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WELD JOINT FRACTURE BEHAVIOUR OF HSLA STEELS DISSIMILAR IN STRENGTH

POTEK LOMA V ZVARNEM SPOJU DVEH TRDNOSTNO NEENAKIH VISOKOTRDNOSTNIH JEKEL

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Effect of strength differences (mis-match) between weld metal and two base metals as well as local variations of strength within weld metal/HAZ zones on the toughness properties are discussed. Significance of local fracture toughness measurement technique is also discussed by comparing the CTOD results of δ_5 and British Standard δ_{BS}. Some differences in two techniques are discussed in particular for CGHAZ toughness of similar and dissimilar joints.

Key words: strength mis-matching, hardness, materials, fracture toughness, fracture path

Obravnavan je vpliv trdnostne neenakosti med strjenim zvarom in dvema osnovnima materialoma, kakor tudi razlike v trdnosti med strjenim zvarom in TVP podro~ji, na lomne lastnosti. Poleg tega je obravnavan pomen tehnik merjenja lomne ‘ilavosti s primerjavo CTOD vrednosti δ_5 z δ_{BS} vrednostjo dobljeno po britanskem standardu. Obravnavane so bile nekatere razlike, ki nastopajo pri obeh tehnikah merjenja, posebno za GZTVP v istovrstnih in razli~nih zvarnih spojih.

Klju~ne besede: trdnostna heterogenost, trdota, materiali, lomna ‘ilavost, potek loma

1 INTRODUCTION

The narrow gap welding procedure is suitable for welding of thick sections because of beneficial arc operation and smaller base material dilution range and HAZ width when compared to conventional welding processes. Furthermore the narrow welding groove preparation enables lower weld joint misalignment and residual stresses. The technique can be particularly useful for welding of two steels of different strength with welding consumable which provides the weld metal (WM) strength properties in between. In this way substantial differences in strength properties (mis-matching) of two welded base materials (BM), WM, and both heat affected zones (HAZ) can occur particularly in the welded structures of high strength steels.

The aim of the present work was to establish the yielding behaviour and fracture toughness of WM and HAZ of similar and dissimilar weld joints of HSLA steels. The differences in mechanical properties among different weld regions affect the development of plastic zone and hence strain distribution around the crack tip during the fracture toughness test and consequently may influence the CTOD fracture toughness values. It is believed that both strength mis-match and toughness would control the fracture behaviour of the dissimilar weld joint depending on the testing temperature. Extensive amount of work is currently being carried out to understand the behaviour of mis-matched weld joints and to develop methodologies for treatment of this issue with respect to testing and defect assessment procedures.

Further the aim of this investigation was to determine the fracture toughness properties of similar and dissimilar weld joints and hence establishing the effect of neighbouring base plate strength (mis-match) on the toughness of HAZ and WM. This has been achieved by comparing the experimental CTOD results obtained from measurement of local δ_5 and standard fracture toughness evaluation techniques.

Furthermore, special treatment was given to the fatigue pre-cracking of CTOD specimens taken from as welded plate. If one uses the prescribed procedure of existing toughness testing standards (valid for uniform materials)[1-3], then the fatigue crack tip front will not be straight due to bi-modal residual stress distribution in thickness direction and the heterogeneous hardness distribution along the crack tip[4,5]. To overcome this problem the modified version of High R-ratio so called GKSS "Step Wise High R-ratio" (SHR) method is useful[6]. By using this method and taking into account the highest value of WM yield stress, more straight crack tip fronts are achieved for full thickness specimens made of as-welded weld joints.

2 MATERIALS, WELD JOINT AND EXPERIMENTAL PROCEDURE

Mechanical Properties and Mis-Matching Factor Determination

Commercial high strength low alloyed (HSLA) steels in thickness of 50 mm were used in quenched and tempered condition (Q+T) corresponding to grade HT50 and HT80. For welding of steel coupons narrow gap welding procedure was selected producing over-matched and under-matched BM similar weld joints. All weld joints were produced with the same welding consumable.

Chemical composition both BMs, real weld metal and original wire are presented in **Table 1**. The mechanical properties of base plates and WM regions of multi-pass weld joints are presented in **Table 2**. Due to the special feature of the dissimilar weld joints (two base materials) the strength mis-match factor M should be determined separately between WM and both sides of the weld joint (MHT50 and MHT80).

Table 1: Chemical composition of base plates and weld metal. Wire composition as provided by the manufacturer is also included

Tabela 1: Kemi~na sestava osnovnih plo{~ in dejanskega zvara. Navedena je tudi sestava varilne ‘ice.

Designation	Composition (wt%)									Pcm
	C	Si	Mn	P	S	Cr	Ni	Cu	Mo	
HT80	0.11	0.28	0.27	0.011	0.003	1.03	2.7	0.19	0.27	0.256
HT50	0.07	0.28	0.43	0.012	0.005	0.51	0.23	0.44	0.27	0.101
Weld Metal	0.084	0.34	0.32	0.026	0.009	0.13	2.15		0.02	0.205
Wire comp.	0.11	0.32	1.22	0.014	0.007	0.06	2.4	0.05	-	

Pcm - Cold cracking parameter

Table 2: Mechanical properties of base metal and dissimilar weld joint

Tabela 2: Mehanske lastnosti osnovnega materiala in zvara trdnostno neenakega zvarnega spoja

Designation	Y.S. (MPa)	U.T.S. (MPa)	Elongation (%)	Charpy (J) at -40°C	Mis-match Factor, M M_{HT80}	MHT50
HT80	690	765	23.0	70	-	
HT50	380	490	33.8	300	-	
WM cap	565	690	21	30(at 0°C)	0.82	1.49
WM middle	595	680	24	70(at 0°C)	0.86	1.57
WM root	585	665	22	0.85	1.54	
Average					Average	
WM	581.6	678.3	22.3	60(at 0°C)	0.85	1.53

M = $Y.S._{WM}/Y.S._{BM}$, M<1 - under-matching condition, M>1 - over-matching condition

The WM mechanical properties were determined by cylindrical tensile specimens extracted from the top, middle and root region, in the weld axis direction of the narrow gap welded joint shown in **Figure 1**. These data represent only the mechanical properties of regions were the specimens were taken from. The yield strength of the WM was calculated by using formula of σ_{yw} = 3.15HV-168 which is proposed for WM[7]. The WM HV1 hardness measurements with the distance of 1 mm between indentations in the three through thickness directions in **Figure 2** have provided the average values of distribution of WM mis-matching factor M across the weld joint, as shown in **Table 3**. They can be compared with those values in **Table 2**. The only exception was the very narrow band on both sides of the fusion line in the WM, the mis-matching factor was locally changed due to alloying/dilution mechanisms from base metal to molten pool and which can not be determined by standard all-weld metal cylindrical tensile specimens. These bands might affect the yielding behaviour at the vicinity of the crack tip and influence the value of locally measured CTOD.

The distribution of global/local mis-matching factor M calculated by hardness values over the weld joint is shown in **Figure 3**.

Table 3: WM mis-matching factor M distribution across dissimilar WM determined by average hardness values

Tabela 3: Porazdelitev M-faktorja skozi zvar dolo~ena preko povpre~nih vrednosti trdote

Mis-matching factor M								
	WM HT50					WM HT80		
WM hardness at fusion line	-0.15 mm	+0.2 mm	+1 mm	WM midd. line		+1 mm	+0.2 mm	-0.15 mm
Average hardness	217	223	225	225		224	227	274
M	1.36	1.40	1.42	1.42	0.78	0.78	0.80	1.14

$Y.S._{BMHT50}$ = 380 MPa $Y.S._{BMHT80}$ = 690 MPa

Series of Charpy impact toughness and full thickness SENB specimens were extracted from the weld joints. Charpy impact toughness specimens were taken from both BMs, CGHAZ, WM cap passes, WM upper section (between cap and middle passes) and WM middle passes. The specimen notch positions are shown in **Fig-**

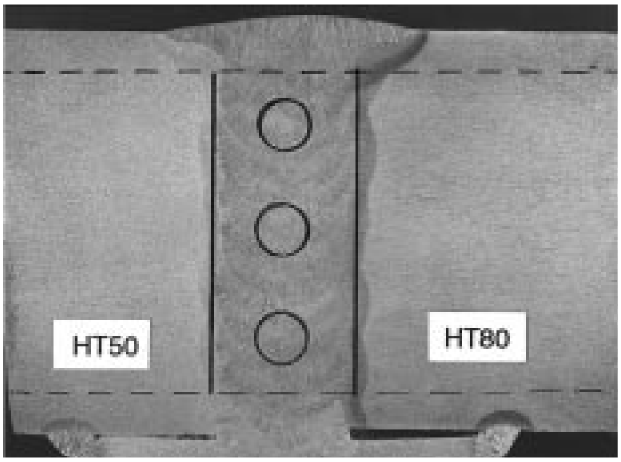

Figure 1: Macro cross showing the position of round tensile specimens and notches for WM and HAZ CTOD specimens

Slika 1: Prerez zvara z vrisanimi polo‘aji nateznih preizku{ancev in CTOD-preizku{ancev

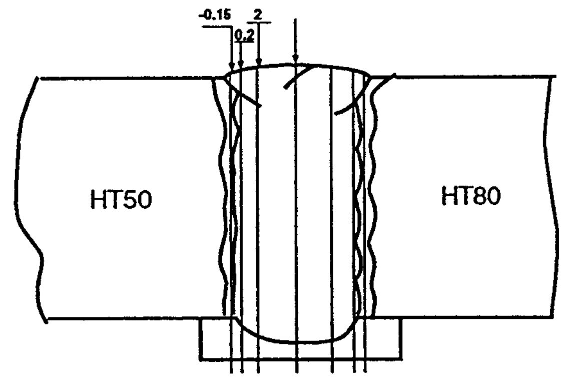

Figure 2: Hardness measurement directions in WM of dissimilar narrow gap weld joint

Slika 2: Podro~ja merjenja trdot v prerezu trdnostno neenakega zvarnega spoja z ozko re‘o

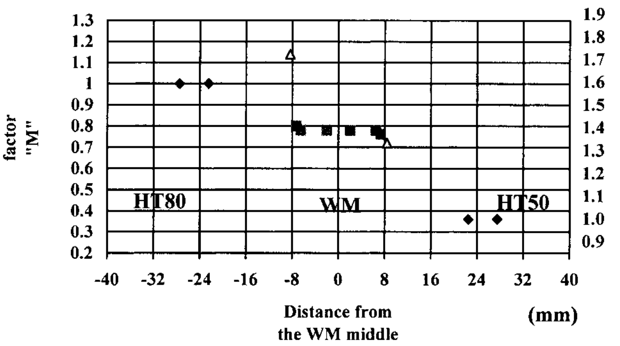

Figure 3: Global/local mis-match factor M in the dissimilar weld joint cross section

Slika 3: Globalni/lokalni M-faktor v prerezu trdnostno neenakega zvarnega spoja

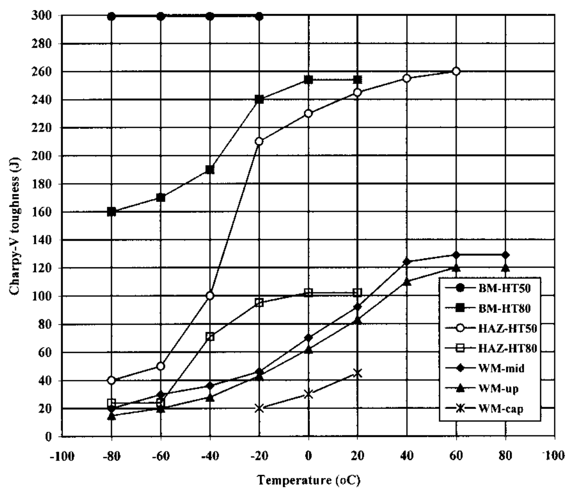

Figure 5: Charpy-V impact toughness values obtained from dissimilar narrow gap weld joint (see **figure 4**); two base metals, BM HT80 and BM HT50 curves are also included for comparison reason

Slika 5: Rezultati preizkusov udarne ‘ilavosti trdnostno neenakega zvarnega spoja z ozko re‘o (glej **sliko 4**); dodani so tudi rezultati osnovnih materialov BM HT80 and BM HT50 za primerjavo

ure 4. The geometry of SENB specimen was B x 2B (B = 40 mm). The through thickness fatigue cracks with ratio a/W ~ 0.5 were positioned in the WM and at the vicinity of the fusion line as shown in **Figure 1**. The testing temperature was -10°C, however some specimens were also tested at -20°C and +10°C. During the test DC potential drop technique was applied for stable crack growth monitoring[8]. The load line displacement (LLD) was also measured with the reference bar to minimise the effects of possible indentations of the rollers. The CTOD values were calculated in according to BS 5762 (δ_{BS})[1] and directly measured with GKSS developed δ_5 clip gauge on the specimen's side surfaces at the fatigue crack tip over gage length of 5 mm[9].

3 RESULTS

3.1 Charpy Impact Toughness

The results of the Charpy-V specimens are shown in **Figure 5** in terms of seven average transition curves which represent different notch locations.

The lowest Charpy toughness represents the material of WM at the weld cap position. The remaining WM material shows better impact toughness than in the cap layer but lower than both HAZs. Both BMs show excellent impact toughness and in fact all data of BM HT50 represent the upper shelf toughness.

Both HAZ transition curves are drastically decreased when compared to the original base plate curves, particularly at lower temperature regime. HT80 HAZ transition temperature is shown at approx. -40°C (~70 J) and for HT50 HAZ at approx. -35°C (~160 J). The upper and middle WM transition temperature is shown at approx. 0°C (~70 J) and for BM HT80 at approx. -40°C (~200 J) while BM HT50 shows in the whole tested region upper shelf values.

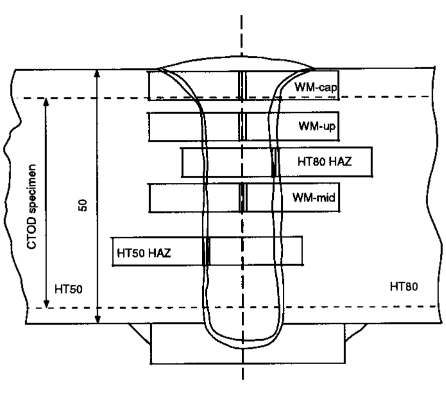

Figure 4: Charpy-V impact toughness specimens extracted from WM and HAZ of dissimilar narrow gap weld joint

Slika 4: Polo‘aj Charpy ‘ilavk v prerezu trdnostno neenakega zvarnega spoja z ozko re‘o

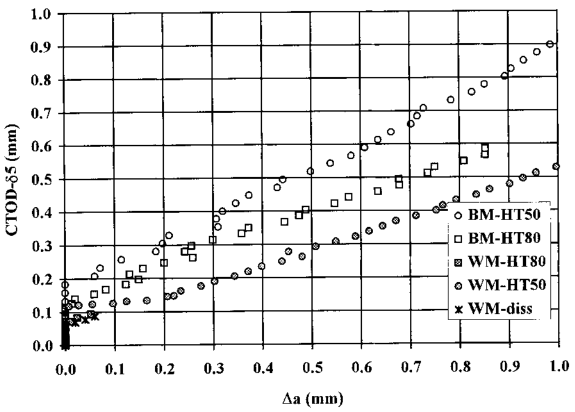

Figure 6: WM and BM R-curves for similar and dissimilar narrow gap weld joints

Slika 6: Odpornostne krivulje osnovnih materialov in zvarov istovrstnih in trdnostno neenakih zvarnih spojev

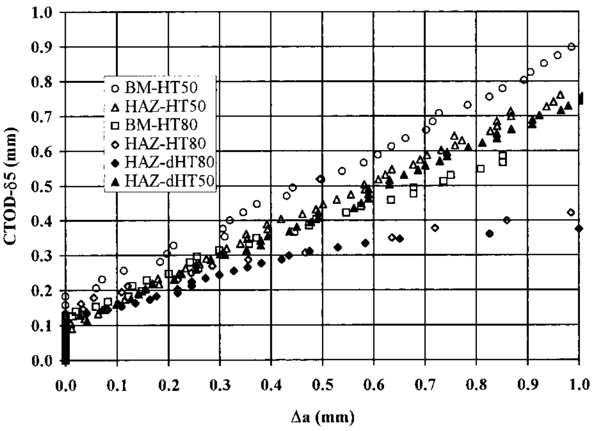

Figure 7: HAZ and BM R-curves for similar and dissimilar narrow gap weld joints
Slika 7: Odpornostne krivulje osnovnih materialov in TVP istovrstnih in trdnostno neenakih zvarnih spojev

3.2 CTOD Fracture Toughness

In **Tables 4 and 5** the typical values of "apparent" CTOD fracture toughness and stable crack initiation toughness, CTOD at Δa = 0.2 mm is intrinsic fracture toughness for both, CTOD(BS) and CTOD(δ_5) are presented to show typical differences. All measured δ_5 values are corrected due to difference between average a_o (because of penny shaped fatigue crack front) and the δ_5 clip gauge position on both specimen sides in accordance with the proposal in reference[10]. According to this proposal the following formula (1) for δ_5 correction was used:

$$\delta_{5_{corr.}} = \delta_5 \frac{(W-a_o)r_p}{(W-a_o)r_p+a_o-a_{\delta 5}} \qquad (1)$$

δ_5 = sides surface measured CTOD at the crack tip
W = specimen depth
a_o = average specimen half crack length
r_p = rotation factor
$a_{\delta 5}$= half crack length measured at the specimen sides surface

In **Table 4**, the SENB CTOD values for each weld joint made on similar BM while in the **Table 5** the SENB CTOD values for weld joint made on both dissimilar BMs are presented. In **Figure 6**, the R-curves which represent the lowest CTOD values for both similar and dissimilar weld joints WMs compared to BMs R-curves are shown, while in **Figure 7** the R-curves which represent the lowest CTOD values for both dissimilar and similar weld joints HAZs compared to BMs R-curves are shown.

Figure 8 presents one of the dissimilar WM specimen failure behaviour; fracture path deviation towards lower strength HT50 base metal and occurrence of brittle fracture at the fusion line.

Table 4: SENB CTOD values of BM HT50 and HT80 and their weld joints
Tabela 4: CTOD vrednosti osnovnih materialov in njunih zvarnih spojev

Material/weld joint, Testing temperature	Δa (mm)	CTOD δ_5 corr. (mm)	CTOD δBS (mm)	CTOD δ_5 Δa=0.2	CTOD δBS 0.2mm (mm)	a_o meas. (mm)	$a_{\delta 5}$ meas. (mm)
BM-HT80	1.02	0.540	0.620	0.222	0.267	41.6	40.4
at -10°C	0.85	0.566	0.549	0.242	0.243	43.9	41.6
"	0.38	0.334	0.376	0.233	0.265	41.1	40.5
BM-HT50	2.57	2.424	2.435	0.405	0.405	43.4	40.0
at -10°C	2.95	2.685	2.723	0.314	0.310	43.5	40.3
"	2.68	2.525	2.667	0.281	0.289	42.5	40.0
WM-HT80	0.51	0.251	0.305	0.165	0.202	42.0	42.0
at -10°C	0.13	0.154	0.190	-	-	41.2	41.2
"	0.05	0.098	0.125	-	-	41.4	41.4
"	0.11	0.142	0.183	-	-	41.6	41.6
WM-HT50	3.19	2.076	2.218	0.199	0.247	41.0	40.6
at +10°C	2.34	1.367	1.521	0.189	0.239	41.1	40.4
at -10°C	0.22	0.070	0.123	-	-	42.5	41.5
"	2.07	1.260	1.277	0.218	0.260	41.8	40.0
"	2.10	1.066	1.260	0.136	0.190	41.5	40.8
at -20°C	0.07	0.072	0.097	-	-	41.9	41.1
HAZ-HT80	0.84	0.609	0.697	0.259	0.294	40.5	40.3
at -10°C	0.48	0.312	0.346	0.227	0.252	41.2	40.2
"	0.89	0.526	0.635	0.203	0.247	40.6	40.2
HAZ-HT50 at +10°C	2.28	1.863	2.429	0.273	0.349	39.5	39.5
at -10°C	2.35	1.841	2.362	0.241	0.339	40.0	40.4
"	2.62	1.994	2.603	0.263	0.376	39.4	40.4
"	2.67	2.162	2.766	0.309	0.290	40.1	41.4
"	2.67	2.280	2.712	0.286	0.340	39.5	40.0

4 DISCUSSION

It was expected that global mis-matching ahead of the crack tip would play an important role in yielding behaviour, crack initiation and fracture path development in dissimilar weld joint. These result from the complex mis-match condition which govern in the dissimilar weld

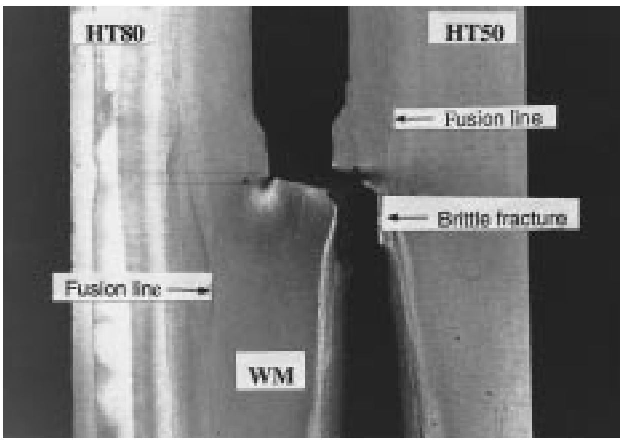

Figure 8: Fracture initiation in the weld metal, slow crack growth deviation to BM HT50 and brittle fracture propagation along the fusion line on WM side
Slika 8: Za~etek loma sredi zvara, stabilna rast razpoke do osnovnega materiala BM HT50 in krhki lom vzdol' linije zlitja znotraj zvara

Table 5: SENB CTOD values of BM HT50 and HT80 dissimilar weld joints

Tabela 5: CTOD vrednosti trdnostno neenakih zvarnih spojev jekel HT50 and HT80

Material/weld joint, Testing temperature	Δa (mm)	CTOD δ_5 corr. (mm)	CTOD δBS (mm)	CTOD δ_5 Δa=0.2	CTOD δBS 0.2mm (mm)	a_o meas. (mm)	$a_{\delta 5}$ meas. (mm)
WM	2.05	0.905*	1.160	-	0.245	40.4	40.1
at -10°C	0.06	0.083°	0.098	-	-	40.1	39.8
"	0	0.088°	0.108	-	-	41.1	40.4
"	4.12	2.473**	2.800	0.150	0.216	36.5	38.7
HAZ-HT80	0.74	0.350	0.640	0.175	0.319	39.8	38.9
at -10°C	0.63	0.392	0.650	0.216	0.346	38.3	38.8
"	1.12	0.676	1.110	0.231	0.368	38.2	38.2
"	0.53	0.323	0.690	0.187	0.383	37.5	38.7
HAZ-HT50	3.18	2.272	2.470	0.186	0.253	44.1	40.7
at -10°C	3.05	2.289	2.930	0.243	0.325	37.9	38.7
"	3.01	2.651	3.040	0.273	0.377	38.1	39.5
"	2.68	0.939	2.630	0.073	2.63	37.8	38.5

* Fracture initiation started at the WM middle and stable crack growth deviated towards the HT50 BM but arrested in the WM (δ_m)

**Fracture initiation at the WM middle section and stable crack deviated towards HT50 BM, passed WM and at the weakest ICCGHAZ portion of HAZ the brittle fracture occurred following the fusion line (δ_u)

° Fracture initiation at the WM and crack remained in WM as LBZ (δ_c)

joint due to different strength and toughness micro structural properties near the fusion line area.

4.1 Weld Joint Impact Toughness

The lowest Charpy impact toughness was obtained WM in the cap region, however in general dissimilar weld metal joint showed lower toughness compared to both base plates, **Figure 5**. From this observation it can be concluded that WM produced by narrow gap welding dissimilar steels would be the most sensitive portion and potential region for LBZ occurrence.

4.1.1 Weld Metal Fracture Toughness

The lowest fracture toughness of dissimilar WM is in two cases equal to some cases appearing in both similar WMs. One can compare the lowest value for both similar and dissimilar WM in **Table 4 and 5**. This fracture behaviour is governed by microstructural toughness and fracture initiation following the WM dendrites grain boundaries as brittle fracture. In other cases, where the fracture toughness was higher, obviously the fracture initiated and propagated through tougher WM regions by ductile crack growth mechanism. In the two remaining dissimilar weld joint cases the fracture is governed by lower HT50 strength properties of HT50 steel. **Figure 8** shows the fracture initiation at the WM and crack, which deviated by slow growth toward HT50 BM. At the weakest HAZ-ICCGHAZ area, before the crack reached BM-HT50- **Figure 9**, the brittle fracture occurred following the unfavourable less tough fusion line. It seems that crack initiation and propagation behaviour in dissimilar weld joints is rather a complex event. We assume that crack propagation after crack initiation in this case was governed by HT50 lower strength properties until the vicinity of higher toughness HT50 HAZ was reached where the fracture was further governed by toughness properties which were lower in ICCGHAZ near the fusion line. So, it its clearly shown that strength mis-match in combination local material properties can affect the fracture behaviour. Similar behaviour has occurred also in another specimen in which the max. loading was attained before fracture occurred and before ductile crack growth has reached the HAZ HT50 fusion line. As mentioned earlier, fracture behaviour has shown high CTOD fracture toughness in both specimens as it can be seen from **Table 5**. It seems that elongated dendrites offer high resistance against fracture propagation perpendicularly to their primary axis.

The R-curves, **Figure 6**, present the results of both similar WMs (provided on HT80 and HT50) and dissimilar WM comparing to both BMs. The lowest value of CTOD fracture toughness is for all three WMs rather equal (0.07 mm for WMHT50, 0.098 mm for WMHT80 and 0.083 mm for WM diss.) and bellow initiation at Δa = 0.2 mm. The similar WM-HT80 has shown some amount of crack extension before fracture while WM-HT80 and dissimilar WM specimen have failed immediately after crack initiation. Unstable events are designated by the arrows on **Figure 6**. On the other hand and as shown in **Table 4 and 5** higher fracture toughness values are predominant for other specimens.

Obviously, the CTOD testing in accordance with standards valid for uniform materials (a/W ~ 0.5) is too conservative for toughness assessment of welded joints provided on HSLA steels. This conclusion results also from the fact that LBZ can appear after some amount of slow crack growth also in HT80 BM despite its high impact toughness as it can be seen from **Figure 6** and **Figure 5**. It would be better to evaluate weld joints (also produced on dissimilar steels) by testing wide plate specimens where the constraint conditions are approx. similar to weld joints operating under their full loading.

4.1.2 HAZ Fracture Toughness

Average HAZ similar weld joint fracture toughness presented in **Table 4** (HAZ-HT80, HAZ-HT50) is in the same order of magnitude when compared to the average HAZ dissimilar weld joint fracture toughness (HAZ-HT80, HAZ-HT50) presented in the **Table 5**. From both tables one can recognise that HT80 HAZ shows lower fracture toughness than HT50 HAZ. This is understandable due to the lower steel strength level but higher impact toughness of the later. Some of specimens tested did not show any instability until the end of testing. This is the consequence of excellent BM toughness and of the influence of narrow gap welding procedure where the heat input direction does not attack the BM in the way as

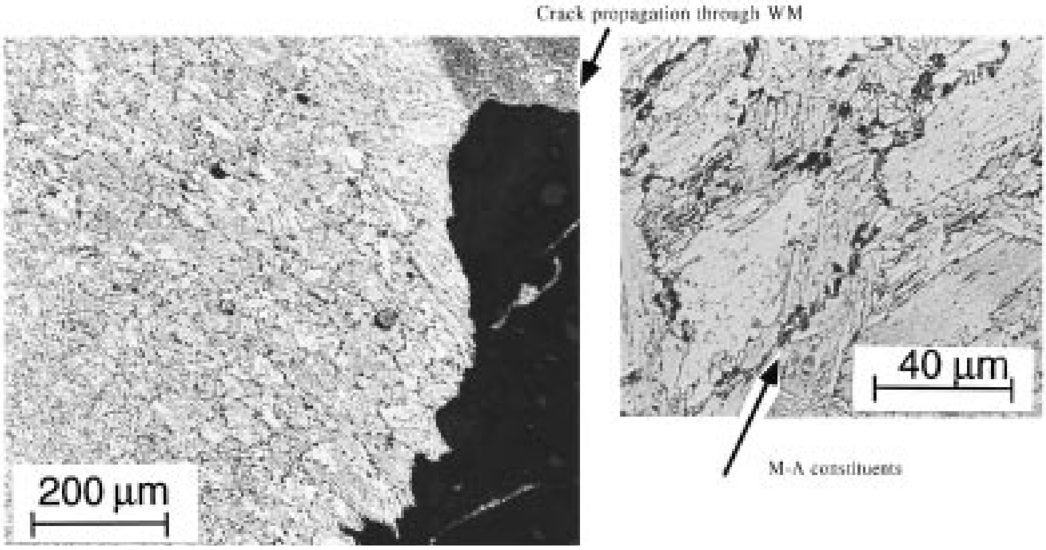

Figure 9: Slow crack growth passing WM at ICCGHAZ (coarse grain M-A constituents) area transformes into brittle fracture mode
Slika 9: Stabilna rast razpoke na prehodu iz zvara v podro~je IKGZTVP preide v krhki lom

it does by welding of conventional bevelled weld joints (X,V,K grooves).

CTOD fracture toughness of HAZs is much better comparing to similar and dissimilar WMs. Their lower band toughness is presented by R-curves comparing to R-curves of BMs on **Figure 7**. In all cases considerable crack extension was recognised before fracture occurred or before reaching the max. loading value. The events where the instability has occurred mainly at the crack extension higher than 1.0 mm as shown are designated by arrows in the figure. The behaviour of HAZ HT80 specimens taken from similar and dissimilar narrow gap weld joints was quite interesting. At testing LBZ appeared in WM after initiation and after transferring the slow crack growth to softer WM. Obviously the influence of softer WM and HT50 BM, comparing to HT80 BM on the crack tip was essential for the development of the plastic zone in WM and the measured CTOD fracture toughness does not represent the toughness property of similar and dissimilar HAZ HT80. This can be observed in **Figure 7** for HAZ-HT80 in similar weld joint and HAZ-dHT80 dissimilar weld joint. The fracture behaviour of both R-curves is similar after the crack entering into WM.

The HAZ-HT50 fracture toughness for similar and dissimilar weld joint does not represent the real toughness properties as well. The fracture initiates at the HAZ-HT50, but later deviates into the BM-HT50 due to WM-HT50 over-matching properties.

It seems that CGHAZ fracture toughness testing should be modified/changed. The crack tip location perpendicular to weld joint direction a few mm before fusion line on straight HAZ side offers a good solution for CGHAZ fracture toughness determination.

5 CONCLUSIONS

An experimental programme has been carried out to compare strength and toughness of mis-matched narrow gap weld joints produced on two HSLA steels in BM similar and dissimilar state by the equal weld consumable.

The results of this research work can be summarised as follows:

1. Due to the beneficial arc operation by narrow gap welding procedure of two dissimilar BMs the base material dilution range as the HAZ width range are smaller than in conventional welding processes. The consequence of it is clearly expressed as global strength mismatch condition. It seems that the only exception is very narrow band along the fusion line on the WM side where weak local mis-matching can appear.

2. Charpy impact toughness in WM and HAZ is for similar and dissimilar weld joint approx. on the same level. The lowest impact toughness is revealed at WM cap layer where the hardness is the highest and no beneficial tempering heat from the subsequent passes is available. The impact toughness of WM is lower than that of both BM HAZs.

3. WM CTOD fracture toughness is in both similar weld joints in some cases good enough in some cases very low. Obviously, the fracture initiation depends on fatigue crack angle to dendrites orientation and either the crack tip is sampling particles/impurities on the dendrite grain boundary or is located in the grain matrix. The same can appear in the dissimilar weld joint. But in case of slow crack growth the crack deviates in the direction of the softer BM. When the fracture passes through WM the brittle fracture can appear if the crack tip reaches the

local less tough ICCGHAZ area before BM with high toughness.

It seems that the fracture initiation and propagation is complex and can be governed by toughness and strength properties around the crack tip.

4. The dissimilar weld joint HAZ CTOD fracture toughness is excellent comparing to WM CTOD one. HAZ toughness of the BM with higher strength can be overestimated due to effect of softer WM and propagation of the crack from HAZ perpendicular to WM dendrites. The same can be recognised for HAZ toughness of the BM with lower strength due to softer BM and crack deviation from CGHAZ to BM.

5. Two CTOD measurement methods used (CTOD δ_5 and CTOD δ_{BS}) especially on dissimilar weld joints have shown in some cases huge differences. Once again it was shown, how important the local measurement is without the need to infer from remotely measured quantities. All measured CTOD δ_5 values were corrected due to difference between average a_0 and the δ_5 clip gauge position on both specimen sides in accordance with the mentioned proposal.

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