STUDIES ON INITIATION TOUGHNESS AND TEARING RESISTANCE IN WELD JOINTS OF AN OFFSHORE STRUCTURAL STEEL

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ABSTRACT

The crack initiation toughness and tearing resistance studies have been conducted in a microalloyed steel weldment, a material for offshore structure and oil - gas pipeline. The CTOD resistance curves were obtained for the base metal, weld metal (WM) and the heat affected zone (HAZ) along weld direction (i.e. long transverse direction) and the thickness direction of crack propagation. The initiation toughness and tearing modulus were compared for the different zones of the weld joint and correlated with corresponding microstructural features and strength properties.

KEYWORDS

Tearing modulus, Heat affected zone, Weldment, CTOD toughness

INTRODUCTION

The microalloyed steel finds extensive application in the manufacture of offshore structures, oil and gas pipelines, pressure vessels, storage tanks for chemical and petrochemical industries etc. where fabrication is done mostly using welding process. The weld joint behaves like a composite material comprising of weld metal (WM), heat affected zone (HAZ) and the base metal (BM). The susceptibility to crack initiation and stable tearing therefore varies, from one zone to another .The present investigation is conducted to study the cracking behaviour of different regions of the joint in a microalloyed steel with C-0.22%, Mn-1.80%, Si-0.35%, S-0.04%, P-0.04%, Nb, V-0.20%.

WELD PARAMETERS

The joints were prepared by single bevel butt welding using single wire DC submerged arc welding machine along the long transverse direction of the plate .The welding conditions were optimized (Purohit, 1995) and presented in Table1.

Table 1. Details of Welding Parameters

Wire – 3.15mm diameter solid wire with composition C: 0.08-0.16%, Mn: 1.60-1.80%, Si: 0.05- 0.25%, S, P: 0.03%.	
Welding Current	250-375 A
OCV	40-45 V
Arc Voltage	26-28 V
Welding speed	50-70 cm/min
Heat input	5.6-12.6 kJ/cm
Nozzle to plate distance	35 mm
Polarity	DCEP
Interpass temperature	150 ^{o} C

The post welding heat treatment (PWHT) i.e. stress relieving was done as per ASM recommendations at 650 C followed by furnace cooling to room temperature.

TENSILE TEST

The tensile tests were conducted on base metal (BM) and the weld metal (WM). Round bars of 5.06 mm diameter and 17.9 mm gauge length were employed. The results on tensile properties are given in Table 2.

Table 2. Tensile Properties

	Base Metal	**Weld Metal (All-weld)**	**Joint**
Yield strength (MPa)	526	485	523
Tensile strength (MPa)	709	587	629
% Elongation	32	29	19
Strain hardening exponent	0.223	0.188	-

FRACTURE MECHANICS TEST

Fracture mechanics tests were conducted to investigate behaviour of crack growth and tearing resistance of steel in the BM, WM and the HAZ . In case of BM, crack propagation along rolling direction as well as long transverse direction were investigated, whereas in case of WM and the HAZ studies were made in weld direction and transverse to weld direction (i.e. thickness direction).

The tests were conducted as per ASTM Standard (ASTM E 1290, 1993) using single edge notch (SEN) bend type specimens of dimensions 10mm (thickness, B) 20 mm (width, W) 80 mm (span length, S) for crack propagation studies along the weld direction and 10 mm 10 mm 80 mm for studies along thickness direction. Tests were conducted using MTS machine under three point bending at ambient temperature. Load (P) vs. Crack mouth opening displacement (CMOD) diagrams were obtained and some typical ones are shown in Fig.1.

MICROSTRUCTURAL STUDIES

Microstructural examinations were conducted from the BM, WM and the HAZ. The BM microstructure consists of proeutectoid ferrite (about 80%) along with pearlite .The WM microstructure in low heat input condition consisted of polygonal ferrite (PF) accompanied with side plate ferrite (AC) and acicular ferrite (AF).The corresponding microstructure of HAZ revealed bainitic structure as well as fine pearlitic structure . Under condition of higher heat input large proportion of grain boundary ferrite (GBF) and some AF were noticed in the WM. The HAZ microstructure on the other hand consisted of both martensitic structure as well as ferrite carbide aggregate.

ELASTIC- PLASTIC CRACK INITIATION TOUGHNESS AND RESISTANCE CURVES

The CTOD initiation toughness, $_{i}$ were obtained for BM, WM and HAZ in different orientations as per ASTM standard. The values of initiation toughness are reported in Table 3 corresponding to 0.2 mm of crack growth. The CTOD values at crack initiation are shown in a bar chart in Figure 2. The CTOD resistance curves i.e. -R curves were obtained for different regions of the weld joint. Typical -R curves are presented in Fig. 3.

The -R curves were fitted in the form of equation, $d = a\left(b + \Delta a\right)^{g}$ where , and are constants. The representative equations of R curves are presented in Table 4.

Table 3. CTOD Initiation Toughness (a=0.2 mm)

Material	$_i$ **m**	**Material**	$_i$ **m**
BL	236	BB	209
WL	201	WB	148
WLR	166	WBR	149
HL	195	HB	119
HLR	141	HBR	144

NB B,W,and H in the beginning connote base metal ,weld metal and HAZ respectively. These are followed by L and /or B which indicate weld longitudinal and thickness direction of crack growth respectively. Symbol R towards the end stands for stress relieved condition of the joint.

Table 4. -R Curve Equations

Longitudinal direction		Thickness Direction	
BL	$=0.523(0.107+\ a)^{0.675}$	BB	$=0.560(0.041+\ a)^{0.690}$
WL	$=0.452(0.100+\ a)^{0.672}$	WB	$=0.356(0.032+\ a)^{0.603}$
WLR	$=0.332(0.040+\ a)^{0.483}$	WBR	$=0.340(0.041+\ a)^{0.580}$
HL	$=0.433(0.040+\ a)^{0.557}$	HB	$=0.425(0.080+\ a)^{1.000}$
HLR	$=0.392(0.026+\ a)^{0.685}$	HBR	$=0.420(0.094+\ a)^{0.872}$

and a are in mm

EVALUATION OF TEARING MODULUS (TM)

The tearing resistance of joint can be quantified in terms of the ‘tearing modulus’(T_M) which is given as

$$T_M = \frac{E}{s_f}\frac{dd}{d\Delta a}$$

where E is the elastic modulus. and $_f$ is flow stress which is given as,

$$s_f = \frac{s_{ys} + s_{UTS}}{2}$$

The tearing modulus were evaluated by obtaining d /d a from the equations of -R curves at different level of crack growth (Purohit, 1995). The tearing modulus is indeed found to depend on the amount of crack growth and it decreases with increasing crack extension. The representative variation of T_M with a is presented in Fig. 4 and the values of ‘tearing modulus’ at initiation of crack growth (i.e. a 0.05mm) and also at a = 0.5mm are shown in Table 5.

DISCUSSION

From Table 2. It is observed that the base metal possesses higher yield and tensile strength as compared to all – weld metal. The lower value of strength properties for the WM is mostly due to presence of coarse grain boundary ferrite and polygonal ferrite in large proportion. This structure is unfavourable both for the strength and fracture toughness. The hardness profile indicated almost similar hardness value (=250VHN) for the WZ and the HAZ, though the base metal showed a somewhat lower hardness (=230VHN).

In general it is found that (Table 3) the initiation toughness, $_{i}$ is lower in thickness direction as compared to the weld direction of cracking. The higher $_{i}$ of BM as compared to WM and the HAZ is attributed to its favourable inclusion morphology and their orientation as well as refined grain structure of ferrite and pearlite (Sundaram et al, 1987). The banded structure of ferrite–pearlite does also appear to be advantageous in this respect as the crack initiation was to take place in a direction transverse to the banded ferrite-pearlite structure. The CTOD toughness of HAZ is lower than that of BM and the WM. Presence of somewhat coarse martensite and AC structure are considered to be responsible for reduced toughness of HAZ. In addition, microcracks were also noticed in HAZ which are likely to bring down its toughness (Parmar, 1993). In case of WM, presence of large proportion of GBF and scattered spherical inclusions are detrimental to fracture toughness; though presence of acicular ferrite is expected to have some favourable effect on toughness (Pandey, 1989).

Table 5: Tearing Modulus in Weld Joint

Material Condition	T_m		Material Condition	T_m	
	Initial	a=0.5mm		Initial	a=0.5mm
BL	200	141	BB	241	159
WL	221	143	WB	188	103
WLR	232	082	WBR	208	100
HL	261	115	HB	155	155
HLR	223	120	HBR	164	146

The T_m values can be used to assess integrity of structures where some amount of crack growth is permissible. Based on initial T_m values, it is observed from Table 5 for the longitudinal direction of crack growth that the as-welded HAZ provides the maximum resistance to tearing and is followed by the stress-relieved weld metal. The tearing resistance in other conditions is almost the same. On the other hand for the thickness direction crack growth the trend of tearing resistance is reversed. The BM possesses the maximum resistance to tearing whereas the HAZ has the minimum value. At a = 0.5 mm, it may be noticed that the stress relieved weld metal provides interestingly the minimum tearing resistance for both the longitudinal and thickness direction of tearing initiation. In general, the stress relieving heat treatment does not appear to have much beneficial effect on the crack growth resistance of the weld joint especially when the crack growth is significant (0.5 mm or more) although during the initial stage of crack growth it does produce some positive effects.

The stress relieving PWHT is believed to reduce the level of residual stress. However in the present case, the WM and the HAZ toughness remained practically unaffected after PWHT. Apparently, the 650 C heat treatment causes simultaneously microstructural changes such as carbide precipitation, coarsening of fine carbides etc. leading to deterioration of strength and toughness. This partly negates the beneficial effects of the PWHT.

CONCLUSIONS

1. The -R curves for the microalloyed steel can be expressed in the form of = (+ a) where , , are lying in the range of 0.33-0.56, 0.03-0.10 and 0.48-1.0 respectively.
2. The base metal possesses higher initiation toughness ($_{i}$) and yield strength values as compared to WM and the HAZ for both as weld condition and the PWHT condition and the HAZ has generally the minimum toughness. Also the weld direction toughness is higher than the thickness direction toughness.
3. The TM decreases with a in all cases. The as-welded HAZ provides maximum TM value followed by stress relieved WM for weld direction crack growth. In the other direction, the BM shows maximum TM

whereas the HAZ shows the minimum. The behaviour of initiation toughness and the tearing resistance has been correlated with microstructure.

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CMOD, mm

FIG 1. TYPICAL LOAD VS CMOD DIAGRAMS IN MICROALLOYED STEEL