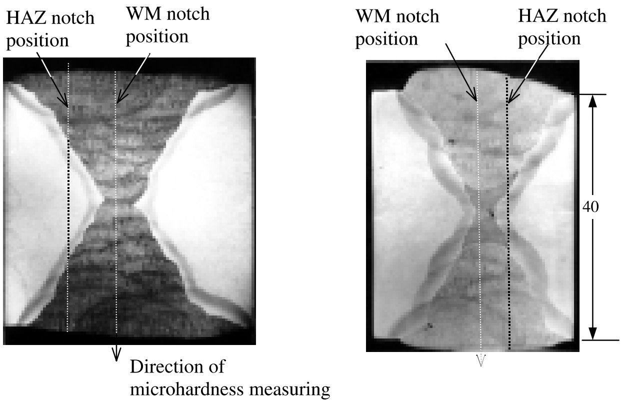

Figure 1: Weld joints cross-sections
Slika 1: Prerez skozi zvarna spoja

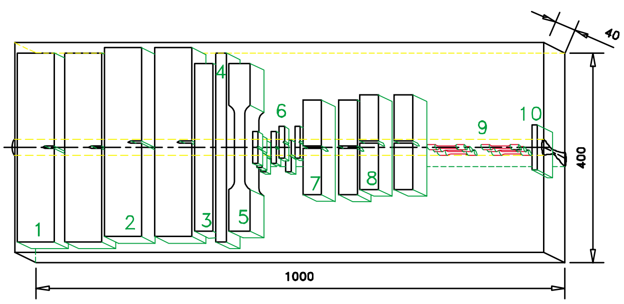

Figure 2: Specimens sampled in welded plates
Slika 2: Vzorčenje preizkušancev v zvarjenih ploščah

1. Series of CTOD specimens Bx2B, with notch tip (through thickness) completely in weld metal - 2. Series of CTOD specimens Bx2B, with notch tip (through thickness) partly in the base metal - 3. Full thickness flat bend specimen, (normal bending) - 4. Full thickness flat bend specimen (transverse bending) - 5. Full thickness flat tensile specimen - 6. Series of the Charpy-V tests specimens with machined notch in the weld metal and in HAZ - 7. Series of CTOD specimens BxB, with surface notch tip completely in the weld metal - 8. Series of CTOD specimens BxB, with surface notch tip completely in the HAZ - 9. Series of round tensile specimens - 10. Sample for metalographic sectioning.

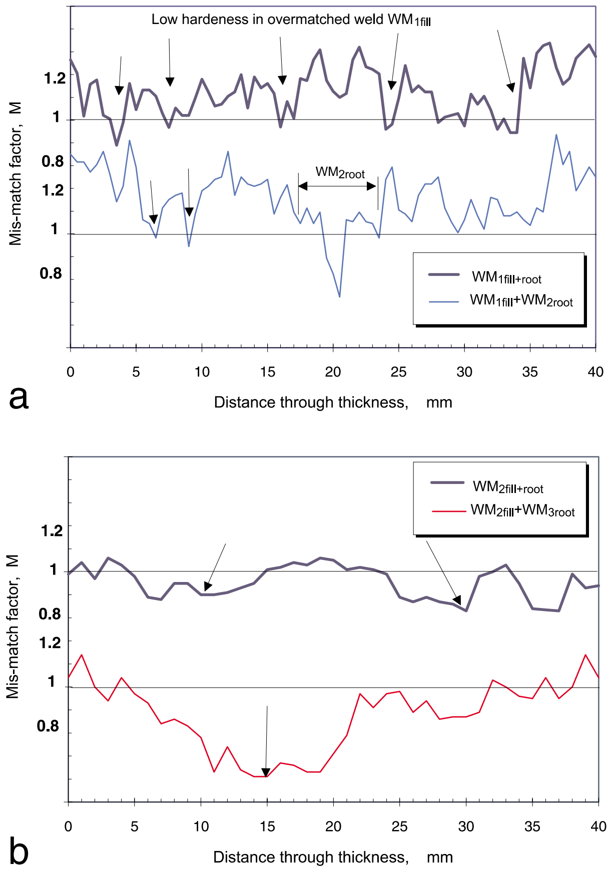

Figure 3: Mis-match distribution across the midthickness of a) over-matched, b) under-matched weld joint

Slika 3: Porazdelitev trdnostne neenakosti skozi debelino a) visokotrdnostnega b) nizkotrdnostnega zvarnega spoja

results. Hardness measurements with a distance of 1 mm between two hardness indentations in the WM through thickness direction have shown factor M deviations over the whole WM thickness.

Local mismatching distributions calculated from the hardness values are plotted **in Figure 3a and 3b**. They can be compared with those in Table 6. It is evident that the determination of the real weld-joint mismatching properties is a complex task, due to the presence of different alloying and dilution mechanisms acting during the welding in the welding pool and the influence of different bead-quenching and tempering effects on the strength. Local mismatching distribution determined by the hardness measurement in the through thickness direction across the WM, CGHAZ and BM gives even higher local deviations. The local mismatching along the prefatigued crack-tip line will certainly play an important role in crack initiation and propagation. Therefore, the analysis of the appearance and origin of brittle crack initiation reveals the local brittle zones (LBZs). Thus, the mechanical properties shown in Table 6 represent only the average properties of the exact areas where the tensile specimens were taken from and cannot give the exact mismatching condition of the whole weld

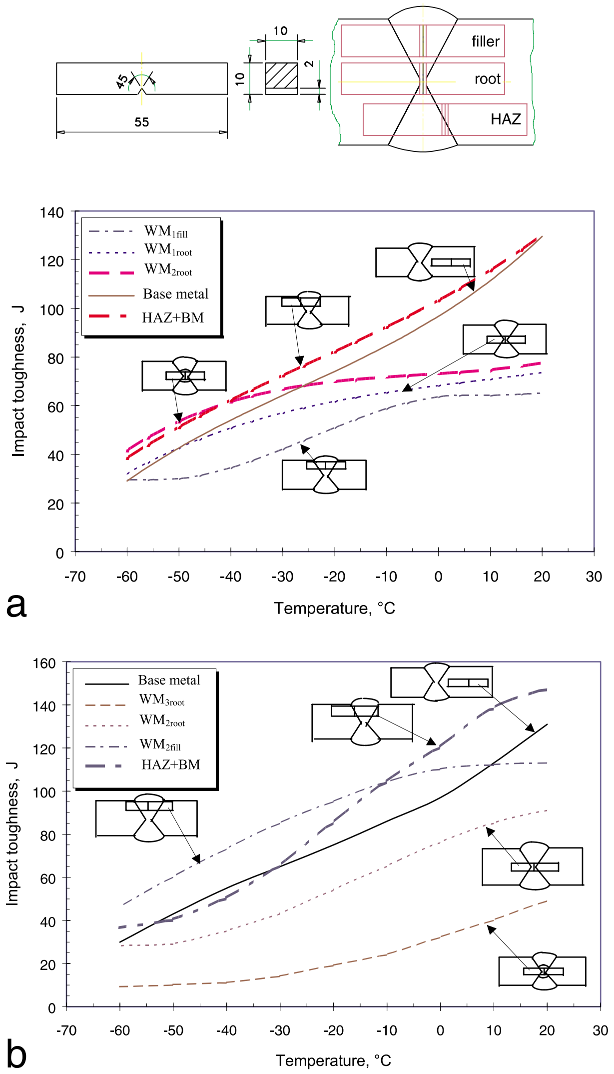

Figure 4: Impact toughness transition curves for a) over-matched b) under-matched weld joint

Slika 4: Krivulje udarne žilavosti za a) visokotrdnostni b) nizkotrdnostni zvarni spoj

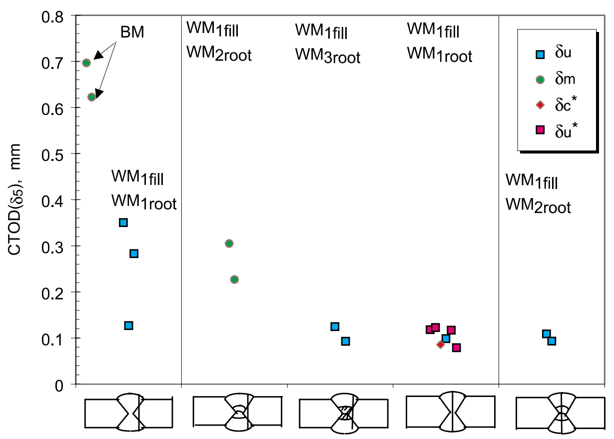

Figure 5: CTOD(δ_5) values for specimens with the crack front through the HAZ and WM in the over-matched weld joints, measured at -10 °C

Slika 5: CTOD(δ_5) vrednosti za preizkušanec z fronto razpoke skozi TVP in zvar v visokotrdnostnih zvarnih spojih, izmerjenih pri -10 °C

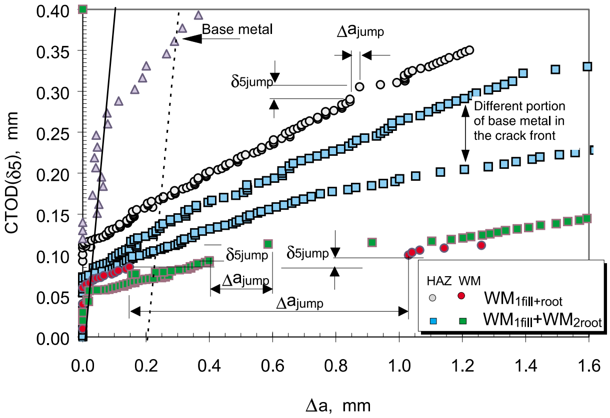

Figure 6: CTOD-R resistance curves for specimen with the crack front through the HAZ (crack depth a/W=0.5) and WM in the over-matched weld joints

Slika 6: CTOD-R odpornostne krivulje za preizkušance z fronto razpoke skozi TVP (globina razpoke a/W=0,5) in zvar za visokotrdnostne zvarne spoje

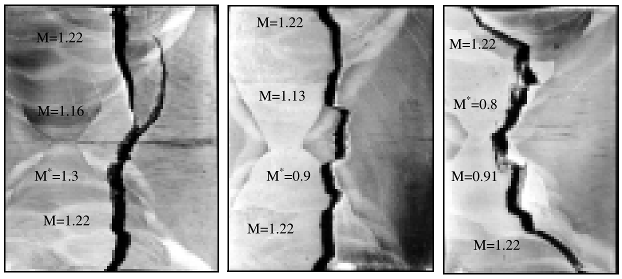

Figure 7: The crack growth path deviation of cleavage crack propagation on the macro-etch sectioning 8 mm below of fatigue pre-crack front, as the consequence of global/local mis-matching

Slika 7: Sprememba smeri krhkega širjenja razpoke na odaljenosti 8 mm pod utrujenostno fronto, kot posledica globalno/lokalne trdnostne neenakosti

joint. It seems that the local mismatching, which is extremely pronounced in the narrow CGHAZ region and often involved in the mechanism of the appearance of LBZs, can be established by the available data on micro-hardness measurements.

2.4 Impact toughness measurement

The V notch of the Charpy impact toughness specimen was introduced into the BM, CGHAZ, WM cup layers (WM-C) and the WM root layers (WM-R), to plot the transition curve. In **Figure 4a** the transition curves are plotted for the over-matched weld joint, whereas in Figure 4b the same curves are presented for the under-matched weld joint. In both figures, the V-notch position in the weld joint is marked.

For the over-matching condition (**Figure 4a**) the lowest impact toughness is measured in the weld-joint cap area. The alloying elements Mn, Ni and Mo due to the melting of the lower alloyed BM, compared to filler metal B800, reduced slightly (higher Y.S.), whereas the reduction of Mn, Ni and Mo in the root region is more pronounced (lower Y.S.). A higher Ni content improves slightly the impact toughness of the WM-R. The upper-shelf impact toughness is approximately the same for WM-C and WM-R. The impact toughness for BM and the area where the V-notch is sampling the WM, the fusion line and the HAZ is, in the single specimen approximately the same for all the tested temperatures. The impact toughness of the soft root layer is due to the alloying of C, Si, Cr, and Ni and because of to the reducing of Mn and Mo it is not the lowest. It is between the BM and the WM-R/WM-C values.

For the under-matched condition the lowest impact toughness is obtained where the yield stress is the highest, see WM-R from **Table 6 and Figure 4b**. Due to alloying elements such as C, Si, Cr and Mn, Ni, Mo reducing because of the dilution and alloying of this region from the BM and the filler metal. The whole transition curve is considerably lower than the transition curve of the BM and the upper-shelf toughness is found to be the lowest. This indicates the position where, due to the lowest toughness and more pronounced plane strain condition, the potential danger of LBZ appearance can exist. Better impact toughness can be recognised in the cap layers. This is the consequence of Mn and Mo reducing and Ni alloying. The upper- shelf impact toughness for the BM is lower than that in the area where the V-notch is sampling the WM, the fusion line and the HAZ in the single specimen. The impact toughness of the soft root layer is very low. The alloying of C, Mn, Cr and Mo can be recognised. The yield stress and the strength are increased considerably and the ductility and the impact toughness are reduced, see **Table 1 and Table 6**.

2.5 CTOD fracture toughness

According to the BS 7448 codes, all specimens should be fatigue precracked. The consequence of the usual prefatigue procedure is the appearance of a

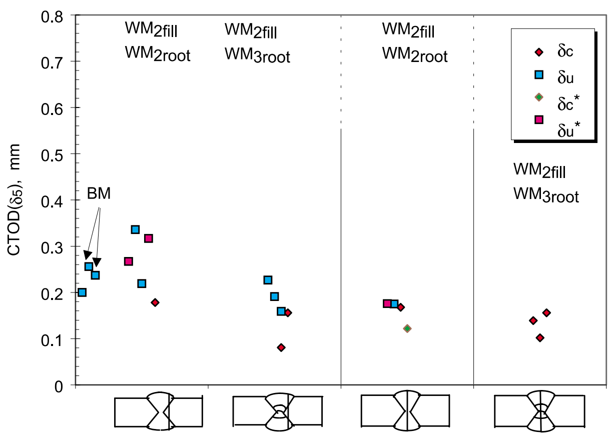

Figure 8: CTOD(δ_5) values for specimens with the crack front through the HAZ and WM in the under-matched weld joints, measured at -10 °C

Slika 8: CTOD(δ_5) vrednosti za preizkušanec z fronto razpoke skozi TVP in zvar v nizkotrdnostnih zvarnih spojih, izmerjenih pri -10 °C

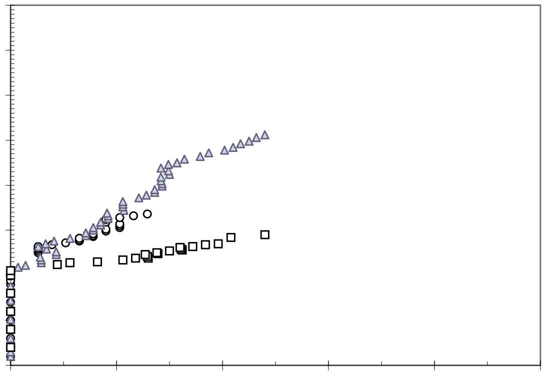

Figure 9: Comparison of R curves for HAZ and WM of homogeneous and heterogeneous undermatched weld joints

Slika 9: Primerjava med R krivuljami za TVP in zvar za homoegene in heterogene nizkotrdnostne zvarne spoje

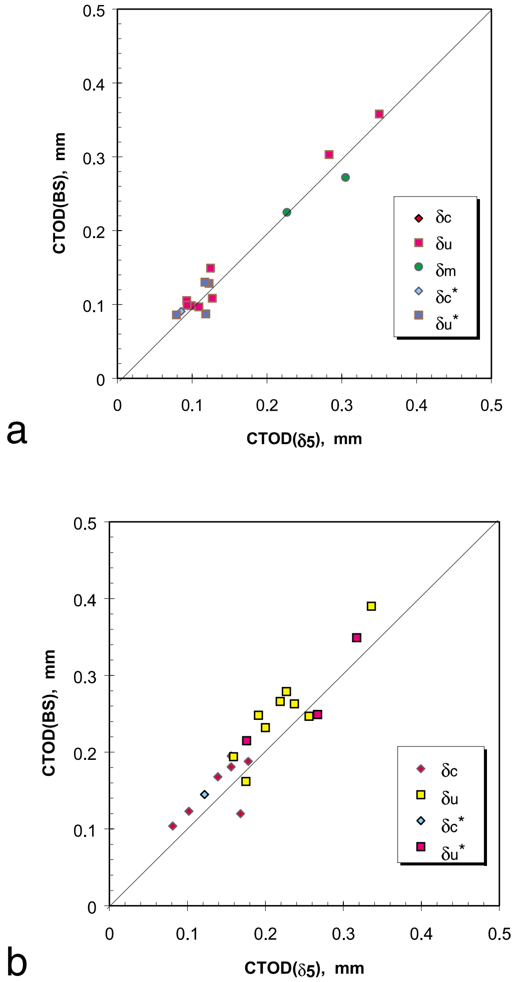

Figure 10: Comparison of directly measured (δ_5) and calculated (δ_{BS}) CTOD fracture toughness values in homogeneous and heterogeneous a) over-matched b) under-matched weld joints

Slika 10: Primerjava direktno izmerjenih (δ_5) in izračunanih (δ_{BS}) CTOD vrednosti lomne žilavosti v homogenih in heterogenih a) visokotrdnostnih b) nizkotdrnostnih zvarnih spojih

non-straight crack-tip line, because of the non-uniform through-thickness residual stress distribution in the weld joint. To overcome this problem the Step-Wise High-R-ratio method for precracking was used for the rest of the specimens [1,11]. When a crack initiation and growth of about 1 mm R=0.1 is used then the stress ratio is increased to R=0.7 with an allowable maximum load to the required a/W ratio. The allowable maximum load for both ratios was calculated using the Ref. [1] equations.

Some of specimens treated with the described R-ratio method were also invalid. The reason is probably the unknown effect of the distribution and magnitude of the residual stresses. The R-ratio method was improved [15], on the basis of determining the residual stress-intensity factor through the weld-joint thickness in the plane of the fatigue crack propagation, and so, the limit conditions for the R-ratio procedure under the standard requirements for maximum precracking load were determined.

For CTOD testing a single-specimen method was used. The geometry of the SENB specimen was Bx2B (B=40 mm) and the through-thickness notches were positioned in the WM and in the vicinity of the mid thickness CGHAZ (CTOD composite notch specimen) as shown in Figure 1. The testing temperature was -10 °C. During the CTOD tests the DC potential-drop technique was used for monitoring the stable crack growth [14]. 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 7448, Part 2, and designated (δ_{BS}) [1] and also directly measured with a GKSS developed δ_5 clip gauge on the specimens side surfaces at the fatigue crack tip over a gauge length of 5 mm [3].

The HAZ and WM CTOD data measured on the SENB specimen extracted from the multipass over-matched weld joints are given in **Figure 5**. For all specimens except the clear BM specimens, where M is equal to 1, after some of slow crack growth (δ_c/δ_u values) the "pop-in" event appeared as a consequence of the LBZ presence and as the brittle fracture had interrupted the testing. Nevertheless, the measured WM and HAZ CTOD fracture-toughness values of the homogeneous over-matched weld-joint conditions were different in magnitude, the HAZ fracture toughness being higher than the WM toughness [16]. This can be seen from **Figure 6** which represents the R-curves for the HAZ and the WM comparing the homogeneous weld joints and the weld joint with a soft root layer [12]. But the fracture-toughness magnitude when comparing the differences between the two weld joint was approximately the same in the HAZ and the WM. The fracture path in the case of the notch position in the HAZ was not affected by the softer root layer, shown in **Figure 7b**. This was not, however, when using, for example a soft root layer which can locally reduce the fracture toughness as shown in **Figure 5 and Figure 7c**.

The HAZ and WM CTOD data measured by the SENB specimen extracted from the multipass under-matched weld joints are given in **Figure 8**. Due to the dilution of BM in the root region the over-matched condition appeared in the homogeneous WM despite an under-matched filler metal being used as can be seen from **Figure 3b**. This was the reason that the specimen failed in the softest regions which were placed among WM cap and root passes [16]. Obviously the local mismatching of the through-thickness in the WM and the CGHAZ had affected the yielding behaviour along the crack tip. The HAZ fracture toughness was the highest, this was also proven when testing impact toughness, see **Figure 4b**. The reason was the over-matched condition in the root region and the fracture was deviated into the BM as in the case of the over-matched weld joint. But the HAZ fracture path changed when using a soft root layer [17]. Due to the lower root strength the initiating fracture was deviating into root WM where "pop in" appeared as a consequence of the presence with very low toughness, see **Figure 4b**. Similarly the same local effect was recognised in the specimens which were notched in the WM. Both affects can be clearly seen on **Figure 9**.

3 DISCUSSION

It is a dilemma to decide whether to choose a high-loaded weld-joint under-match or over-match condition. When choosing the over-matched condition the most difficult problem is to prevent cold cracking in the WM even after 48 hours where the possibility of delayed cracking could appear. One can overcome this problem by introducing pre- and/or post-heating. The problem of the required WM toughness which is officially prescribed by the codes is still unsolved. The use of the recently introduced ETM [18,19] offers a good solution when the WM moderate toughness compared to the higher BM toughness is prevailing in the weld joint. The ETM concept does not incorporated the affect of residual stresses which could probably cause some additional solutions and which should be incorporated into it for proper usage. When choosing an under-matched condition the use of a preheating procedure is reduced or even omitted, but due to the softer WM strength properties, a high toughness is needed locally which should prevent the occurrence of brittleness when strains are introducing into the WM. So, the purpose of this research work was to answer the question whether the soft root layers in over/under-matched weld joints for a high-loaded condition can be used. To get the proper solution a careful analyses of the results should be carried out.

3.1 Fracture properties of an over-matched weld joint

CTOD specimens taken from over-matched weld joints show WM CTOD values which are lower than those for the HAZ where a composite notch is used. Due to the lowest 2H/(W-a) ratio and the presence of higher stress intensity where the constraint is the highest (the conditions are similar to those by the narrow bi-metal mismatch) the initiation point was expected in the weld root region of the homogeneous weld joint (H is half of the weld width). But due to the higher root hardness shown in **Figure 3a** which is the consequence of the BM dilution, two LBZ on both sides of the root regions appeared, where the lowest mismatched properties were revealed. When the WM soft root layer was introduced, a so-called heterogeneous weld joint was appeared. The soft root layer did not change the fracture properties, as can be seen from **Figure 5 and Figure 6**, compared to the homogeneous weld joint. This is probably the consequence of the not-too-low undermatching in the root region compared to the over-matched remaining WM portions (M~0.9).

The HAZ composite notch specimen was sampled WM-C (see **Figure 1**) on both sides, the CGHAZ at two points and the BM at the mid thickness section. At the fatigue-tip front a pronounced crack blunting and strain hardening over the whole mid thickness appeared in the BM with high fracture toughness due to the over-matched WM properties of the homogeneous weld joint. The first unstable event appeared in the CGHAZ region as a small pop-in with the crack deviation from the fusion line towards the BM. Because of the lower WM fracture toughness two LBZs appeared later where the crack tip is sampling the WM. This is the consequence of the WM matching condition attained due to the blunting and strain hardening of the softer BM. The crack tip was no longer protected, whereas a ductile fracture of the mid section followed in the plane which deviates due to the overall weld-joint over-matching condition towards the BM. In the case of the same heterogeneous weld-joint HAZ sampling, the soft root layer did not change the fracture properties either. This can be seen from **Figure 7b**. CGHAZ at the fusion line was again the position of the LBZ spreading into less tough over-matched WM. The reason was the same as described for the WM fracture. The under-match was not low as to affect the fracture path as can be seen in the case when using lower undermatched properties, M<0.8, and the fracture is directed by a soft root layer as shown in **Figure 7c**.

3.2 Fracture properties of an under-matched weld joint

For the WM specimens taken from the under-matched homogeneous weld joints "pop-ins were expected at the LBZ's weld root where the 2H/(W-a) ratio is the smallest. These expectations were not fulfilled and were probably due to the over-matched shielding effect which is evident in the root region and can be clearly seen in **Figure 3b**. The weld width (2H~30 mm) at the weld cap is approximately the same as the size of the uncracked ligament (W-a~35-40 mm). Therefore, the brittle-fracture initiation points appeared in the softest WM region where 2H is much smaller than the uncracked ligament. The LBZs appeared in the areas of the lowest M value (see **Figures 3b** arrows). After the initiation the main brittle-fracture event appeared at the root as a consequence of a sudden rise in the stress intensity and lower toughness. For the WM specimen taken from the under-matched heterogeneous weld joint with soft root layer the "pop-in" appeared at the LBZ's weld root where it was expected, due to the softest weld-joint portion and due to the lowest tough region as the consequence of theb BM dilution. The CTOD fracture toughness is slightly lower compared to the homogeneous WM as can be seen from the **Figures 8 and 9**. A fracture example for both weld joints CTOD(δ_5) versus Δa is given in **Figure 9**.

The behaviour of the HAZ specimen taken from the homogeneous under-matched weld joint precracked by the composite notch through WM-C, HAZ, WM-C was a result of higher HAZ hardness and over-matched conditions in the root region as the appearance of visible LBZ in the remaining WM with the lowest M. After the LBZ crack initiation a rise in the stress intensity of the tempered HAZ and the remaining BM took place. A final ductile fracture across the HAZ with a deviation into the tougher BM in the middle of the specimen was the consequence. CTOD(δ_5) versus Δa for the HAZ composite notched SENB specimen is also given in **Figure 9**. The behaviour of the HAZ specimen taken from the heterogeneous under-matched weld joint with soft root layer was quite different. After the LBZ crack initiation at the CGHAZ and the remaining WM the soft root layer was the cause of the fracture-path transformation into the soft layer with poor toughness. The lowest CTOD fracture toughness is the consequence, which can be seen from **Figure 8 and Figure 9**.

Finally, in **Figure 10**, the CTOD(BS) and CTOD(δ_5) values are compared for homogeneous and heterogeneous over- and under-matched weld joints. Discrepancies in the CTOD data shown, also suggested by other research [9,20], can be recognised. This is probably the consequence of local strength inhomogeneities, and no general rule is available at present on how to use the proper value of the yield stress in CTOD standard formulations. A local CTOD(δ_5) technique offers a potential advantage when mismatched weld joints are tested. This is especially important in the case presented this paper where local mismatch is the dominating mechanical effect because of the low WM toughness level [21].

The above discussion is based on detailed metallographical examinations (LM and SEM) by using the sectioning method to determine the LBZ initiation points, fatigue crack tip microstructure at the initiation point, and the fracture deviation nature.

The results were achieved on weld joints made of the Q+T HT80 type, which were used frequently for high-pressure penstocks with large diameters and thick walls. We are convinced that the presented philosophy of soft-root-layer use can also be applied to pressure vessels steel weld joints which are recently made of lower strength steels as the HT 80 steel.

4 CONCLUSIONS

An experimental programme to compare the strength and toughness properties of a mismatched weld joint produced on quenched and tempered HT 80 steel has been carried out. The results can be summarised as follows:

4.1 It was found that besides the global mismatch defined as the ratio of the average WM and BM strengths, very distinctive strength differences in the through thickness exist (local mismatch) in over- and undermatched homogeneous weld joints for the WM and HAZ. This can be clearly shown by measuring the micro-hardness. In the under-matched WM the local mismatch is mostly the consequence of dilution and alloying from the BM, whereas in the overmatched WM local quenching and tempering is more important. The local mismatch can be the dominating mechanical effect controlling the fracture behaviour in areas with low toughness.

4.2 Introducing the soft root layer is beneficial for the overmatch weld joint if the root mismatching is not lower than M=0.9 and the heterogeneous weld joint behaves as a homogeneous joint. This means that lower preheating or even its omission is possible. Introducing the soft root layer into the undermatched weld joint is due to the root overmatching condition, the obligation to prevent sensitivity to cold cracking and to reduce or even to omit the preheating.

4.3 Charpy impact toughness values of both the undermatched and overmatched weld joints were similar in the HAZ but in the WM they were lower for the over-matched condition. The lowest toughness of the under-matched WM was observed in the root region, whereas for the over-matched WM it was in the cap region. A soft root layer for the over-matched weld joint has to be selected by the filler metal not lower than M=0.9. The better root portion impact toughness compared to the remaining WM portions is the consequence. For the under-matched weld joint the soft root layer introduction was not beneficial and due to the formation of the M/A constituents as an affect of the root layer alloying, the lowest weld-joint impact toughness appeared.

4.4 The CTOD fracture toughness values measured on the SENB-Bx2B specimens (a/W=0.5) with the notch in the WM were lower for both mismatched homogeneous weld joints than those with the HAZ composite notch. LBZs appeared in both mismatched homogeneous weld joints in the CGHAZ, followed by a more-or-less brittle fracture spread into the less tough WM and at the end the ductile fracture followed through the BM. In the under-matched WM a local root over-matching condition prevented a fracture initiation at the root despite its lower toughness and the brittle-fracture initiation (LBZ) has appeared in the local lowest strength WM area. An introduction of the soft root layer did not change the HAZ and WM fracture behaviour of the overmatched weld joint. Because the heterogeneous over-matched weld joint with soft root layer behaves like the homogeneous joint, the recommendation for reducing or even omitting the preheating can be expressed by a suggested welding procedure. This is not the case when using a soft root layer for an under- weld joint. The poor root toughness of the HAZ and the WM precracked specimens and the deviation of the fracture path into the lowest tough root LBZs is the consequence. The use of a soft root layer to prevent cold cracking in an undermatched weld joint cannot be recommended, unless high toughness can be provided in this region.

4.5 The direct measurement of local CTOD(δ_5) provides CTOD values for which no material properties are required for the toughness calculation. This is particularly important in the case when treated crack-tip plastic zone involves different local microstructures of mismatched weld joints where the strength and toughness can vary substantially.

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