EFFECT OF LOCAL WELD METAL MIS-MATCHING ON FRACTURE TOUGHNESS OF QT STEEL WELD JOINTS

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Welding of high strength structural steels is a complex task due to the sensitivity of CGHAZ and WM to cold cracking. Generally, preheating is used to prevent it in the root. A softer consumable is recommendable to reduce costly and time consuming preheating. Existence of WM materials of different strength and toughness in the weld increases the complexity of local mis-matching and affects the failure behaviour of weld joints. CTOD results on 40 mm thick weld joints (X-groove weld) with and without soft root layer are discussed in the present article. The effect of layer's size on CTOD was examined. Experimental study of all weld joints containing soft root layers showed no cold crack appearance. In spite of soft layers transverse tensile strength of the weld joints were higher than of BM. CTOD results are used to explain the effect of strength heterogeneity between cap and root regions of weld.

INTRODUCTION

Considerable strength differences (mis-matching) among base material (BM), weld metal (WM) and heat affected zone (HAZ) exist in the welded structures of high strength steels. Over-matched WM can be useful due to its shielding effect keeping small defects in WM out of plastic deformation domain (1). But, because of worse weldability cold cracking can appear in WM, especially in the weld root. Root cold cracking can be avoided by use of soft root layer. Its yield stress has to be lower than those of BM and the rest of WM. Three over-matched X-groove multipass weld joints were studied, one with homogeneous and two with nonhomogeneous weld. The aim of this research work was to find out if the welding procedure with soft root layer is recommendable for weldability improvement without any essential lowering of full size weld joint strength and fracture toughness.

MATERIALS, WELD JOINTS AND EXPERIMENTAL PROCEDURE

High strength low alloyed grade HT 80 steel (t=40 mm) was used in quenched and tempered (QT) conditions (BM in Tables 1 and 2). FCAW procedure (CO_2 shield gas) was used and two consumable were selected. The first ensured global over-matching (WM_1), the latter enabled to introduce soft layer (WM_2).

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TABLE 1 - Mechanical properties of base metal, all-weld metals and significant regions of actual welds

material	σ_y	σ_u	elong.	vE	M
	MPa	MPa	%	J	
BM	711	838	20	$54_{-40°C}$	-
WM_1	770	845	16	$58_{-40°C}$	(1.08)
WM_2	403	466	32	$153_{-40°C}$	(0.57)
WM_{hom-c}	861	951	12	$56_{-10°C}$	1.21
WM_{hom-r}	807	905	15	$61_{-10°C}$	1.14
$WM_{2\ pass}$	623	677	16	-	0.88
$WM_{4\ pass}$	632	674	16	$23_{-10°C}$	0.89

Homogeneous weld joint was made using consumable WM_1. Nonhomogeneous weld joints were made using consumable WM_2 and that for two and four pass soft root layer and consumable WM_1 for the rest. Mechanical properties of significant regions of actual welds were determined by round tensile specimens extracted from the root and the cap passes of X-groove welds in the weld axis direction. They are listed in Table 1. Mis-matching factor $M=\sigma_{yWM}/\sigma_{yBM}$ is also shown. Data in brackets are designed values (theoretical) and do not correspond to the actual welds. Chemical composition of material used and of actual weld regions is listed in Table 2. Carbon equivalent parameter P_{cm} the measure of sensitivity to cold cracking is shown for BM and analyzed regions.

Additionally, Vickers hardness measurements in the weld through thickness direction (indentation on each 1 mm) were conducted and corresponding yield stress was calculated using formula $\sigma_{yWM}=3.15$ HV-168 (2). Mis-matching factor distributions over the whole thickness calculated from measured hardness are plotted in Figure 1 for actual welds.

Series of impact toughness specimens and of almost full thickness SENB specimens were extracted from weld joints. Different testing temperatures were used for S curve designing. The geometry of SENB specimen was Bx2B with B=36 mm. Through thickness fatigue cracks were positioned in the middle of the welds (a/W ~ 0.5) as it is sketched in Figure 3. CTOD testing temperature was -10°C. Single specimen method was used. During the test DC potential drop technique was applied for stable crack growth monitoring (3). CTOD values were directly measured with in GKSS developed δ_5 clip gauge (4).

RESULTS

S curves for BM, WM_{hom-c}, WM_{hom-r} and $WM_{4\ pass}$ are shown in Figure 2. CTOD values determined on BM and three different multipass over-matched welds without and with soft root layer are given in Figure 3. Some specimens were made with straight fatigue crack front and some with nonstraight one (5). In all specimens except BM (M=1) after some amount of slow crack growth brittle

TABLE 2 - Chemical composition of base metal, all-weld metals and some regions of actual welds

material	C	Si	Mn	P	S	Cr	Ni	Mo	P_{cm}
	%	%	%	%	%	%	%	%	%
BM	.09	.27	.25	.015	.004	1.12	2.63	.25	.228
WM_1	.06	.35	1.43	.011	.008	.86	3.01	.56	-
WM_2	.05	.25	.61	.011	.008	.06	.07	.03	-
WM_{hom-c}	.07	.36	1.27	.008	.015	.86	2.21	.47	.257
WM_{hom-r}	.08	.32	.78	.012	.013	.99	2.50	.35	.252
$WM_{2\ pass}$	.08	.26	.32	.012	.007	.38	.82	.16	.148
$WM_{4\ pass}$	.08	.26	.43	.011	.008	.20	1.32	.12	.150

fracture commenced. An example of R-curves obtained by CTOD experiments on all three types of over-matched welds are shown in Figure 4. They represent experiments by which CTOD fracture toughness values near average of those shown in Figure 3 were obtained.

DISCUSSION

Disagreement between designed mis-matching factors (values in brackets in Table 1) and actual ones are the consequence of weld pool dilution/alloying by molten BM (see chemical composition in Table 2). Cooling rate by welding of actual homogeneous weld ($\Delta t_{8/5} \sim 9$ s) was obviously different from that during all-weld metal sample preparation by the consumable producer. The alloying effect from BM is more pronounced in the cap region than in the root one. Local tempering or quenching during cooling caused by additional weld pass deposition is also present in both weld regions. This is the main reason why local mis-matching from pass to pass in the weld through thickness appeared even in the case of homogeneous weld joint.

It was expected that local mis-matching along the crack tip line would play an important role in crack initiation and propagation. Mechanical properties shown in Table 1 are average values of the domain where the tensile specimens were taken from. They can not show the exact mis-matching condition valid for the whole welds. Taking into account CTOD and impact toughness results it is obvious that local mis-matching is involved in the mechanism of local brittle zone (LBZ) appearance (6). The evaluation of its influence was made on the basis of known local mis-matching depicted by hardness data. The analysis of brittle crack initiation point by CTOD test revealed LBZ for treated mis-matching conditions.

Taking into account only impact toughness values in Figure 2, LBZ could not be expected at the weld root of homogeneous over-matched weld joint. Impact toughness of the root was slightly higher than impact toughness of the cap material (Figure 2). But, over-matching protection in the root was lower than in the cap due to local mis-matching (Figure 1). Additionally, ratio 2H/(W-a) was the smallest in the root of X-groove weld (H is half of the weld width at the certain position) and therefore the constraint was there the highest. These influences prevailed over impact toughness and consequently, brittle fracture initiation occurred in the root region by CTOD testing. So, LBZ in such kind of over-matched weld joint exist in the region with the lowest mis-matching factor M in spite of somewhat higher root material impact toughness. As the consequence of sudden stress intensity raise in the weld region of lower impact toughness (cap) immediately after crack initiation in the root brittle fracture has spread across the rest of weld.

LBZs in the weld joints with soft root layer were revealed in the soft layer where mis-matching factor M was intentionally lower (see M factor in Figure 1). CTOD values of weld joints with four pass soft root layer were slightly lower than two pas ones. Impact toughness of soft layer material was lower than anywhere in the of homogeneous weld joint (Figure 2). Impact toughness of four pass soft root layer material was determined, not with two. The size of this layer was not sufficient. After root LBZ activation in this low impact toughness region (see $WM_{4\ pass}$ data in Figure 2) the main brittle fracture has spread into the remaining weld material with higher mis-matching factor M and higher impact toughness. CTOD values of welds with soft root layers are slightly lower than those of homogeneous weld (Figure 3).

The difference in fracture behaviour of homogeneous and both nonhomogeneous welds is clearly seen in Figure 4. CTOD value at crack initiation in two pass soft root layer nonhomogeneous weld joint is ~30% higher than in four pass one. Slow crack extension up to the first brittle fracture occurrence is far below 0.2 mm, which is an engineering measure of fracture toughness. It means that CTOD values at brittle event refers to δ_c(7). But, pop-in in weld with two pass soft root layer was not so extreme (see further part of its R-curve) as in the case of weld with four pass soft root layer. CTOD at crack initiation in homogeneous weld is also lower, but, first brittle occurrence happened after slow crack growth of 0.2 mm. First brittle occurrence (pop-in) which is not so extreme refers to CTOD value δ_u(7).

Fracture and impact toughness of actual welds presented in this study are lower than those of BM. Therefore, the overall over-matching condition should be ensured all over the weld. By high strength QT steels is difficult to obtain high WM impact and fracture toughness. Overall strength of weld with two pass soft root layer is also satisfactory. Mechanical properties from Table 2 and thickness of layer ~9 mm yield an overall over-matching factor M~1.1.

It seems that welding procedure with two pass soft root layer is more applicable than that without soft root layer and that with four pass soft root layer. This is based on satisfactory fracture behaviour of such kind of weld joints and on weldability regarding root cold cracking sensitivity. Cold cracks in the weld namely act as a potential danger for later brittle fracture initiation which can be followed by the whole weld joint disintegration.

But, in the case of softer root layer an open question remains, how to handle the under-matching condition when $M<1$ in the weld root, but the overall weld joint is over-matched, i.e. $M>1$.

CONCLUSIONS

It was found that besides global mis-matching very distinctive strength differences in the through thickness exist in over-matched welds. This local mis-matching can be depicted by hardness measurement. In over-matched weld local mis-matching can be introduced intentionally but an additional mis-matching also exist, mostly as the consequence of multi-pass welding where subsequent passes cause tempering of the previous ones. This can be the dominating mechanical effect controlling fracture behaviour in the regions of less tough WM material.

The selection of soft and tough weld consumable does not always bring on the tough root layer. CTOD of nonhomogeneous weld with four pass soft root layer was lower than those of homogeneous one and lower even than those with two pass soft root layer. The same tendency is obvious by impact toughness. Because of significantly lower fracture toughness of all treated over-matched welds against BM an over-matching condition in the weld ($M > 1$) should be always ensured due to its shielding effect.

The application of welding procedure with two pass soft root layer for the purpose to reduce or even omit preheating is recommendable in over-matched weld joints on steel grade HT80. Alloying from BM and tempering effect of subsequent weld passes should be taken into account. Both cause either reduction of the root material ductility or affect local mis-matching. Determination of mis-matching conditions in the real weld joints is a complex task especially for weld joints with WM strength heterogeneities (global/local mis-matching).

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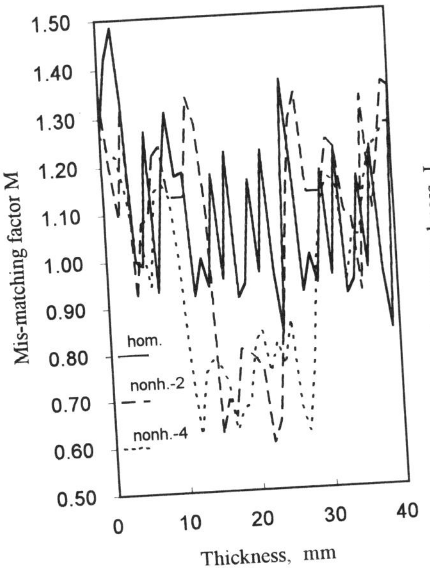

Figure 1 Mis-matching factor across the actual over-matched welds

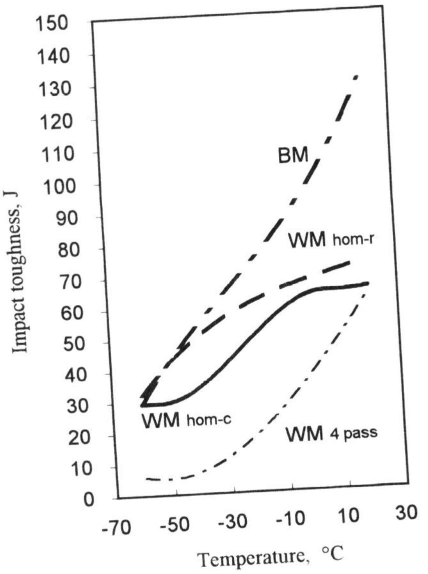

Figure 2 Impact toughness in terms of temperature (S curves)

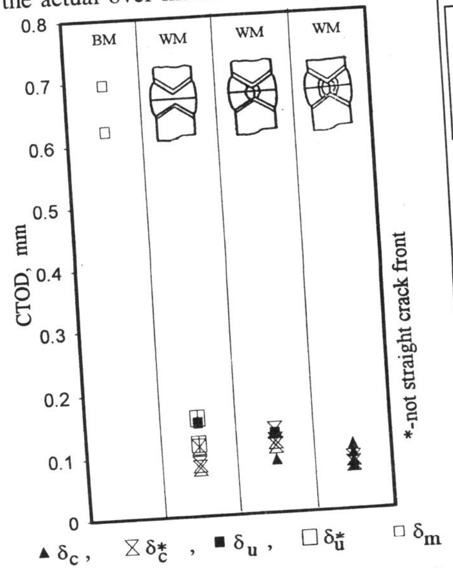

Figure 3 CTOD values in terms of weld joint type

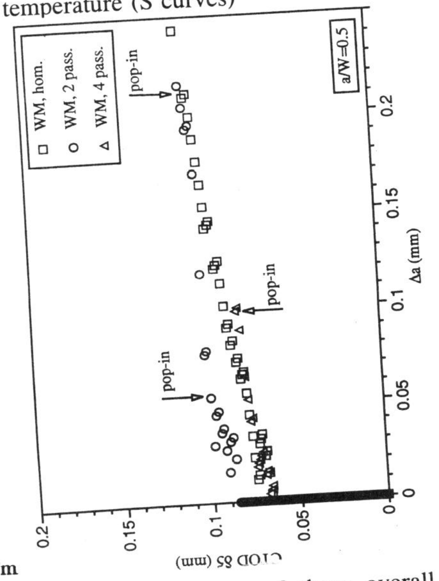

Figure 4 R-curves of three overall over-matched welds