NUMERICAL AND EXPERIMENTAL INVESTIGATION OF THE INFLUENCE OF HAZ ON THE FRACTURE BEHAVIOUR OF LONGITUDINAL WELDED LINEPIPES

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ABSTRACT

The present paper deals with the influence of heat affected zone (henceforth HAZ) on the fracture performance of longitudinal welded linepipes in dependence on constraint level. It has been shown that toughness values of HAZ obtained from standard fracture mechanics tests lead to uneconomic linepipe design for two reasons. The first reason is that laboratory specimens with higher constraint level generally exhibit lower fracture resistance compared to flawed linepipes. The second one has to do with a higher probability of cleavage failure occurrence in the laboratory specimen than in the linepipes due to larger areas of lower toughness (so called local brittle zones (LBZ)) intersected by crack front. In recent years numerous studies have been initiated with the objective to quantify the constraint level and thus to allow for less conservative linepipe safety assessment by applying constraint corrected toughness values. However, the main focus of these studies has hitherto been on the homogeneous materials, failing to account for the possible effects of different microstructures within the heterogeneous HAZ.

This paper seeks to close this gap by reporting on results from tests on fracture mechanics specimens of a high strength X80 steel, i.e. SENB and SENT specimens as well as results from ring expansion tests. Both, deep and shallow cracks are inserted in the fracture mechanics specimens and rings targeting the fusion line (FL). By varying the initial crack size and sample type, different constraint levels are achieved and subsequently quantified using numerical methods. Besides constraint observations, post metallographic analyses are performed to identify exact HAZ microstructure involved at the crack tip. Finally, the influence of HAZ properties, flaw size and geometry on the failure behaviour of the linepipes has been demonstrated and assessed.

Based on the combination of the results from constraint studies and the post metallographic analyses, the methodology is proposed which enables simple quantitative prediction of toughness values for safe and economic design of linepipes with flaws located in HAZ.

KEYWORDS

X80, HAZ, constraint analysis, linepipe safety, LSAW linepipe, local brittle zones, finite element modeling

INTRODUCTION

The growing world-wide energy demand has resulted in exploration of new gas fields in remote area with harsh climate conditions leading to increasing requirements on the mechanical properties of linepipe material. Hence, the development of high strength steel grades has been recently promoted for longitudinal submerged arc welded (LSAW) linepipes. One of the challenges encountered lies in the production of high quality welds with low defect probability and required combination of strength and toughness properties. The lowest toughness values of the weld have been expected in the discrete microstructural regions of coarse-grained heat affected zone (CGHAZ), referred to as local brittle zones (LBZ). Despite the achieved improvement of overall HAZ toughness by optimizing alloying concept and welding techniques, LBZ cannot be completely avoided, due to restrictions with respect to chemical composition and welding procedure (heat input, cooling time) within specific linepipe production.

In last two decades, especially in the 90's, the focus of many research studies [1]-[8] has been on understanding the LBZ's significance for structural integrity and on derivation of appropriate testing method to determine HAZ toughness properties. These studies investigated the effects of geometry constraint (size, crack depth, global geometry and mode of loading), weld (yield strength mismatch, hardening mismatch) and the LBZ size along the crack front on the toughness values. There has been a general consensus that toughness values obtained from test specimens with high constraint will lead to conservative toughness values penalising material load bearing capacities. Procedures have been proposed, which allow for use of constraint effects in the safety assessment [3], [6], [7] and determination of toughness properties from low constraint geometries [9], [10], [11]. The concept of welding mechanics has arisen from the analyses of weld effects addressing the interdependence of mechanical and toughness properties of weldments. Regarding the LBZ size effect, the results from fracture mechanics tests have shown that the mean (average) toughness values are influenced by the total CGHAZ size, while the minimum values seem to be unaffected [7], [8]. Despite many useful findings and methods resulting from these studies, there is still no clear and satisfactory procedure included in standards on how to evaluate the effect of the HAZ properties on the fracture performance of flawed linepipes.

The overall aim of this paper is to characterise the HAZ toughness properties of longitudinal weld of high strength pipeline steel by taking into account effects from geometry (specimen geometry, crack depth) and weld (softened regions in the HAZ). The geometry constraint effects for fracture mechanics tests on two specimen types (SENB and SENT) with two crack depth ratios (a/W=0.2 and 0.5) and ring expansion tests are investigated numerically. The influence of the weld mismatch is considered by flow curves for all four zones, base metal (BM), weld metal (WM), fine and coarse grain zones (FGHAZ, CGHAZ). By means of post-metallographic analyses the location of initial crack tip is verified regarding microstructure sampled. Furthermore possible correlation between the controlling microstructure and toughness values should be recognised. The achieved results should serve derivation of methodology for the safety assessment of flawed longitudinal welded linepipes.

MATERIAL PROPERTIES OF INVESTIGATED WELD

Chemical composition and weld microstructure

The material properties of high-strength X80 steel are determined on the sections extracted from a pipe with an outer diameter 42" and a wall thickness of 33.5mm. The results from chemical analysis are presented in Table 1.

Steel	C	Si	Mn	P	S	Al	N
X80	0.063	0.305	1.881	0.012	0.001	0.036	0.023
Other alloying elements: Ni, Mo, Nb and Ti							

Table 1: Chemical composition of X80, mass contents in %

Longitudinal welds of high strength large diameter linepipes are produced using submerged arc welding (SAW) in two passes. The formation of the microstructure and herewith the mechanical properties depend primarily on the weld cooling time, the maximum reheating temperature and alloying concept. Typical macrograph of weld cross section is given in Fig. 1 showing three characteristic zones, i.e. base metal (BM), weld metal (WM) and heat-affected zone (HAZ), which consists of FGHAZ and CGHAZ.

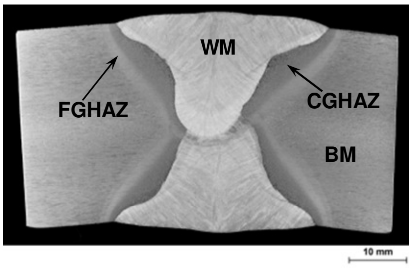


Fig. 1: Macrograph of weld cross section

The base metal exhibits homogeneous bainitic-ferritic microstructure with distinct volume fraction of carbide particles and ferritic phases. The difference in microstructure between HAZ and WM can be observed in Fig. 2. The fine grain HAZ heated to around 900-1200℃ shows upper bainitic microstructure with non-aligned MA constituents and grain boundary ferrite. The grain coarsened HAZ adjacent to WM is heated above 1200℃ and consists of upper bainitic microstructure with aligned MA constituents and Widmanstatten ferrite. These microstructural entities are responsible for poor toughness properties. As the alteration of cooling conditions in two passes SAW is very limited, the improvement of the HAZ properties can be induced by varying the chemical composition. The microstructure of weld metal comprises phases of fine acicular ferrite with expected higher toughness level compared to HAZ. The nucleation of acicular ferrite is promoted by presence of numerous oxide inclusions which provide favourable heterogeneous nucleation sites.

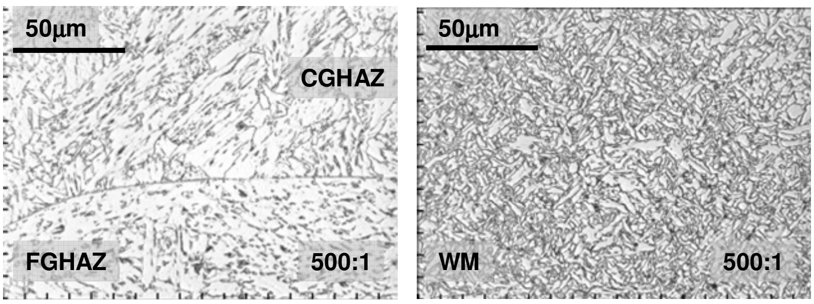


Fig. 2: Microstructure of HAZ and WM

Mechanical properties

Mechanical properties of BM and WM are obtained from tensile tests on 8x40 smooth round bar and 3x15 all weld specimens. The results from mechanical tests summarised in Table 2 show anisotropy only in terms of yield stress (11%).

Steel	Zone	Direction	R_{eH} [MPa]	R_{eL} [MPa]	$R_{p0.2}$ [MPa]	R_m [MPa]	$R_{p0.2}/R_m$ [%]	A [%]
X80	BM	L			557	641	87	22
		T			624	642	97	22
	WM	outer	640	619	621	688	90	21
		inner			679	716.3	95	22

Table 2: Mechanical properties of X80 for BM and WM

In order to estimate strength values for CGHAZ and FGHAZ, Vickers hardness (HV10) of the weld are measured 2.5 mm away from the outer ("outer") and inner surface ("inner"). The results of hardness measurement are depicted in Fig. 3, showing hardness drop in HAZ. Based on the results from tensile tests and hardness measurements true stress-strain curves are generated as input data for numerical simulations, s. Fig. 3.

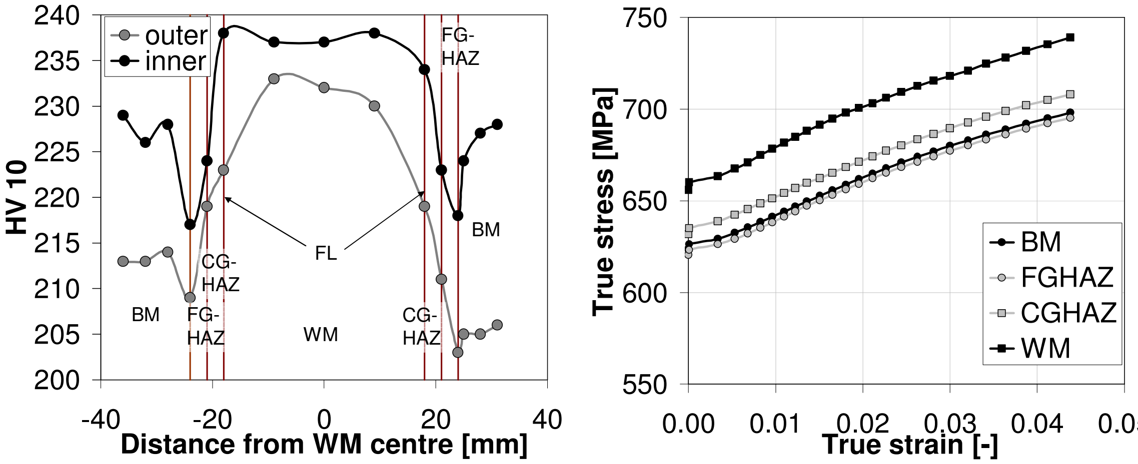


Fig. 3: Hardness values HV10 of X80 weld (left), true stress-strain curves (right)

EXPERIMENTAL INVESTIGATIONS

Fracture mechanics tests

Fracture mechanics tests are performed at room temperature on two types of specimens (SENB and SENT) with the objective to evaluate the effect of HAZ on failure behaviour of X80 steel. Compared to standard SENB specimens, SENT specimens should allow for less conservative assessment of flawed linepipes due to the lower constraint level [9],[10]. The dimensions (square cross-section) of specimens extracted from the circumferential direction are 27x27[mm²] and 25x25[mm²] for SENB and SENT specimens, respectively. In all cases the target location of fatigue pre-crack tip is at the fusion line on the outer diameter bead. Besides different specimen and test types, the constraint variation has also been achieved by varying the crack depth ratio a/W. Hence, the shallow notch configuration (a/W=0.2) is introduced for both types of specimens in addition to standard deep notched (a/W=0.5) SENB specimens, which should serve determination of baseline values. The test procedure of the SENB tests is in accordance with [12] as far as possible, although notch depth criteria are not acceptable. On the other hand tests on pin-loaded SENT specimens are conducted according to [11].

The results from fracture mechanics tests show distinct dependence of the achieved toughness values in terms of both fracture toughness parameters (J-integral and CTOD) on constraint level. With exception of two outliers, all 6 tested deep notched SENB specimens failed in the brittle manner with toughness values ranging from CTOD=0.03mm

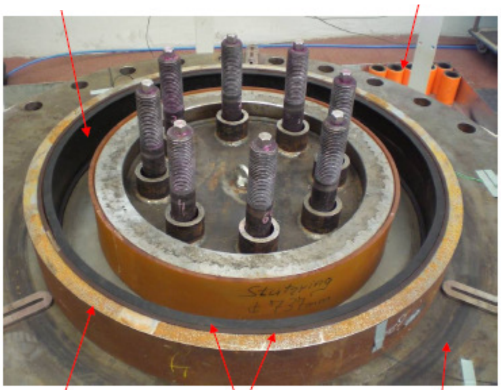
(J=28N/mm) to 0.17mm (J=162N/mm). With decreasing a/W ratio to 0.2 for SENB specimens, the lower ductile-brittle transition region is reached with toughness values from CTOD=0.14mm (J=125N/mm) to 0.46 (J=409N/mm). In almost all tests the failure ductile tearing is less than 0.2mm. By applying shallow notched SENT specimens the toughness values are determined in upper transition region revealing higher scatter in toughness values when compared to values from SENB tests. The values range from CTOD=0.03mm (J=50N/mm) with pop-in occurrence to 0.92mm (J=714N/mm). The maximum measured ductile tearing is 0.51mm. After testing, post-metallographic analyses are carried out on sectioned specimens to check the location of the initial crack tip with respect to microstructure sampled and to measure the distance between crack tip and FL. The results show, that toughness values from tests on the SENB specimens with a/W=0.5 do not depend on the distance from the FL as long as the crack tip is located in CGHAZ. Regarding shallow notched specimens the critical values are obtained with crack tip sampling CGHAZ in distance <0.3mm from the FL, where the influence of stress concentration resulting from geometrical and material discontinuity at the interface is also relevant besides low toughness properties. However, no clear correlation between these toughness values and the distance from the FL can be established. While in case of ductile tearing, the crack will deviate towards softer FGHAZ, the instable crack propagation takes place parallel to FL.

In order to assess the influence of constraint level on the HAZ toughness, the measured toughness values are statistically evaluated according to master curve approach [13]. The decreasing constraint level due to reduction of crack depth for SENB specimens causes decrease in calculated reference temperature from T_0=-5.1 to -34.3°C. Compared to effect of crack depth the reference temperature shift resulting from using SENT instead of SENB specimen is lower with T_0= -44.7°C for SENT specimens.

Ring expansion tests

In order to estimate the effect of HAZ on the fracture performance of flawed linepipes, ring expansion tests are conducted at room temperature on 4 pipe rings with a height of 150mm. The rings are extracted from the pipe section and notched along the whole height targeting the FL. Two different notch depths of 6 (shallow) and 12mm (deep) are inserted for each two rings by spark erosion. Fig. 4 shows set-up for ring expansion tests. The rings are positioned between two steel plates and subjected to hydraulic pressure. The free expansion of the rings in the radial direction can be ensured by applying seals slightly higher than the ring.

The minimum burst pressures reached for shallow and deep notched rings are 316 and 400bar, respectively, s. Fig. 4. These pressures are equal to 99% and 97% of pressure level at calculated plastic collapse. This result and the fact that higher CTOD (J-integral) values are determined in case of deep notch configuration (s. Fig. 4) indicate that the failure of the flawed rings has been governed by the plastic collapse and not by the deteriorated toughness properties of HAZ.



Ring	Crack depth a [mm]	Pressure [bar]	CTOD [mm]	J [N/mm]
2	6	406	0.80	707
3	6	400	0.67	587
1	12	316	0.99	879
4	12	320	1.12	998

Fig. 4: Ring expansion test set-up (left), major test results (right)

NUMERICAL INVESTIGATIONS

Constraint analyses

The constraint level for different geometries and crack depth is quantified by means of numerical analyses. The elastic-plastic analyses of local stress fields are carried out using commercial FE analysis software ABAQUS v 6.9. In order to ensure the accuracy of performed analyses, all models of investigated specimens are calibrated on the global load-displacement curves. The constraint is evaluated in terms of parameter Q+M [14], which takes both geometry Q and mismatch M constraint into account. The investigations of the mismatch effect for crack located at the FL according to [7] and [10] have shown that increasing weld metal overmatch will lead to increasing constraint level and thus to critical toughness values. In this study the mismatch constraint is held constant, while the geometry constraint is varied.

Fracture toughness values (CTOD and J-integral values) are plotted in dependence of the constraint parameter Q+M, s. Fig. 5. It should be noted that calculated constraint parameters result from elastic-plastic analyses without considering ductile tearing. Although the prevailing tendency of increasing toughness with decreasing constraint is evident, the assessment of obtained data is influenced by degree of scatter. In general, the results show distinct benefit of reduced constraint and can therefore be used for the design of linepipes within constraint correction procedures. However, the results from ring expansion tests suggest that constraint level in the flawed rings and hence pipe is low enough to significantly diminish the effect of LBZ on the failure behaviour.

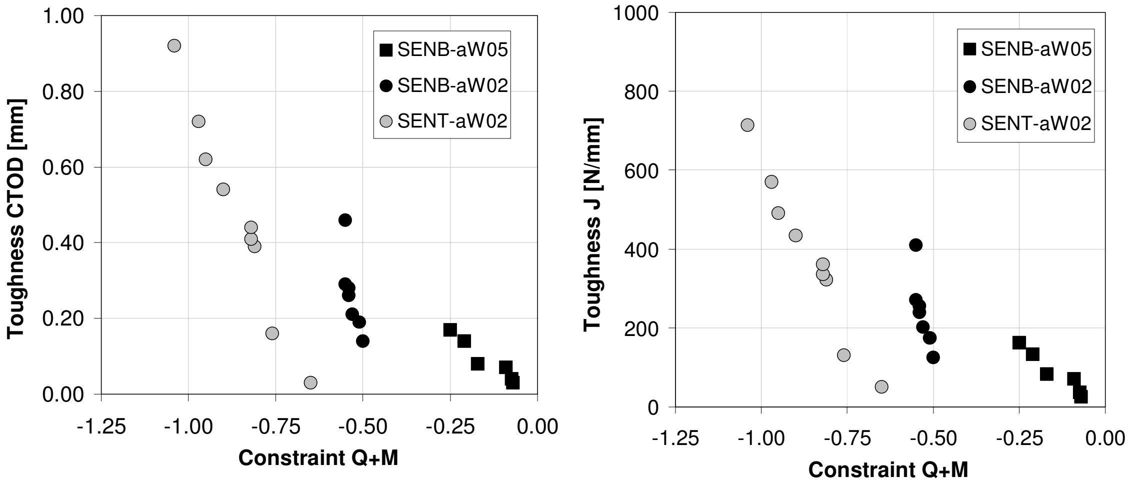


Fig. 5: CTOD (left) and J (right) toughness values vs. constraint Q+M

Beremin Model

Besides constraint analyses, the failure probabilities (P_f-values) for analysed specimen configurations are determined by applying Beremin local approach model, This model is based on the probabilistic Weibull theory [15]. Despite many deficiencies, the main advantage of this model arises from the possibility to capture the effect of the constraint level on the failure behaviour by taking the local stress state directly into account. The required Beremin parameters m=21 and σ_u=2794MPa result from the maximum likelihood method.

The experimental and predicted failure probabilities for fracture SENB and SENT tests are depicted in Fig. 6.

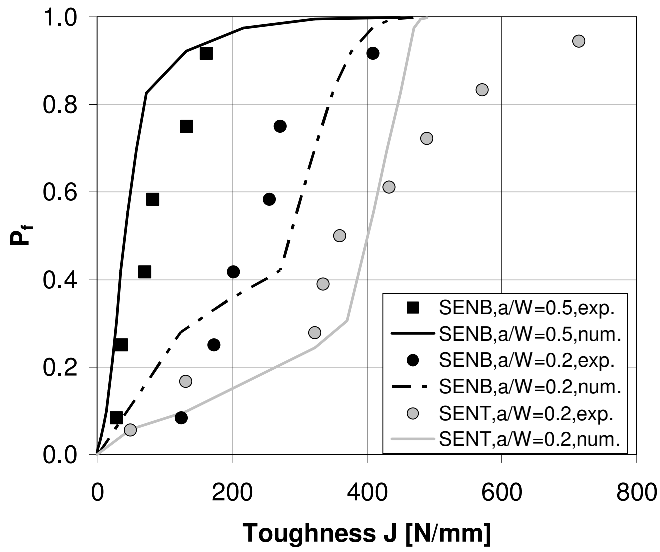


Fig. 6: Experimental and predicted P_f-values for SENB and SENT specimens

Generally, the shift of the P_f-J curve towards higher toughness values with decreasing constraint can be reproduced well by numerical model. In case of deep notched SENB specimens, Beremin model overestimates the experimental P_f-values by maximal 16%. Due to increasing scatter band for lower constraint geometries, the larger data are required for the construction of the experimental curves and calibration of parameters.

The significant advantage for linepipe design due to geometry effect on the toughness values can be demonstrated by the model. Hence, the application of shallow notched SENT instead of SENB specimens would lead to maximal reduction of predicted failure probability by ca. 20% for J<250N/mm. For shallow notched SENT specimens and J<300N/mm the P_f-values are underestimated by the model in the range of ca.10%. By considering the effect of ductile crack growth, the prediction accuracy can be improved [10].

Regarding the evaluation of ring expansion tests for the shallow notch geometry, it can be shown that the Weibull stress (σ_w=2368MPa) at the onset of net section yielding is lower than the Weibull stress (σ_w=2386MPa) corresponding to the lowest toughness value CTOD=0.03mm (J=50N/mm) obtained by shallow notched SENT specimen. Thus, the probability that brittle failure may occur for pipe ring prior to net section yielding is lower than 5%.

SUMMARY

This paper outlines the effect of HAZ properties on the fracture behaviour of high strength longitudinal welded linepipe. The performed studies include besides fracture mechanics and ring expansion tests also numerical analyses for the quantification of constraint effects. The following conclusion can be drawn based on the results obtained by these studies:

- The application of shallow instead of deep notched SENB specimens causes shift from low shelf to lower transition region. On the other hand, the change of specimen type from shallow notched SENB to SENT specimens leads to failure occurrence in the upper transition region.
- Based on the results from master curve approach, the benefit from using shallow notched geometry is higher than from different specimen type.
- Toughness values gained by standard deep notched specimen with highest constraint level seem not be sensitive towards differing microstructure along the FL and the distance from the FL as longs as the CGHAZ is sampled by a crack tip.
- By applying low constraint geometry, the most critical toughness values are determined for the initial crack tip located maximal 0.3mm away from the FL.
- Constraint corrected values correspond well to experimental values with respect to three different failure probabilities (P_f=5%, 50% and 95%), s. Table 3. Thus, effective assessment can be preformed by either using constraint corrected toughness values from standard fracture mechanics specimens or toughness values obtained from low constraint specimens.
- The Beremin model provides conservative predictions of toughness values for P_f=5%, s. Table 3. On the other hand the values for P_f=50% are underestimated. Despite the inaccuracy of the predicted values, the general trend of increasing toughness values with constraint reduction can be described well by the model.
- The pressure levels for shallow notched ring test (burst pressure=394bar) corresponding to J values at P_f=5% (master curve) for SENB (a/W=0.5), SENB (a/W=0.2) and SENT (a/W=0.2) specimens are 285, 345 and 358bar, respectively. These pressures correspond to 72%, 87% and 90% of calculated plastic collapse load. The result demonstrates once again the significant advantage when applying low constraint specimen for assessment of flawed linepipes.

Specimen type	a/W	Toughness value	Master-Curve (MC)			Constraint-Correction			Beremin model		
			P_f=5%	P_f=50%	P_f=95%	P_f=5%	P_f=50%	P_f=95%	P_f=5%	P_f=50%	P_f=95%
SENB	0.5	CTOD [mm]	0.03	0.08	0.18	0.03	0.08	0.18	0.01	0.04	0.18
		J [N/mm]	32	90	172	32	90	172	8	42	173
SENB	0.2	CTOD [mm]	0.09	0.24	0.50	0.09	0.24	0.40	0.03	0.31	0.43
		J [N/mm]	75	222	447	71	222	360	28	284	390
SENT	0.2	CTOD [mm]	0.13	0.38	0.80	0.13	0.39	0.70	0.06	0.47	0.59
		J [N/mm]	104	314	639	101	319	561	43	380	478

Table 3: Summary of toughness values for three different levels of failure probability

Further studies will be conducted to take account for low temperature effects on the toughness properties. All results obtained by these investigations will be used to derive the methodology for effective design of longitudinal welded linepipes.

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