INFLUENCE OF WELD JOINT MECHANICAL PROPERTIES ON FRACTURE TOUGHNESS

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ABSTRACT

Considerable strength differences among base material (BM), weld metal (WM) and heat affected zone (HAZ) may exist in the welded structures made of high strength steels. Three over-matched weld joints were made using either single consumable with yield stress higher than BM or two consumable, where the softer one was used for the root. Use of softer consumable has resulted in improved weldability. Its presence in the weld root did not worsen overall weld joint strength and over-matching conditions. Mechanical properties of vital regions of X-groove weld joints were determined experimentally. WM specimens were taken from the actual welds. Microstructure of HAZ regions was made by weld thermal cycle/cycles simulation. Fracture toughness was determined on full thickness weld joints. The aim was to explain the effects of strength heterogeneity on weld joint fracture behaviour precracked either in the middle of the weld or over the HAZ. Limited soft root layers have not jeopardized weld joint fracture toughness.

KEYWORDS

Mis-matching, weld metal, heat affected zone, mechanical properties, fracture toughness.

INTRODUCTION

High WM toughness is difficult to assure, therefore, over-matched weld joint is very useful due to its shielding effect, keeping small defects in the WM out of plastic deformation domain. This was well proved by wide plate tests (Denys, 1994). But welding of high strength structural steels in over-matching conditions is not simple because of increasing WM sensitivity to cold cracking. Weld root defects extremely jeopardize weld joint integrity. Generally, preheating is used to prevent cold cracking. Another possibility to avoid cold cracking in the weld root is the use of a softer consumable reducing or even omitting costly and time consuming preheating. Yield stress of the root WM has to be lower than yield stress of BM and the rest of WM. Existence of HAZ and two WM materials of different strength and toughness in the single weld joint increases the complexity of weld joint mis-matching and affects its failure behaviour. Fracture toughness of a ≈40 mm thick over-matched X-groove weld joints with and without soft root layer is discussed in the present article. The aim was to find out if the welding procedure with the soft root layer is recommendable for weldability improvement without essential lowering of full size weld joint strength and fracture toughness.

MATERIALS, WELD JOINTS AND EXPERIMENTAL PROCEDURE

High strength low alloyed grade HT 80 quenched and tempered steel (t=40 mm) was used in the experimental work. Its mechanical properties and chemical composition are shown in Table 1. Flux cored arc welding (FCAW) procedure was selected to make weld joints. Two different consumable were used. Mechanical properties and chemical composition of both all-weld metals (WM_1, WM_2) are shown in Table 1. The first ensured global over-matching, the latter enabled to introduce soft root layer. Theoretical mis-matching is assessed as $M=\sigma_{yWM}/\sigma_{yBM}$ (data in brackets). This value is treated as the designed M, because it is not

Table 1 Mechanical properties and chemical composition of the base metal and the all-weld metals

material	σ_y	σ_u	elong.	$vE_{-40°C}$	M
	MPa	MPA	%	J	
BM	711	838	20	54	-
WM_1	770	845	16	58	(1.08)
WM_2	403	466	32	153	(0.57)

%	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	(.274)
WM_2	.05	.25	.61	.011	.008	.06	.07	.03	(.095)

corresponding to the actual weld. Parameter P_{cm} is the measure of material susceptibility to cold cracking. The selected welding parameters resulted in cooling times from 800° to 500°C ($\Delta t_{8/5}$) ~9 s. They were measured during welding by thermocouple inserted into the weld before its solidification. Heat inputs were 1.8-2.0 MJm^{-1}, while preheating/inter-pass temperature was ~100°C. The soft root layers and the rest of heterogeneous welds were made without preheating.

Homogeneous weld joint was made using consumable WM_1, while heterogeneous ones were made using consumable WM_2 for soft root layer (two and four passes) and WM_1 for the rest. Mechanical properties of WM were determined by round tensile specimens taken from the root and the cap of actual X-groove welds in the weld axis direction at room temperature. Impact toughness specimens with the notch in the same weld regions were also taken from the actual weld joints transverse to the weld axis. Series temperatures were used for impact toughness S-curve designing. Vickers hardness measurements in the weld through thickness (indentation at the load 10 N on each 1 mm) were conducted and yield stress was calculated using relation σ_{yWM}=3.15 HV-168 (Pargerter, 1978) for local weld joint mis-matching determination.

HAZ mis-matching conditions adjacent to the fusion line were determined using synthetic microstructures made by thermal cycle simulator (Smitweld). The samples for simulation were cut from the plate in the rolling direction in size 15x15x70 mm (mechanical properties), 11x11x55 mm (hardness and impact toughness) and 9x15x70 mm (fracture toughness). They were heated rapidly to the peak temperature T_p>1350°C and then immediately cooled down. Cooling time $\Delta t_{8/5}$ was ~9 s, the same as that of the actual welds. The consequence of such weld thermal cycle simulation on as-delivered BM is synthetic microstructure very similar to coarse grained heat affected zone (CGHAZ) microstructure of the real weld joint. By rapid heating of samples with CGHAZ microstructure to peak temperature T_{p2} synthetic double cycle HAZ microstructure adjacent to the fusion line was made. The range of T_{p2} was 700°-1350°C. Cooling speed of the second thermal cycle was the same as that of the first one, i.e. ~9 s. T_{p2} lower than α/γ transformation start temperature (Ac_1) has not caused retransformation of the previous CGHAZ microstructure, while T_{p2} higher than α/γ transformation finish temperature (Ac_3) has caused it. Weld thermal cycle with T_{p2} in the range between Ac_1 and Ac_3 temperatures has retransformed previous microstructure only partially. For T_{p2} lower than 800°C cooling time from 500° to 300°C ($\Delta t_{5/3}$) was used instead of $\Delta t_{8/5}$.

Dilatation was measured during thermal cycle applications. Temperatures of austenite decomposition start (finish) during cooling and corresponding moments were determined by dilatation curves analysis. Microstructures were metallographic analyzed and hardness was measured. These data were sufficient for designing CCT diagrams valid under welding conditions as it was demonstrated in one of our previous works (Gliha et al., 1994).

Due to limited size of synthetic HAZ microstructure made by welding simulation (a few mm) hourglass shaped tensile specimens of diameter 4.5 mm were used for determination of mechanical properties. Stress concentration factor K_t was 1.05. Impact toughness and CTOD fracture toughness (for single T_{p2} only) were determined on 10x10x55 mm V-notched and 8.5x14.5x70 mm SENB specimens at -40°C respectively. Hardness HV10 was measured too.

Table 2 Mechanical properties and chemical composition of regions of the actual welds

material	σ_y	σ_u	elong.	$vE_{-10°C}$	M
	MPa	MPa	%	J	
WM_{hom-c}	861	951	12	56	1.21
WM_{hom-r}	807	905	15	61	1.14
$WM_{2\ pass}$	623	677	16	-	0.88
$WM_{4\ pass}$	632	674	16	23	0.89

%	C	Si	Mn	P	S	Cr	Ni	Mo	P_{cm}
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	.244
$WM_{2\ pass}$	.08	.26	.32	.012	.007	.38	.82	.16	.148
$WM_{4\ pass}$	.08	.26	.43	.011	.008	.20	1.32	.12	.150

The exact size of almost full thickness SENB specimens were Bx2B with B=36 mm and a/W~0.5. Through thickness fatigue cracks were positioned either in the middle of the welds or crossing fusion line and HAZ (composite crack). They were made in two different ways using standard (BS, 1979) and so called "Step Wise High R-Ratio" procedure (Koçak et al., 1990). The CTOD testing temperature was -10°C. Single specimen method was used. During the test CTOD was directly measured with in GKSS developed δ_5 clip gauge (GKSS, 1991). DC potential drop technique was applied for stable crack growth monitoring.

RESULTS AND DISCUSSION

Fusion welding is a very effective way for huge steel structure and heavy machine production and erection. The integrity of weld joints is the basis of their reliable and safe use for a long period. A local brittle zone (LBZ) existence intensively affects fracture behaviour of weld joint. The possibility of LBZ appearance is depending upon material capability in the certain weld joint region to withstand a cleavage fracture and upon mechanical properties of this region and its surroundings, i.e. upon mis-matching conditions (Koçak et al., 1992). LBZs use to appear in the WM and HAZ regions. Global weld joint mis-matching is usually designed but local mis-matching can be also present in the WM as well as in the HAZ.

Mechanical properties and chemical composition of homogeneous weld in the root and the cap regions (WM_{hom-c}, WM_{hom-r}) and two heterogeneous welds in the root regions, ($WM_{2\ pass}$, $WM_{4\ pass}$) are listed in Table 2. Mis-matching factor M and cold cracking parameter P_{cm} are also shown. Mechanical properties of various HAZ regions adjacent to the fusion line are listed in Table 3. M-values are calculated on the basis of BM yield stress determined in the same way as those of HAZ. Distributions of M over the whole weld joint thickness obtained from hardness are plotted in Figure 1. S-curves for BM, HAZ, WM_{hom-c}, WM_{hom-r} and $WM_{4\ pass}$ are shown in Figure 2. Microconstituents formed in the HAZ at different T_{p2} temperatures of the second thermal cycle and their impact toughness are shown in Figures 3 and 4.

CTOD values determined on BM and three multipass over-matched weld joints without and with soft root layer are given in Figure 5. Some specimens were made with straight fatigue crack front and some with nonstraight ones as it is reported by Rak et al. (1995). The position of cracks is sketched in the figure. In all specimens except BM brittle fracture was recorded after slow crack initiation.

Weld pool dilution/alloying by molten BM is the reason for changed chemical composition of the real weld joint WM regarding all-weld metal. So, mechanical properties and toughness of the actual WM are also rather different. Yield stress can be either higher or lower. As a rule the WM toughness of an over-matched weld joint is lower than that of carefully selected all-weld metal. But, additional embrittlement is also possible. It is caused by the thermal treatment during subsequent weld passes deposition. Contrary to the WM regions, hardening/softening and possible embrittlement of sufficient tough BM in the HAZ region are

Table 3 Mechanical properties of synthetic heat affected zone microstructures at the fusion line

HAZ regions	T_{p2}	σ_y	σ_u	ε_f	$vE_{-40°C}$	M
	°C	MPa	MPa		J	
single cycle CGHAZ	-	935	1171	0.92	40-55	1.28
"tempered" CGHAZ	~700	865	1027	1.05	95-115	1.19
partly austenitized CGHAZ	~780	704	937	1.19	110-130	0.97
austenitized CGHAZ	~960	939	1176	0.98	45-65	1.29
"homogenized" CGHAZ	~1150	958	1185	1.02	70-90	1.32

the result of unavoidable thermal treatment during weld joint execution. Its effects depend mostly on chemical composition, peak temperatures and cooling rates.

Shielding effect of weld over-matching is well proved for defects away from the weld fusion line which is the border of higher and lower yield stress materials, i.e. WM and BM (Denys, 1991). In the case of homogeneous over-matched weld joint the situation is clear, but it is changed if heterogeneous weld joint with the defect in softer layer is treated. The additional unclearness is the result of local mis-matching. Anyway, defects in the HAZ adjacent to the fusion line, irrespective of its yield stress, act at the border separating high and low yield stress materials. Extremely inconvenient for the weld joint integrity is the fact that the softest weld joint region is strained above its elastic limit in the case of overloading due to firm surroundings having higher yield stress (Schwalbe, 1993).

Hard HAZ regions near the fusion line are protected against brittle fracture by over-matched WM in spite of their possible lower toughness. Therefore, in the over-matched weld joint very soft HAZ region close to the fusion line could be potential LBZ. If its toughness is not extremely high the effect of local under-matching can prevail upon it and activates LBZ due to raising local plasticity constraint. Very narrow and brittle HAZ region close to the fusion line often involved in LBZ appearance and brittle crack extension (CGHAZ and some other HAZ parts) can be the decisive material reason for crack path deviation (Thaulow et al., 1994) either due to high or due to low yield stress and strength.

One of the reasons for the disagreement about designed and actual weld joint M-values in the WM (Tables 1 and 2) could also be cooling rate. By welding of actual welds $\Delta t_{8/5}$ was not the same as before when consumable producer was testing all-weld metal properties. As it is seen, the effect of dilution/alloying is pronounced more in the root WM than in the cap. Local

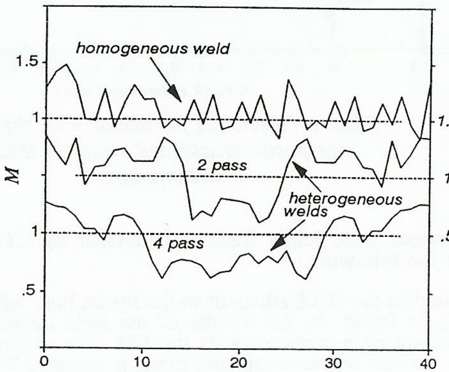

Figure 1 *Mis-matching factor M distribution through the weld joints*

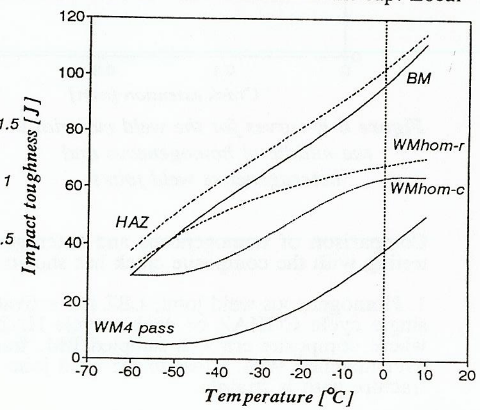

Figure 2 *Impact toughness of significant weld joint regions (S-curves)*

softening or hardening during heating and cooling sequence caused by subsequent weld passes is present in both weld regions of all three types of weld. The exception is the last weld pass, which does not undergo the additional thermal cycle. These is the reason for local mis-matching in the weld through thickness shown in Figure 1. As it was expected P_{cm} in both analyzed weld regions of homogeneous weld is higher than that of BM, while in the soft layers is considerably lower in spite of partial contribution of BM (Table 2).

Taking into account impact toughness values in Figure 2, LBZ could not be expected at the weld root of homogeneous weld joint while in soft root layers of heterogeneous weld joints LBZs are predicted. Impact toughness of the root material (WM_{hom-r}) is slightly higher than of the cap (WM_{hom-c}) while impact toughness of soft root layer ($WM_{4\,pass}$) is the lowest. Impact toughness of the HAZ in the figure is the highest at all. But, actually it does not correspond to the pure HAZ microstructure. According to Figure 4 it is obvious what kind HAZ microstructure of multipass weld joint on treated BM is more and what kind is less tough and firm (see also Table 3). The most tough double cycle HAZ microstructure correspond to the softest HAZ which was during the second thermal cycle austenitized only partially. HAZ microstructures (single and double cycle) with the lowest toughness are hard. It seems to be in contradiction with the results of Haze et al. (1988). An explanation is that double cycle HAZ of the lowest impact toughness was already austenitized (proved by dilatometric analysis) but probably not satisfactorily homogenized. Double cycle HAZ microstructure which is the result of completely homogenized austenite decomposition is firm (hard) but also tough.

Fracture behaviour of real weld joints from Figure 5 is clearly seen on R-curves in Figures 6 and 7. Those experiments are shown by which median CTOD values from Figure 5 were recorded. Mis-matching plasticity constraint along the crack front due to under-matching in the middle of homogeneous weld (root), that is clearly seen in Figure 1, was decisive for crack initiation and its extension by CTOD testing. Additionally, ratio H/(W-a), the measure of constraint (Eripret, 1996) is the smallest in the root of X-groove weld (H is half of the weld width at the certain position). Because of deep crack (a/W ~ 0.5) stress state is here more like to plain strain than anywhere in the weld joint promoting cleavage fracture. Above mentioned reasons (mis-matching and geometrical constraint) have prevailed over impact toughness and as the consequence brittle fracture initiation has appeared in the root region (pop-in). LBZ in such kind of over-matched weld joint with not extremely tough material at the root exists in the region of the lowest local factor M and strongly affects fracture behaviour and CTOD fracture toughness (Figure 5). Immediately after crack initiation in the root material brittle fracture has spread across the rest of the weld as the consequence of sudden stress intensity raise in the region of somewhat lower impact toughness (cap).

CTOD testing of heterogeneous weld joints with the crack in the middle of the weld has revealed LBZ in the soft layers where factor M was intentionally lower. In these joints, as

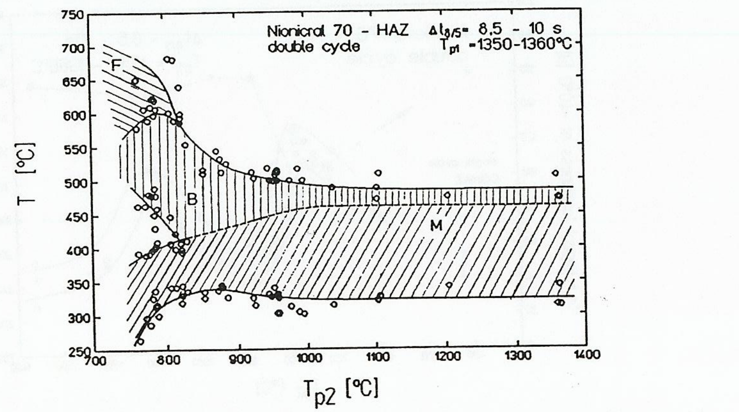

Figure 3 *Microconstituents in the heat affected zone adjacent to the fusion line upon peak temperature of the second thermal cycle (F-ferrite, B-bainite, M-martensite)*

regards homogeneous weld joint, above mentioned geometrical and mis-matching plasticity constraints were much more expressive. The consequence was P_{cm} lower than those of BM and the weld cap region. This is convenient for weldability reasons ensuring material clearness (no defects). CTOD fracture toughness results of weld joint with two pass soft root layer were not lower than those of homogeneous weld joint. A slightly lowered CTOD values are noticed by weld joint with four pass soft root layer. Impact toughness of soft layer material was lower than anywhere in the rest weld joint material and also in the homogeneous weld joint (see Figure 2). Only impact toughness of four pass soft root layer material was determined, not of two. The size of two pass root layer was not sufficient for impact toughness testing.

As can be seen from Figure 6 CTOD value at stable crack initiation of two pass soft root layer heterogeneous weld joint was ~30% higher than in four pass and homogeneous ones. Stable crack extension up to the brittle fracture appearance is far below 0.2 mm, an engineering measure of fracture toughness. But, pop-in in this weld was not so expressive as in the case of heterogeneous weld with four pass soft root layer at lower CTOD value and greater crack extension, probably due to smaller size of the soft layer. Brittle fracture (pop-in) in homogeneous weld has appeared after stable crack extension of almost 0.2 mm, although CTOD value was not higher than that of weld with two pass soft root layer. Anyhow, these CTOD values at brittle event refer either to δ_c or δ_u (BS, 1979) as can be seen from Figure 5.

In Figure 7 one can compare R-curves for composite crack of homogeneous and heterogeneous welds with R-curve obtained on synthetic HAZ microstructure of the lowest possible yield stress adjacent to the fusion line. Testing temperature of synthetic HAZ was 30° lower. In spite of higher impact toughness of the treated synthetic HAZ microstructure at -40°C (compare data in Figures 2 and 4) CTOD values at stable crack initiation and extension to 0.2 mm correspond to the lower values than those recorded by thicker real weld joint CTOD specimens. But, fracture behaviour was fully different. It was not brittle in spite of lower testing temperature (-40° against -10°C), on the contrary, it was ductile fracture.

CTOD testing of homogeneous and heterogeneous weld joints with the crack crossing the fusion line at two positions has revealed the weakest point in weld joint with four pass soft root layer. Stable crack extension up to the brittle crack initiation was here the lowest. Crack tip front has approached soft root layer more than in the case of the weld joint with two pass soft root layer. The reason is shape of weld joint (X-groove). By homogeneous weld joint stable crack extension up to the brittle fracture initiation is the greatest, because, there is no strong influence of intentionally made soft root layer. This is the reason for higher CTOD fracture toughness values in Figure 5. It seems that soft root layer has an important effect on fracture toughness of over-matched weld joints not only for the crack in the middle of the weld but also in the case of composite crack.

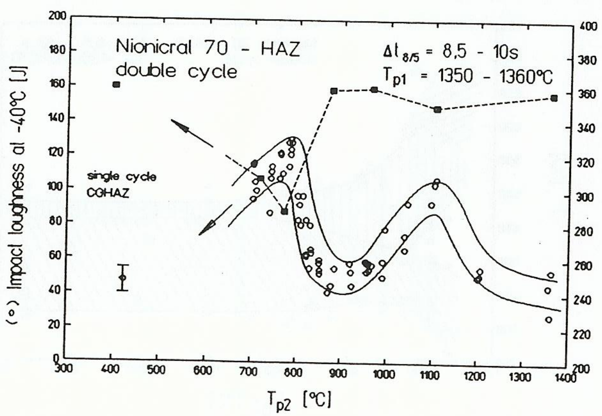

***Figure 4** Impact toughness and hardness of the single and double cycle heat affected zone adjacent to the fusion line upon peak temperature of the second thermal cycle*

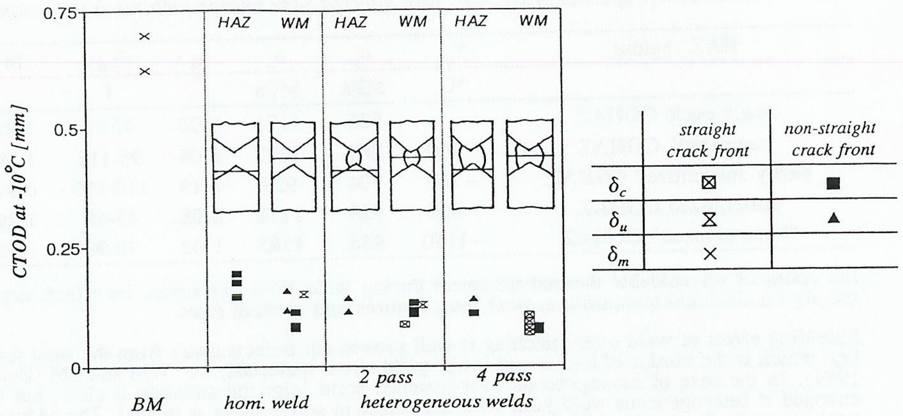

***Figure 5** CTOD fracture toughness of base material and over-matched weld joints with the crack in the middle of the weld and in the heat affected zone*

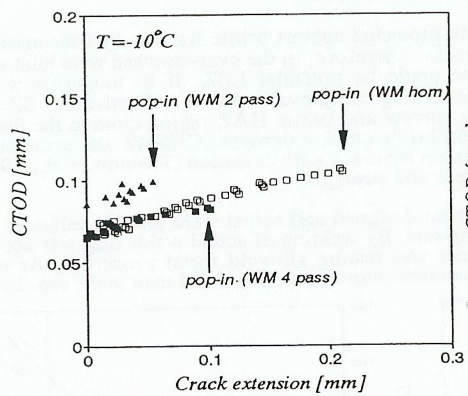

***Figure 6** R-curves for the weld material in the middle of homogeneous and heterogeneous weld joints*

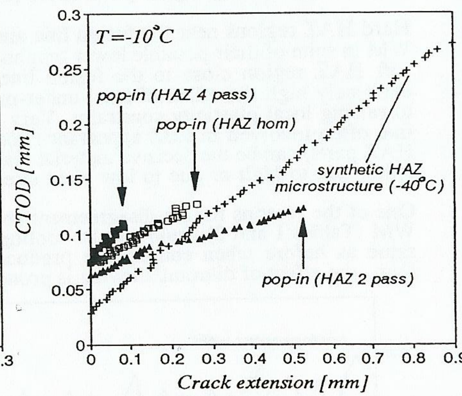

***Figure 7** R-curves for actual HAZ region (composite crack) and synthetic HAZ microstructure*

Comparison of homogeneous and heterogeneous weld joints fracture behaviour by CTOD testing with the composite crack has shown the following:

1. Homogeneous weld joint; LBZ has activated in the HAZ adjacent to the fusion line, where single cycle CGHAZ or double cycle HAZ is found. In the middle of the weld thickness where composite crack is sampled BM, fracture path turns towards the BM. The reason is over-matched WM. Close to the weld joint surface where composite crack is sampled WM, fracture path is straight.

2. Heterogeneous weld joints; LBZ has activated at the same position as in homogeneous weld joint. In the middle of the weld thickness where composite crack is sampled BM, fracture path turns towards the weld root. The reason is local under-matched root WM. Close to the weld joint surface where composite crack is sampled WM, fracture path is also straight.

CONCLUSIONS

Besides global over-matching, local strength differences among BM, WM and HAZ regions exist in weld joints. In over-matched multirun weld joints local mis-matching can be introduced intentionally but an additional local mis-matching also exists. It is the consequence of multi-pass welding procedure where thermal treatment causes either hardening or softening of WM and HAZ of previous weld passes. Both can be the dominating mechanical effect controlling fracture behaviour in the less tough WM and HAZ domains. Local mis-matching in the WM can be depicted by hardness measurement.

It is not easy to ensure sufficient tough WM and HAZ in over-matched weld joints on high strength quenched and tempered steels. Critical values of CTOD by fracture toughness measurement of actual weld joints were lower than those of BM. In this respect either over-matching condition all over the weld joint or excellent weld joint material clearness should be assured. The first is convenient due to its shielding effect, the later due to the lack of defects. Use of soft and tough weld consumable for the weld root cold cracks risk lowering does not always assure the existence of tough WM.

In weld joints containing soft root layer cold cracks have not appeared. These cracks are acting as a potential danger for brittle fracture initiation which can cause the whole weld joint disintegration. Overall strength of both heterogeneous weld joints was satisfactory. Transverse tensile strength was higher than that of as-delivered BM. So, over-matching conditions were ensured. CTOD of heterogeneous 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. In this respect, welding procedure with two pass soft root layer is found to be more appropriate than those without and with four pass soft root layer. This conclusion is based on satisfactory fracture behaviour of such kind of weld joint as regards homogeneous weld joint and lowered root cold cracking susceptibility. But, welding consumable for soft root layer should be carefully selected and appropriate welding procedure should be used to reduce too extensive toughness degradation.

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