THE INFLUENCE OF MICROSTRUCTURE
ON FRACTURE TOUGHNESS
OF UNDERMATCHED WELD METAL

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A set of $B \times B$ specimens was taken from homogeneous and heterogeneous welds and tested to obtain fracture behaviour of undermatched welded joints. The critical crack-tip opening displacement (CTOD), as the relevant parameter for safe service of welded structure, was used to evaluate the influence of microstructures. Surface cracks of different depths were positioned in weld metal with fatigue-crack-tip front in different microstructures. It was shown that selection of soft weld consumable (wire) does not guarantee tough root layer in the undermatched weld.

Key words: crack-tip opening displacement (CTOD), CTOD fracture toughness test-
ing, CTOD-R resistance curve, welded joints

VPLYV MIKROŠTRUKTÚRY NA LOMOVÚ HÚŽEVNATOSŤ
ZVAROVÉHO KOVU S NIŽŠOU POMERNOU MEDZOU SKLZU

Sústavu $B \times B$ vzoriek vybranú z homogénnych a heterogénnych zvarov sme testovali s cieľom zistiť lomové správanie zvarových spojov s nižšou pomernou medzou sklzu. Na vyhodnocovanie vplyvu mikroštruktúr sme použili kritické rozovretie vrcholu trhliny ako relevantný parameter pre bezpečnú prevádzku zváranej konštrukcie. Povrchové praskliny rozdielnych hĺbok boli umiestnené vo zvarovom kove s ukončenou únavovou trhlinou v rôznych mikroštruktúrach. Ukázalo sa, že vybraný mäkký prídavný materiál (drôt) nezaručuje húževnatosť koreňovej húsenice v danom zvarovom spoji.

1. Introduction

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

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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 pre-heating, especially, for welded joints made of HSLA steels with yield strength above 700 MPa. Namely, the HSLA steels usually require pre-heating if matching or overmatching welding consumable is used, which is not only expensive, but also needs a carefully designed and strictly followed welding procedure [3]. Finally, there is a frequent need for additional thermal or mechanical treatment afterwards.

One should pay attention to the level of strength mismatching which should provide sufficient toughness of the weld metal by using an appropriate welding consumable (wire, electrode) and welding procedure. High toughness of weld metal is necessary to enable local plastic deformation and to prevent brittle fracture. It is of utmost importance to exclude the possibility of plane faults (hydrogen cracking, lack of fusion, etc.) and local-brittle-zone (LBZ) appearance in HSLA steel undermatched welded joints, which can cause failure [2].

The aim of this research was to estimate the weld metal CTOD fracture toughness using standard procedures [5, 6, 7, 8] for three differently undermatched welded joints.

2. Materials and mechanical properties

High-strength low-alloyed HSLA steel in a quenched and tempered condition, corresponding to the grade HT 80, was used. The Fluxo Cored Arc Welding process (FCAW) was used and two different tubular wires were selected. Three different types of global undermatched welded joint were produced, one homogeneous and two heterogeneous. Homogeneous welded joint was made with pre-heating and post-heating 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 pre-heating 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. Chemical composition of the base metal and all-weld metals is given in Table 1.

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 Tables 2 and 3. The reason was weld metal alloying with elements from the diluted base metal.

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

Table 1. Chemical composition of base material and all-weld metals

Chemical composition [%]	C	Si	Mn	P	S	Cr	Ni	Mo	Cu	Al
HT 80	0.16	0.68	0.75	0.020	0.003	0.79	0.09	0.032	0.24	0.037
WELTEC B 575	0.05	0.04	1.52	0.011	0.008	0.08	1.45	0.66	–	–
WELTEC B 370 soft root	0.05	0.25	0.61	0.011	0.008	0.06	0.07	0.03	–	–

Table 2. Mechanical properties of base material and all-weld metals

Designation	R_p [MPa]	R_m [MPa]	Elongation [%]	Charpy toughness [J]	Expected M
HT 80	710	810	15.5	85, 91, 100 at 0 °C	–
WELTEC B 575	542	591	23	47, 70, 71 at −40 °C	0.76
WELTEC B 370 soft root	403	466	32	100, 215, 145 at −40 °C	0.56

thickness direction of homogeneous and heterogeneous welds (see chemical analysis given in Tables 1 and 3).

Having in mind the values of strength mismatch factors M in Table 3 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 an undermatched joint with two-pass ($M = 0.81 \Rightarrow 19\%$ undermatching) or four-pass ($M = 0.91 \Rightarrow 9\%$ undermatching) soft root layer in order to prevent cold cracking without pre-heating of the base material.

3. Experimental procedure

The set of $B \times B$ specimens was taken from undermatched homogeneous and heterogeneous welds to obtain fracture behaviour of welded joints with defects like cold cracks and lack of fusion, which often exist in real welded joints. By CTOD testing of welded joints, they are treated as planar (plane) faults. Thus, in the CTOD specimen the surface cracks with different depths were positioned in weld metal with the aim to locate the fatigue-crack-tip front in different microstructure regions of mismatched welded joint and to analyse the material behaviour at the crack tip in regard to the nearby microstructure influence.
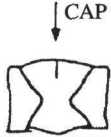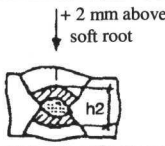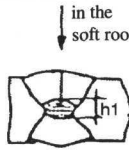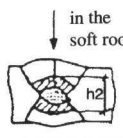
Table 3. Mechanical properties and chemical composition of homogeneous and hetero-
geneous undermatched weld joints

Designation	R_p [MPa]	R_m [MPa]	Elongation [%]	Charpy V [J] at $-10\,°C$	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 – 2× soft root passes	567	625	19.7	–	0.56 at the root	0.81 at the root
WM – 4× 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 – 2× soft passes	0.12	0.41	0.78	0.015	0.006	0.40	0.10	0.17	0.16	–	–	–
WM – 4× soft passes	0.10	0.33	0.78	0.012	0.007	0.24	0.13	0.11	0.13	–	–	–

Fracture toughness of homogeneous and heterogeneous undermatched welded joints was evaluated using the standard static CTOD test at GKSS Research Center Geesthacht in Germany. Specimen loading was carried out with constant crosshead speed $v = 0.5$ mm/min. The test temperature was $-10\,°C$ according to the recommendation of the OMAE (Offshore Mechanics and Arctic Engineering) association. For CTOD testing the single specimen method was used. To evaluate fracture toughness of undermatched welded joints, standard [5, 6] single-edge notched-bend (SENB) specimens ($B \times B$, $B = 36$ mm) with surface notch in the weld metal were used, as shown in Table 4.

The $B \times B$ specimens were fatigue pre-cracked from the surface to a distinct

Table 4. Fatigue crack positioning in SENB specimens ($B \times B$) at undermatched weld joints

Weld groove width $2H$ (at the crack tip)	Fatique crack position	Crack depth $[a/W]$
$2H = 14.1$ mm	CAP	~ 0.25
$2H = 13.9$ mm	+ 2 mm above soft root	~ 0.25
$2H = 6.8$ mm	in the soft root	~ 0.48
$2H = 7.4$ mm	in the soft root	~ 0.43

welded joint microstructure. For all specimens the fatigue pre-cracking 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 load line displacement – LLD was also measured with a reference bar to minimize the effects of possible indentations of the rollers. The CTOD values were calculated in accordance with BS 5762 (δ_{BS}) [5] and also directly measured by specially developed δ_5 clip gauge on the specimen side surfaces at the fatigue crack tip over a gauge length of 5 mm [7] (Fig. 1).

Fractographic and metallographic examinations

In order to determine the influence of crack-tip microstructure on fracture behaviour, the metallographic and fractographic examinations were performed. For fractographic examinations the Scanning Electronic Microscope (SEM) was used, while the metallographic investigations were performed by the Optical Light Microscope. After fractographic examinations the specimens were cut in crack-growth
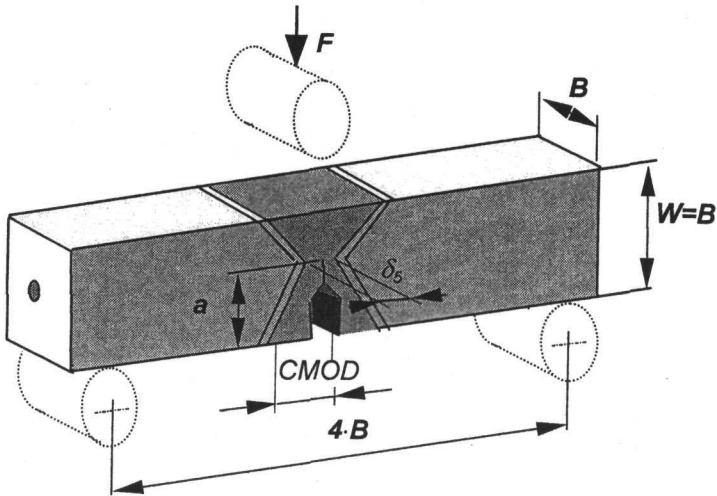
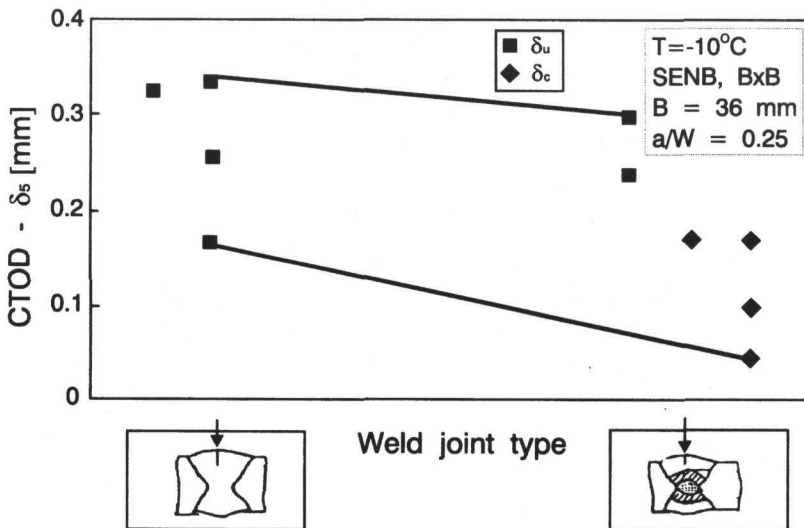Fig. 1. Three point specimen ($B \times B$) and measuring points (CMOD, δ_5).

Fig. 2. Weld metal CTOD fracture toughness of homogeneous and heterogeneous under-matched weld joint.
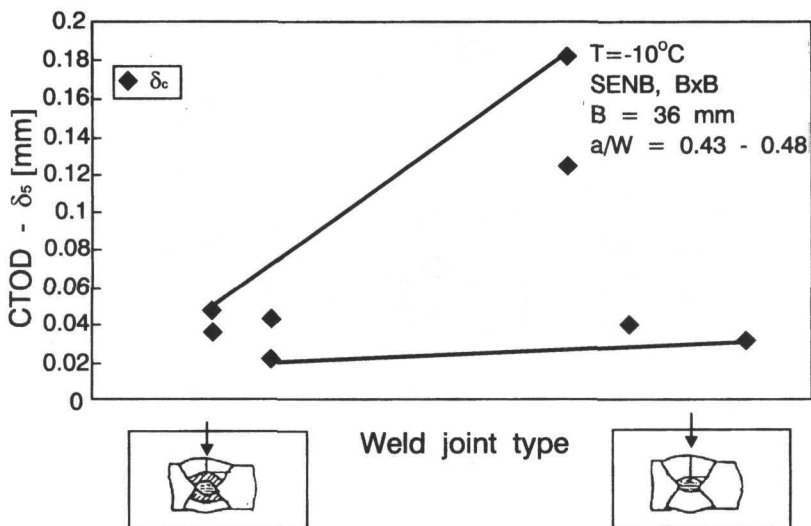
Fig. 3. Soft root layer CTOD fracture toughness of heterogeneous undermatched weld joints.

direction and polished and etched by 3% Nital. At low magnification, the fracture surfaces of each type of specimen exhibited different fracture surfaces, strongly affected by the type of the welded joint region [1].

4. Analysis of results

The results of CTOD fracture toughness of $B \times B$ specimens with surface crack in undermatched homogeneous and heterogeneous welds are shown in Figs. 2 and 3. As a consequence of different crack depths (a/W) different constraints act at the crack tip, significantly influencing the CTOD fracture toughness values. Therefore, only the comparison of CTOD values obtained using specimens with the same crack depth is reasonable. Average crack depths a/W are given in Table 4 for a set of specimens.

The influence of soft root layer on fracture toughness of filler passes (WELTEC B 575) in heterogeneous weld metal is noticeable from the comparison of CTOD values obtained using specimens with surface crack $(a/W = 0.25)$ positioned in filler passes of homogeneous and heterogeneous weld (Fig. 2). The fracture toughness was higher for specimens with surface crack in filler passes of the homogeneous weld than for specimens with surface crack in filler passes of the heterogeneous weld.

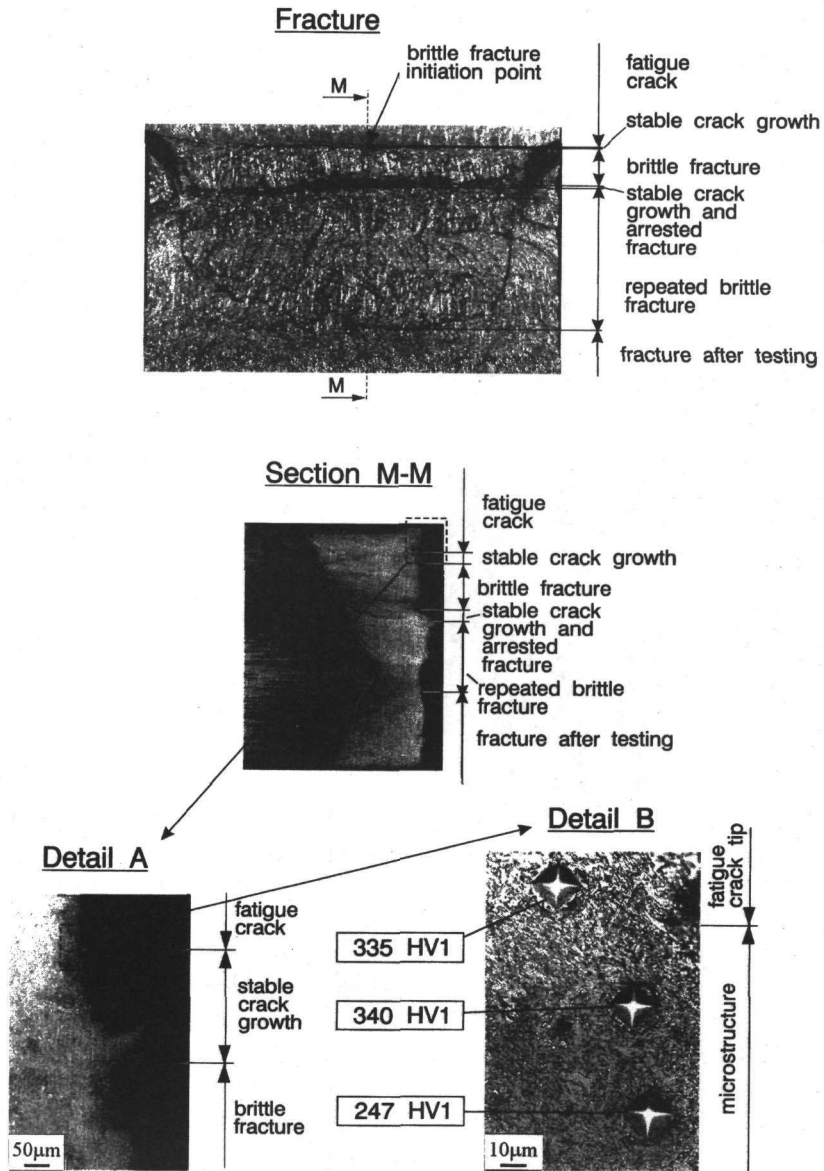After initial stable crack growth (δ_u – Fig. 2 and Fig. 4 – fracture and cross-

Fig. 4. Fracture and microstructure in the vicinity of brittle fracture initiation point of specimen $B \times B$ with surface crack ($a/W = 0.25$) in filler region of homogeneous weld. At the vicinity of brittle fracture initiation point a bainitic microstructure (Detail – A) is visible and at higher magnification (Detail – B) contours of primary ferrite (PF) can be seen, formed at primary γ grains.

-section M-M), in all CTOD specimens from homogeneous weld, brittle fracture has occurred when crack tip (Fig. 4 – cross-section M-M and detail A) reached LBZ, i.e. low toughness bainitic microstructure (Fig. 4 – detail B) with precipitated Fe_3C at boundaries of M-A phases (Fig. 5), as was proven with the appearance of significant pop-in and arrested brittle fracture (Fig. 4 – fracture and cross-section M-M) [2]. Hardness increase ($\approx$ 340 HV1) at the crack tip was noticeable (Fig. 4 – detail B), being a consequence of material strengthening just before brittle fracture occurred.

In order to analyse the effect of soft root layers on fracture toughness of filler passes and also of heterogeneous welds as a whole, it was necessary to lo-cate the fatigue crack so that it gradu-ally approaches the soft root layer (Ta-ble 4). From the comparison of CTOD results (Figs. 2 and 3) the effect of crack depth a/W and weld width $2H$ (Ta-ble 4) on CTOD fracture toughness is clear, being the lowest for the speci-mens with deep crack ($a/W \approx 0.5$) in soft root layer, where the weld width $2H$ is the smallest. The effect of con-straint on fracture toughness is also noticeable from the comparison of the curves F-CTOD [2], where it is clear that the final instabilities and higher CTOD values have appeared at higher forces and for specimens with a shorter crack, where the crack tip was located approximately 2 mm above the soft root layer (Fig. 6 – cross-section N-N and detail A). This was not only a conse-quence of the remaining ligament $W - a$ and the effect of weld groove width, $2H$, on the CTOD values, but also a consequence of the beneficial effect of bainitic mi-crostructure at the fatigue crack tip, which directly reflects the fracture toughness values. Because of that, the final fracture of specimens with the crack positioned close to the soft root layer appeared after prior stable crack growth (Fig. 6 – detail A) through tougher bainitic microstructure (Fig. 6 – detail B) of filler passes, when the crack tip reached the soft root layer.

Fig. 5. Bainitic microstructure with pre-cipitated Fe_3C at M-A phase boundary in the weld metal of the homogeneous welded joint.

The soft-root-layer low toughness was determined by Charpy impact V test-ing (Table 3). The main cause for low soft-root-layer toughness was a change of microstructure of all-weld metal obtained by wire WELTEC B 370, which was ex-posed to different alloying mechanisms during welding in the root region. Namely, the all-weld metal microstructure of soft root weld metal was bainitic [2], having high toughness, but because of the above-mentioned reasons its microstructure was
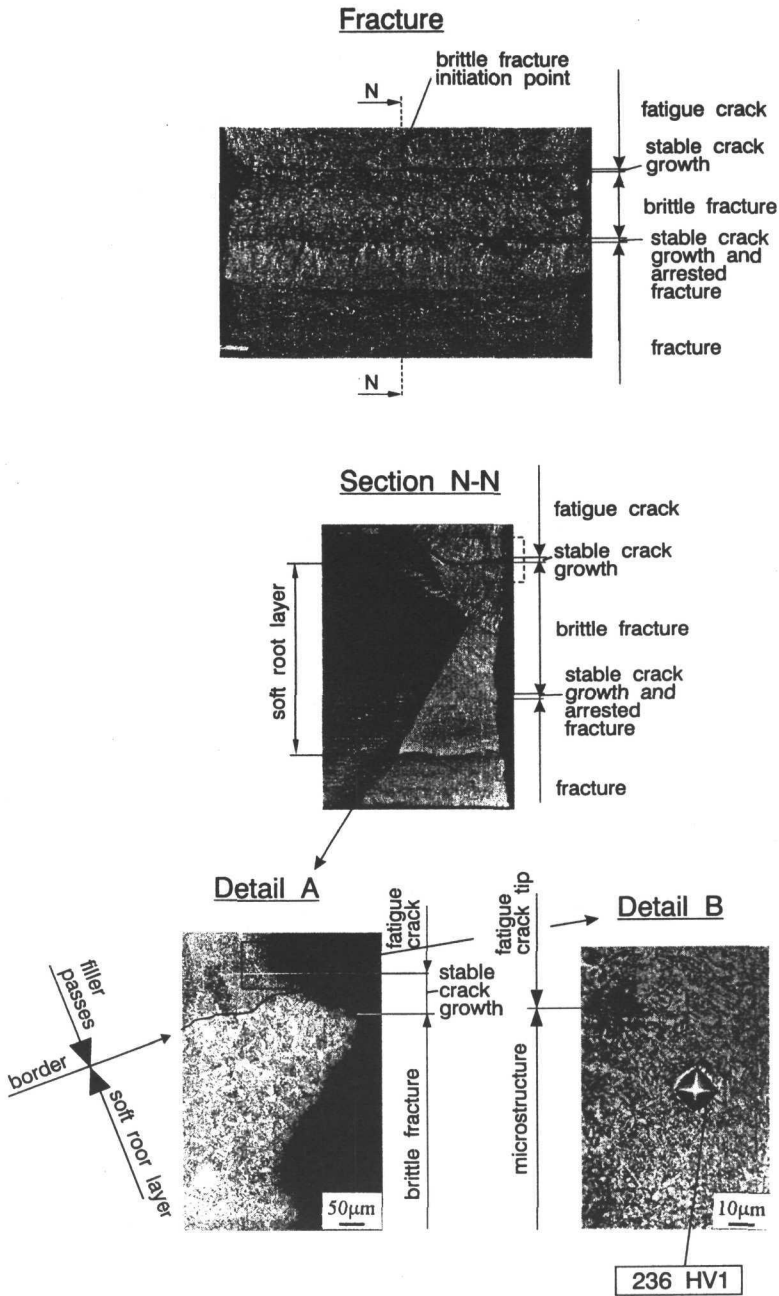
Fig. 6. Appearance of fracture surface and evaluation of microstructure at fatigue crack tip in specimen $B \times B$ with surface crack ($a/W = 0.43$) close to the boundary of soft root region. Bainitic microstructure at fatigue crack tip can be seen (Detail – A). At higher magnification (Detail – B) contours of primary ferrite (PF) are visible, formed on primary γ grains.
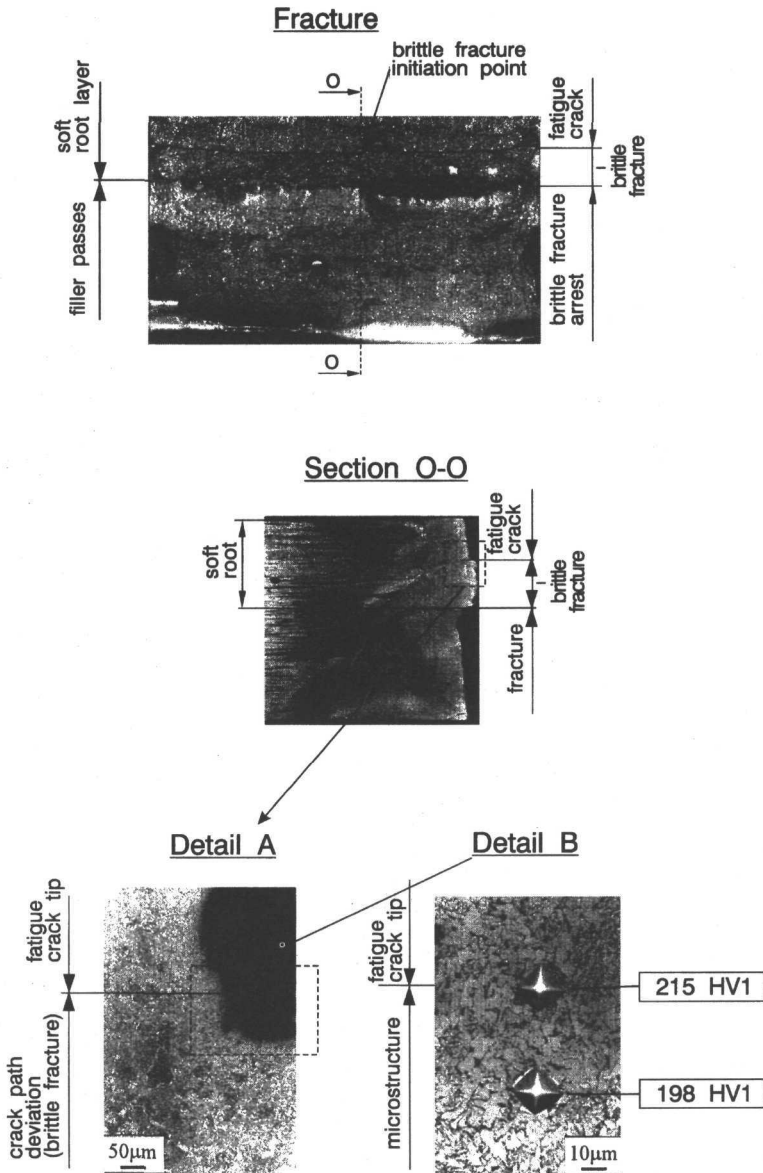
Fig. 7. Fracture and microstructure in the vicinity of brittle fracture initiation point of specimen $B \times B$ with fatigue crack ($a/W = 0.48$) positioned in soft root region. Ferritic--bainitic microstructure of soft root weld metal (Detail – A) is visible with distributed brittle M-A constituents along ferrite grain boundaries (Detail – B).
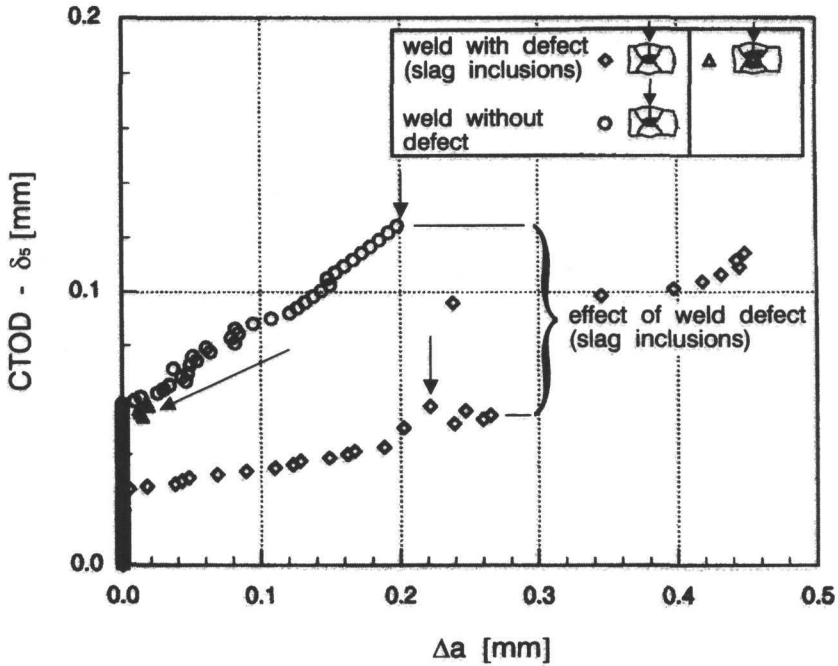
Fig. 8. R curves for specimens $(B \times B)$ with surface crack $(a/W \approx 0.43)$ in soft root layer.

changed to harmful ferritic microstructure (Fig. 7 – detail B), causing low toughness of soft root layer. The brittle fracture has appeared due to low fracture toughness of the soft root layer, being specially emphasized for specimens with the fatigue crack directly positioned in the soft root layer (Fig. 7 – cross-section O-O and detail A), where such brittle fracture appeared (without prior stable crack growth) and finally arrested in the tougher filler region with beneficial bainitic microstructure (Fig. 6 – cross-section N-N and detail B). The CTOD values of the soft root layer were additionally reduced because of constraint, being largest in the soft root layer of these specimens, because the crack depth a/W was the largest, weld groove shape coefficient $2H/W - a$ the smallest, and heterogeneity the most prominent.

Comparison of CTOD fracture toughness results (Fig. 2) shows a significant influence of the soft root layer on fracture toughness of filler region (WELTEC B 575) in heterogeneous welds, causing weld-metal fracture toughness to be much higher for the specimens with a surface crack $(a/W = 0.25)$ in the homogeneous weld than in a heterogeneous one. The results of CTOD fracture toughness (Fig. 3)
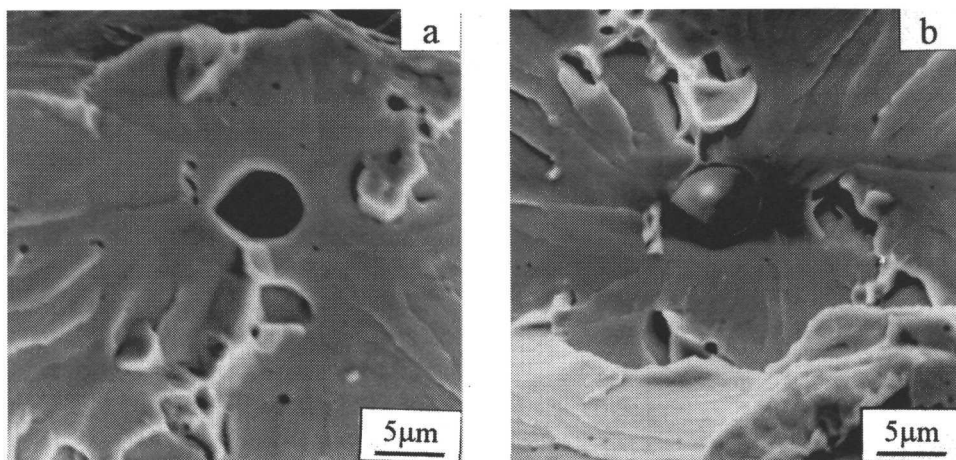
Fig. 9. Appearance of brittle fracture initiation point (Al-Si-Mn inclusion) on left a) and right b) fracture surface of specimen $B \times B$ with surface crack in the heterogeneous weld, indicated by EDX analysis.

for specimens with surface crack ($a/W = 0.43$–0.48) in two-passes and four-passes soft root layer indicate somewhat higher toughness of the former one. From Fig. 8 one can notice the influence of defects (slag inclusion) on fracture toughness of two-pass soft root layer, because the fatigue crack tip was positioned in it, causing premature specimen fracture and thus low fracture toughness of soft root layer.

The most frequent brittle-fracture initiation points of specimens with crack-tip position in the soft root layer were Al-Si-Mn inclusions (Fig. 9) and TiCN carbides. The reason for low fracture toughness of soft root layer is already mentioned microstructure modification due to alloying effect of base metal.

5. Conclusions

1. Selection of soft tough weld consumable (wire) does not guarantee tough root layer in the undermatched weld. Improper selection of weld consumable and thermal effects of subsequent passes on soft root layer can cause modification of the microstructure and reduction of its toughness.

2. Weld metal CTOD fracture toughness, measured by surface notched $B \times B$ specimens with homogeneous and heterogeneous weld metal, is higher for the homogeneous weld. Weld metal CTOD fracture toughness for the heterogeneous weld decreases as the soft root volume increases.

3. Fracture behaviour of CTOD specimens with surface cracks depends on the following three parameters: geometrical constraint due to the different crack depth

a/W, groove shape coefficient $2H/(W-a)$, and local plastic constraint in the root region of the weld joint, due to strength mismatching.

4. For the CTOD testing of heterogeneous welded joints, specimens with surface cracks starting from the surface and directed toward weld thickness should be used.

Acknowledgements

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