38th International Conference
Experimental Stress Analysis
Třešť, Czech Republic, 6 - 8 June 2000
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pp. 281/288

FRACTURE BEHAVIOURS OF FRACTURE TOUGHNESS TESTING SPECIMENS WITH HETEROGENEITY ALONG CRACK FRONT

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Abstract

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

Key Words:
High Strength Low Alloyed Steel, CTOD Fracture Toughness Testing, CTOD-R Resistance Curve, Welded Joints

1. Introduction

Welding of high strength low alloyed (HSLA) steel to produce undermatched weld joint presents a technological challenge for modern welded structure production. When the yield point is lower in the weld metal compared to the base material the welded joint is undermatched. The strength mismatch factor (M) is defined as the ratio of weld metal to base material yield strengths, so that $M < 1$ defines an undermatched welded joint.

Undermatched welded joints are used for repair welding of joints damaged during hard operation conditions or by short-period overloading [1]. They are also recommended to prevent hydrogen cracking without preheating, specially for welded joints made of HSLA steels with yield strength above 700 MPa.

Crack tip opening displacement (CTOD) as a fracture toughness parameter is determined as the lowest toughness of different microstructure along crack front, according to the weakest link model [2]. In the case of undermatched welded joints the redirection of stable crack growth toward low strength materials occurs [3]. It means that the obtained critical value of fracture toughness can be higher for mis - matched welded joints, even if local brittle zones (LBZ) exist in the crack tip process zone. Therefore, the aim of this paper is to analyse fracture behaviour of under-matched welded joints, and also to determine relevant parameters which contribute to higher critical values of fracture toughness. Toward this end three differently under-matched welded joint were analysed using results of testing the composite notched specimens with through thickness crack front positioned partly in the weld metal, partly in heat affected zone (HAZ) and partly in base material (BM).

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2. Experimental procedure

High strength low alloyed HSLA steel in a quenched and tempered condition, corresponding to the grade HT 80, was used. The Fluxo Cored Arc Welding process (FCAW) was used and two different tubular wires were selected. Three different type of global undermatched welded joint were produced, one homogeneous and two heterogeneous. Homogeneous welded joint was made with preheating and postheating of the base material, entirely with the same consumable (wire WELTEC B 575). Two different types of heterogeneous welded joints were made using a softer consumable (wire WELTEC B 370) for the soft root layer, one with two and the other with four passes, in order to avoid preheating of the base material and to prevent cold cracking. The filler passes were made with the wire WELTEC B 575, as well as the cap passes.

Weld metal mechanical properties were determined by round tensile specimens extracted from the root and the filler region of X–groove welds in the weld direction. The expected mechanical properties of homogeneous and heterogeneous undermatched welded joints have been reached neither in the filler region, nor in the root region, as shown in Tab. 1. The reason was weld metal alloying with elements from the diluted base metal.

Table 1. Mechanical properties and chemical composition of homogeneous and heterogeneous undermatched weld joints.

Designation	R_p [MPa]	R_m [MPa]	Elongation [%]	Charpy V [J] at -10^{O} C	Expected M	Achieved M
Base material						
HT 80	693	830	19.6	79, 78, 64	-	-
Homogeneous weld joint - filler material WELTEC B 575						
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
Heterogeneous weld joint - filler material WELTEC B 370 in the root (the rest WELTEC B 575)						
WM - 2x soft root passes	567	625	19.7	-	0.56 at the root	0.81 at the root
WM - 4x soft root passes	631	673	21.9	35, 17, 34	0.56 at the root	0.91 at the root

Composition [%]	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al	Ti	Nb
WM hom. - cap	0.04	0.44	1.48	0.010	0.009	0.12	1.63	0.49	0.12	-	-	-
WM hom. - root	0.10	0.33	0.89	0.013	0.008	0.73	1.11	0.42	0.13	-	-	-
WM - 2x soft passes	0.12	.041	0.78	0.015	0.006	0.40	0.10	0.17	0.16	-	-	-
WM - 4x soft passes	0.10	0.33	0.78	0.012	0.007	0.24	0.13	0.11	0.13	-	-	-

The alloying effect was more pronounced in the root region than in the filler region, and it was also the main reason for local strength mismatch appearing in thickness direction of homogeneous and heterogeneous welds (see chemical analysis given in Tab. 1). Having in mind the values of strength mismatch factors M in Tab. 1 one can see that the root in homogeneous weld metal is actually overmatched ($M=1.05 \Rightarrow 5\%$ overmatching), which leads to strongly increased cold cracking susceptibility, whereas the filler region has practically the same strength as the base material (M = 0.99). This effect approves the concept of heterogeneous weld in undermatched joint with two-pass (M=0.81 ⇒ 19% undermatching) or four-pass (M=0.91 ⇒ 9% undermatching) soft root layer in order to prevent cold cracking without preheating of the base material. For CTOD testing the single specimen method was used at testing temperature -10^{O}C. To evaluate fracture toughness of undermatched welded joints standard [5,6] single edge notched bend (SENB) specimens (B x 2B, B = 36 mm) with crack tip (a/W = 0.5) encompassing the weld metal, HAZ and base material were used (Fig. 1).

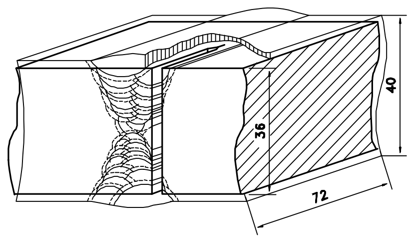


Figure 1. Location of fatigue pre-crack tip in the welded joint

For all specimens the fatique precracking was carried out with the GKSS Step-Wise High R ratio method (SHR) procedure [4]. During the CTOD tests the DC potential drop technique was used for stable crack growth monitoring. The CTOD values were calculated in accordance with BS 5762 (δ_{BS}) [5] and also directly measured by GKSS [7] developed δ_5 clip gauge on the specimen side surfaces at the fatique crack tip over a gauge length of 5 mm (Fig. 2).

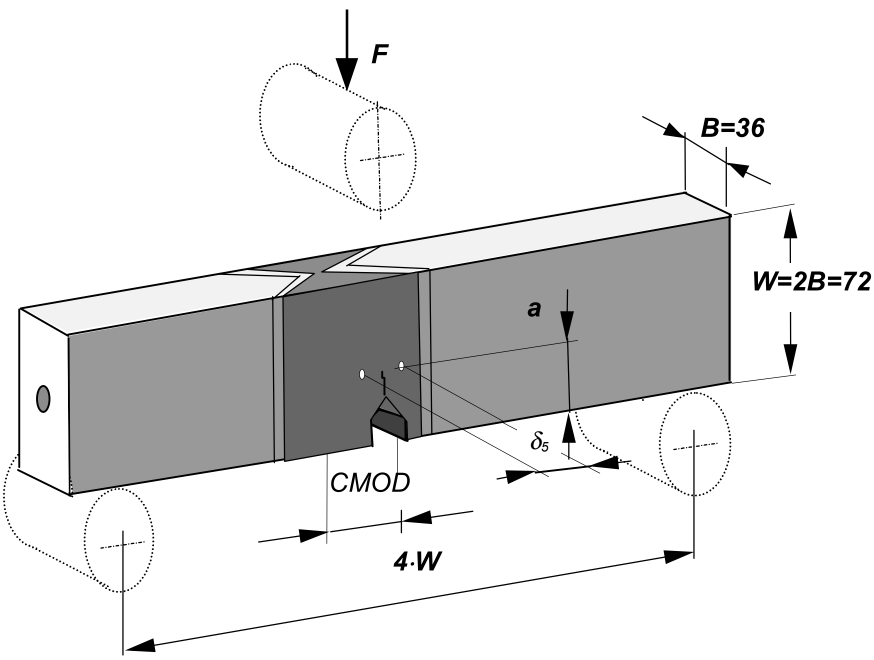
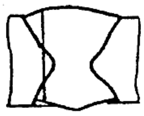
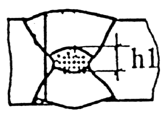
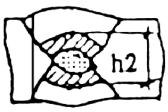


Figure 2. Three point bending specimen (Bx2B) and measuring points (CMOD, δ_5)

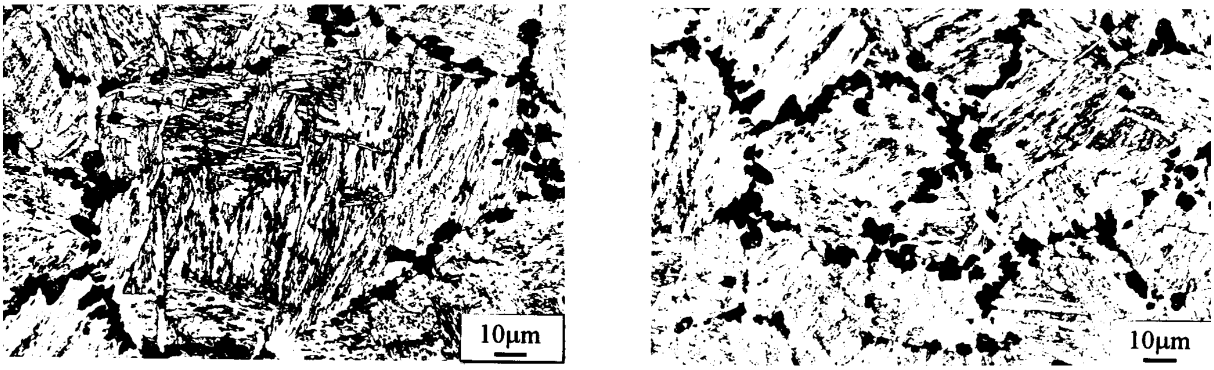
3. Results and discussion

HAZ fracture toughness is relatively high and in the case of homogeneous weld it is much higher than the base material toughness (Tab. 2).

Table 2. Measured (δ_5) and calculated (δ_{BS}) CTOD fracture toughness values for composite notched specimens B x 2B with deep crack (a/W = 0.5) in homogeneous and heterogeneous undermatched weld joints

Crack depth (a/W = 0.5)	CTOD (δ_5) (mm)	CTOD (δ_{BS}) (mm)	Estimation δ (mm)	Δa (mm)	$\delta_{i(0.2)}$ (mm)	δ_i (mm)
HAZ	0.336	0.390	δ_u	0.305	0.277	0.151
	0.219	0.366	δ_u	0.266	0.196	0.121
	0.317	0.349	δ_u	0.592	0.230	0.132
	0.267	0.249	δ_u	0.498	0.187	0.131
	0.178	0.188	δ_c	0.104	-	0.142
HAZ	0.227	0.279	δ_u	1.611	0.086	0.076
	0.191	0.248	δ_u	0.570	0.130	0.080
	0.159	0.194	δ_u	0.414	0.135	0.112
	0.156	0.195	δ_c	0.227	0.143	0.090
	0.081	0.104	δ_c	0.008	-	-
HAZ	0.093	0.091	δ_c	0.010	-	-
	0.157	0.154	δ_c	0.055	-	0.125
	0.200	0.186	δ_u	0.350	0.159	0.118
	0.200	0.277	δ_u	0.363	0.147	0.082
BASE MATERIAL	0.256	0.247	δ_u	0.240	0.239	0.109
	0.237	0.263	δ_u	0.253	0.225	0.096
	0.200	0.232	δ_u	0.231	0.183	0.101

One of the reasons for high toughness in the HAZ was composite fatigue crack front, including narrow HAZ region with the coarse grain (CG) HAZ of extremely low fracture toughness (LBZ), but the remaining part, i.e. most of the fatigue crack front sampled the tougher weld filler metal, base material and remaining fine grain HAZ (fine grain (FG) and intercritical (IC) HAZ). From Tab. 2 it is clear that the HAZ fracture toughness is much higher for homogeneous weld than for heterogeneous one. The main reason for this was different root welding heat input energy [3], causing different width of HAZ in the root region of homogeneous and heterogeneous weld, and consequently affecting initiation of the final brittle fracture of the specimen. Namely, the distance of fatigue crack tip front from the fusion line was approximately the same ($\approx$ 3.5 mm) for the CTOD specimens with and without soft root layer, cf, Praunseis [9].

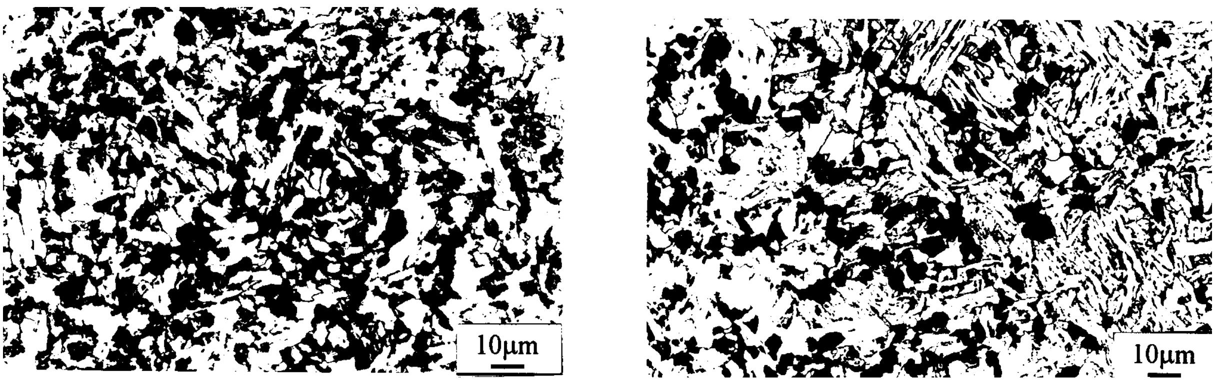


a) b)

Figure 3. CG HAZ with bainitic - martensitic microstructure, which was subsequently heated at temperature between A_{c1} and A_{c3} i.e. IC CG HAZ with distributed brittle M-A constituents along grain boundaries of primary grains (ASTM 4) with directed bainitic microstructure in the HAZ of root region of homogeneous a) and heterogeneous b) under-matched welded joint

Apart from that, one must not forget that the fatigue crack was sampled CG HAZ of two different widths related to CG HAZ region of different grain sizes (Fig. 3), which has partially caused the appearance of brittle fracture origins and has influenced the HAZ fracture toughness of both welds.

In CTOD specimens with the crack in the HAZ of homogeneous weld brittle fracture initiation has started in a weld material with the lowest value of mismatch factor M because of the shielding effect of overmatched root weld metal. The LBZs were recorded during testing already as pop- ins [3, 8]. After that an increase in stress intensification followed in HAZ, leading to the final brittle fracture of the specimen through CG HAZ and base material, which has provided the final resistance in the specimen center. The origin of final brittle fracture appeared in tougher fine grain IC HAZ (Fig. 4a). Crack path deviated to the softer base material, due to shielding effect of root overmatched weld metal.



a) b)

Figure 4. Figure a) shows subsequently heated fine grained microstructure (IC HAZ) at final fracture of specimen with homogeneous weld joint.
Figure b) shows subsequently heated bainitic (with primary ferrite) coarse grained microstructure (IC HAZ) at final fracture of specimen with heterogeneous weld joint.

In the case of CTOD testing of specimens with soft root layer the first brittle fractures (LBZs) appeared in intercritical coarse grain (IC CG) HAZ (Fig. 3b), which were recorded as small pop-ins [3]. Due to high local strength mismatch between the base material and the soft root layer, the crack propagated towards the region of lower toughness, i.e. towards the fusion line and undermatched weld metal. The Fe_3C carbide was identified as the brittle fracture initiation point at the fracture surface using EDX analysis [3]. The effect of the soft root layer on the strain distribution along the fatigue crack front was so pronounced that it caused strain concentration in the soft root layer. Due to its low toughness this has initiated the final specimen fracture in coarse grain IC HAZ (Fig. 4b) and crack path deviation towards zone of the soft root layer, with further reduction of toughness level, which can be achieved with higher soft root layer toughness.

Classification of CTOD resistance curves (Fig. 5) for specimens with deep crack in HAZ confirms the above mentioned analysis and conclusions, that the HAZ fracture toughness of homogeneous welds is much higher than the HAZ fracture toughness of heterogeneous welds. By increasing the soft root layer thickness the HAZ fracture toughness of heterogeneous weld joint reduces and becomes lowest for the welded joint with a four-pass soft root layer, as it is clear from the classification of CTOD resistance curves in Fig. 5.

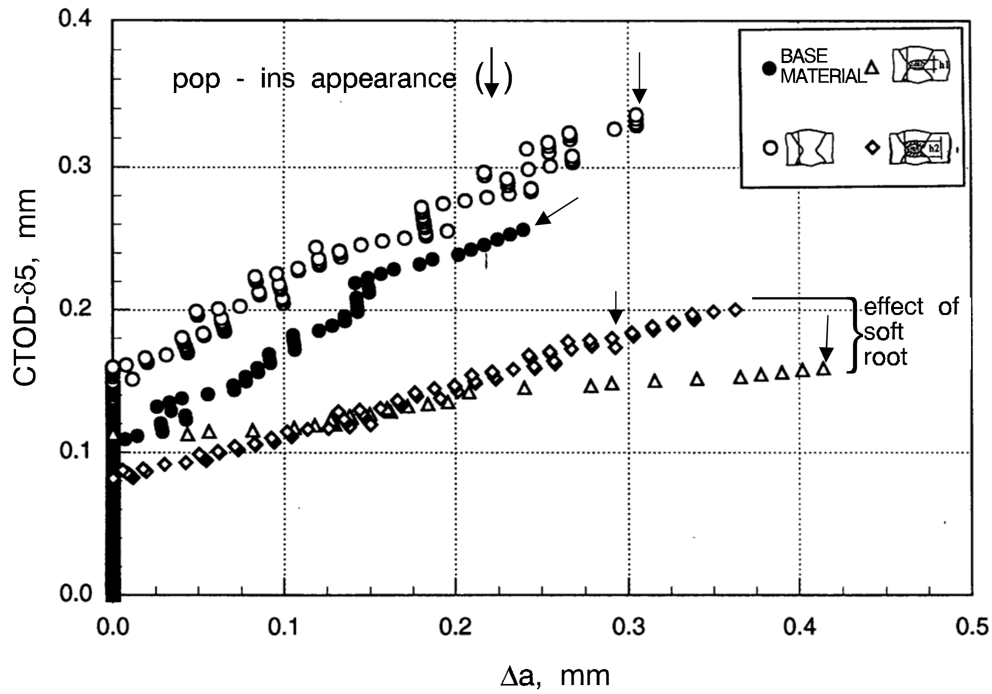


Figure 5. Resistance curves for specimens (B x 2B) with deep crack (a/W = 0.5) in the HAZ of homogeneous and heterogeneous undermatched weld joints.

From comparison of calculated (δ_{BS}) and measured (δ_5) CTOD values (Tab. 2) a good agreement is obvious, which is especially important to verify detailed and directly measured CTOD - δ_5 values, for which one does not need to know the yield strength and the rotation factor as in the case of CTOD - δ_{BS} calculated values. This is very important in cases where the fatigue crack tip front crosses regions with different strength levels and where the effect of local strength mismatch at the crack tip is significant, as shown for fracture behaviour of undermatched joints with homogeneous and heterogeneous weld metal. More detailed analysis shows that CTOD-δ_5 values are generally lower than CTOD-δ_{BS} values, thus being more conservative.

4. Conclusions

Fracture behaviour of specimens notched partly in the HAZ is strongly affected by microstructure at the crach tip. HAZ toughness improvement has been achieved due to its widening by higher input energy (Q + preheating) in the root region, so that one part of the fatigue crack tip front passed through the normalized fine grained HAZ region. The HAZ fracture toughness of heterogeneous weld is appreciably lower than the HAZ fracture toughness of homogeneous weld due to low ductility of the soft root layer, which has caused brittle fracture initiation of welded joint by deviating the fracture path from HAZ to the soft root layer.

Strength mismatch has a significant influence on the real values of HAZ fracture toughness. The values obtain in both examples are not the real values for HAZ fracture toughness, because they were influenced by higher portition of base material and weld root strength properties. Fracture deviation towards the base material (homogeneous weld) overestimates HAZ fracture toughness, whereas fracture deviation towards the soft root layer (heterogeneous weld) underestimates the HAZ fracture toughness. Therefore, HAZ fracture toughness determination is a complex problem which could be solved by synthetic multi-pass microstructures and their fracture toughness.

5. Acknowledgements

The authors wish to acknowledge the financial support of the Slovenian Foundation of Science and Technology, the Forschungszentrum Julich GmbH, Kocevar&Thermotron d.o.o, Aga Gas d.o.o and Arko d.o.o Slovenia is also noted for providing a financial support of this research program.

We also exprees special thanks for many useful discussions and contributions of Prof. Dr. K.- H. Schwalbe, Prof. Dr. B. Petrovski and Dr. M. Kocak.

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