Paper No.

11107

EFFECT OF RESIDUAL STRESSES ON THE HIC RESISTANCE OF ERW PIPES FOR LINE PIPE APPLICATIONS

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ABSTRACT

Four material grades for production of ERW pipes welded by high-frequency induction (HFI) were selected for hydrogen induced cracking (HIC) tests. API 5L Grade B, X52 and X65 were intentionally produced from non sour service material in order to ensure sufficient HIC damage during exposure in NACE TM0284 test solution A.[1] The highest material strength included was grade X70 designed for sour service to investigate whether HIC cracks can be initiated solely by the presence of high residual stresses.

In addition to a substantial characterization of mechanical properties and residual stresses, a series of experiments under simulated residual stress to determine the HIC resistance of these pipe materials in NACE TM0284 test solution A has been carried out using the four-point-bend test setup. The Crack Area Ratio (CAR) accounting for the extent of HIC cracking was as well correlated with basic alloying characteristics of the steels as with residual stresses.

The results of the test series combined with supporting theoretical considerations and finite-element (FEM) modelling revealed that in the case of HFI pipes the pre-material suitability for sour service is of much higher importance than residual stresses induced by pipe forming. It is demonstrated that there is no negative impact of residual stresses on the HIC resistance.

Keywords: HIC, sour service, residual stress, ERW pipe, high-frequency induction welding,

INTRODUCTION

Over the last decades an increase in the exploration and exploitation of impure oil and gas resources in remote environments under aggravated conditions has become necessary. This led to a growing demand for pipes with resistance to sour service. Therefore the product range of High-Frequency-Induction (HFI) welded pipes has been extended to HIC resistant steels in recent years.

For the exploration of such critical wells HIC resistant steel grades are needed because the material is exposed to a specific kind of corrosive medium during production and transport, which can result in Hydrogen Induced Cracking (HIC).[2] Hydrogen atoms diffuse into the steel matrix and recombine under high pressure (>>100,000 kPa) to molecular hydrogen (H_2) at hydrogen traps (Figure 1). Thereby cracks occur in the steel matrix which can lead to failure of the pipe (Figure 2).

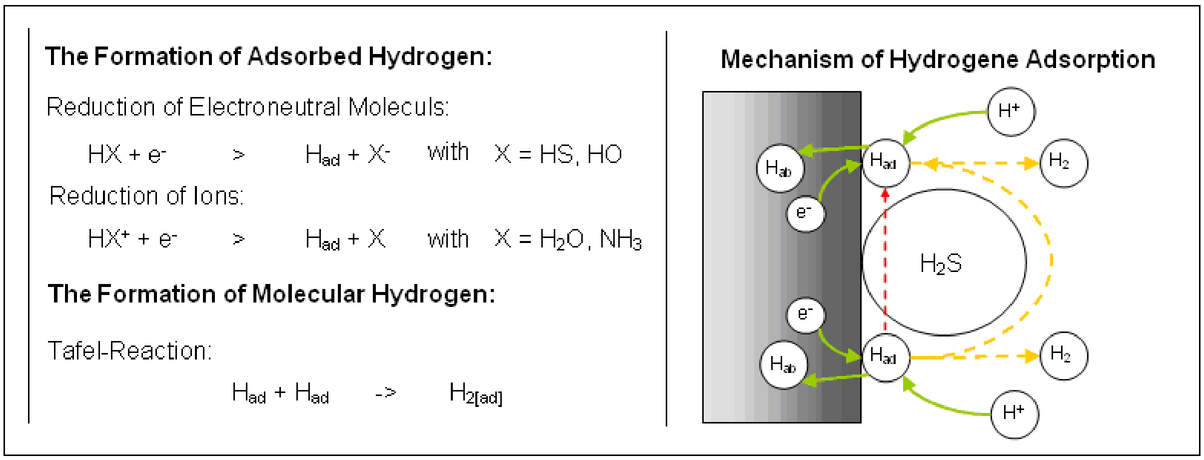


Figure 1: Schematic figure of the HIC mechanism. Formation of adsorbed and molecular hydrogen (left) and inhibition of H_2 formation due to surface adsorbents (here H_2S) on the contact surface medium/steel (right) [3]

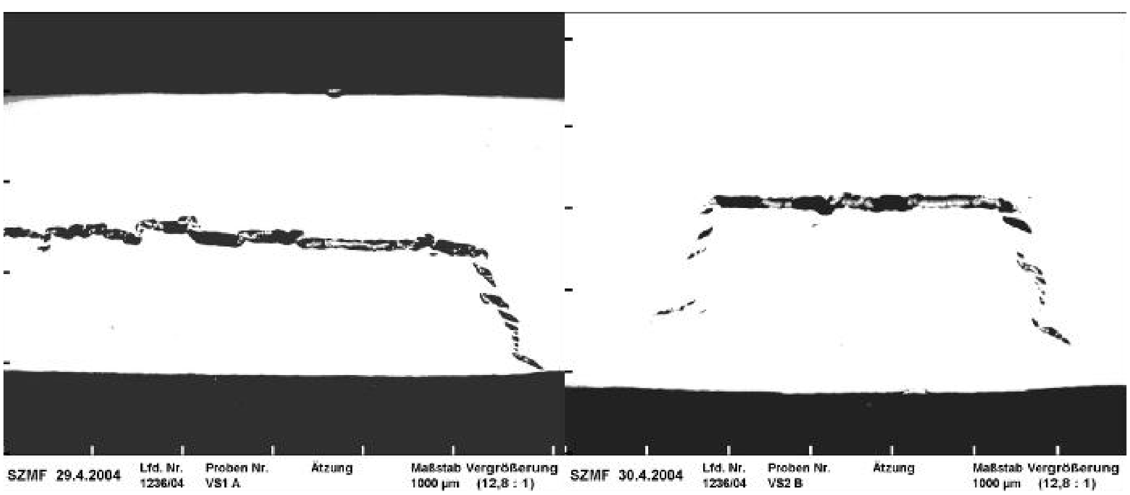


Figure 2: Typical HIC crack (left) and blistering (right) as specific form of hydrogen induced cracking on the inside of a pipe sample

In the process of HFI-welding of pipes, forming roles bend steel coil into a pipe, which is then longitudinally welded without filler metal. The cold forming originating from the pipe forming process results in residual stress, depending on the diameter and wall thickness of the pipe. The current state of the art is based on the perception that this residual stress has an adverse effect on the resistance of line pipes to HIC, because it amplifies the extent – or, if it is sufficiently high – even triggers the onset of HIC. The aim of this paper is to study the influence of residual stress on the resistance in HFI welded pipes to HIC with regard to process-specific influencing factors.

One of the basic parameters for hydrogen induced cracking is the interaction of adsorbed atomic hydrogen with the interface medium/material, absorption of hydrogen, diffusion of hydrogen through the material. The likelihood of HIC cracking is linked to number, kind, size as well as distribution of the hydrogen traps in the material. A sufficient presence of H_2S in the medium (as promoter for hydrogen absorption) is required as well. Gas is called “sour” with respect to NACE MR 0175/ISO 15156 if the hydrogen sulphide partial pressure is above 0.35 kPa (0.05 psi).[4] However, even trace amounts of H_2S have to be considered when HIC is taken into account. Gas with less hydrogen sulphide partial pressure is called “sweet gas”.

RESIDUAL STRESSES DURING HFI WELDING

In the process of HFI welding of pipes, forming roles bend steel coil into a pipe which is then longitudinally welded without any filler metal (Figure 3).

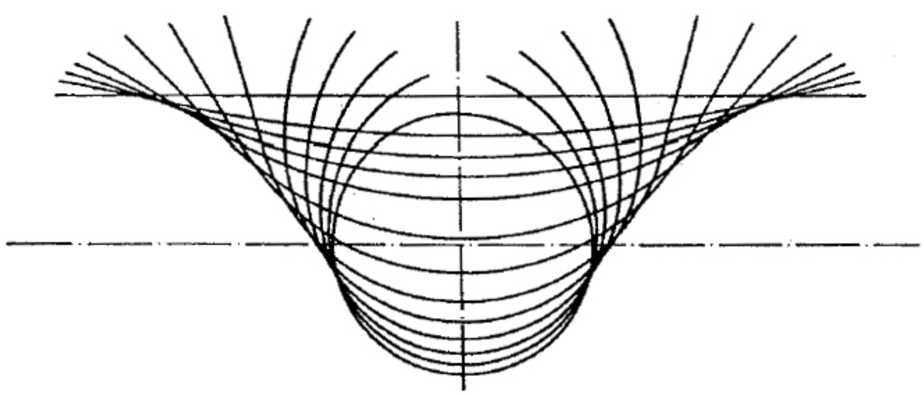


Figure 3: Bending section of the HFI process [5]

This cold forming results in residual stress because of transversal contraction, depending on the diameter and wall thickness of the pipe (**Figure 4**).

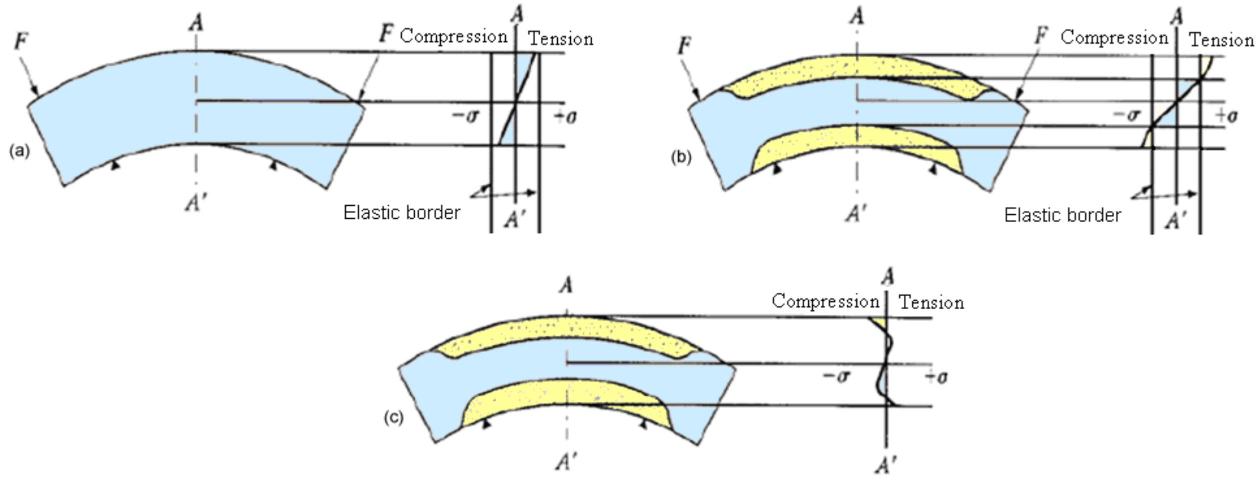


Figure 4: Residual stress distribution (compression/tension) on a beam under bending: a) elastic state of stress, b) and c) elastic-plastic state of stress with plastically deformed areas (yellow) [6]

With help of the cross-sectioning method the longitudinal and circumferential residual stress for steel plates and pipe segments were measured on eight specific process influencing steps and two different steel analyses (non sour /sour) for an API5L steel grade X42N (Figure 5/6).[7]

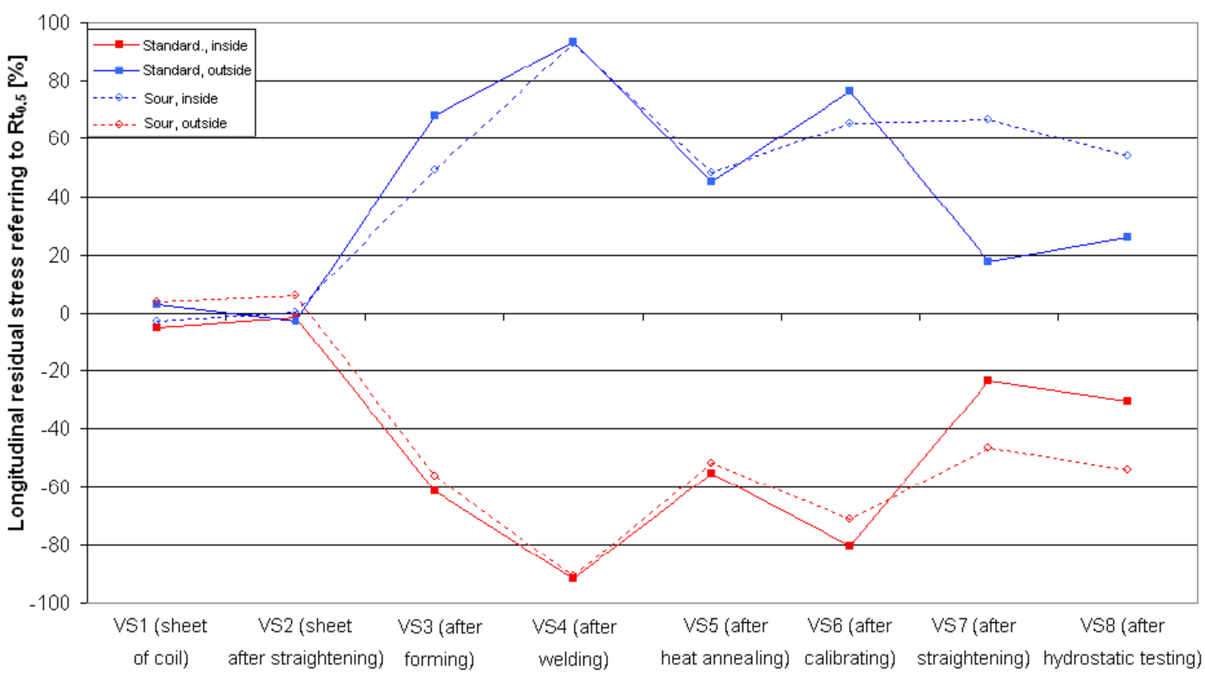


Figure 5: Comparison of the longitudinal residual stress [in %] of conventional (non sour) steel pipes and steel pipes for sour service in the API5L grade X42N; 114.3 mm x 5.0 mm

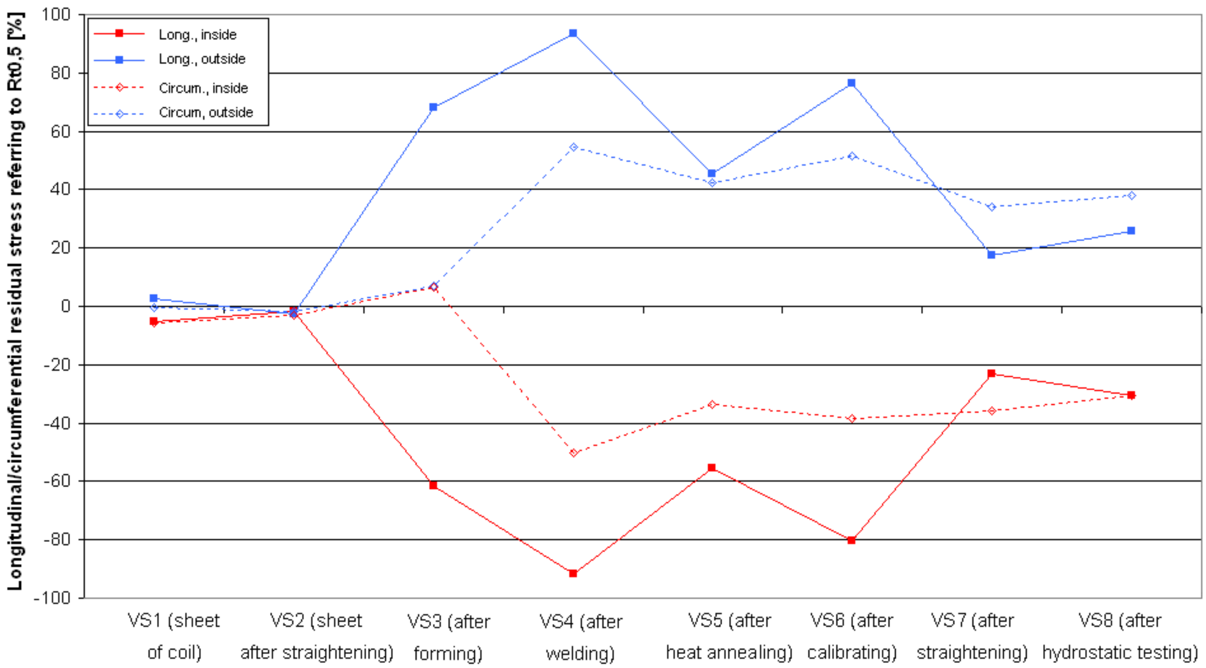


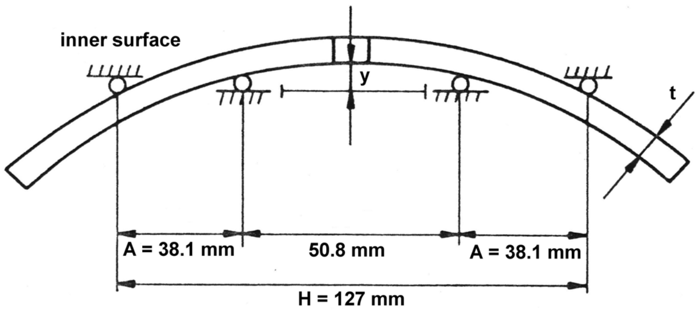
Figure 6: Comparison of the longitudinal and circumferential residual stress of conventional (non sour) steel pipes in the API5L grade X42N

The longitudinal residual stress can amount nearly to 100% referring to the yield strength of the specific material. The highest residual stresses are located in the process steps of forming and welding and after calibration of the pipes. A strong variation of longitudinal residual stress can be measured over process step 4 to 6. At least there is no big difference between the residual stress behaviour of the sour and non sour material. They both can be considered as equivalent within the normal process variation (Figure 5).

The circumferential stress behaves more uniformly over the last five process steps than the longitudinal stress and it is lower by almost the half (Figure 6). At the end of all process steps the residual stress of HFI pipes varies in a range of ~20-50% referring to the yield strength in longitudinal as well as in circumferential direction.

INFLUENCE OF RESIDUAL STRESSES ON THE HIC BEHAVIOR

Based on the above mentioned results of residual stresses in HFI pipes laboratory tests were carried out to determine the impact of the maximal residual stress – depending on the material strength - on the HIC triggers and on the HIC resistance expressed with the Crack Area Ratio value (CAR) determined by use of an ultrasonic in-house technique. A series of experiments were carried out using the four-point-bend test according to ASTM G39 (Figure 7)[8]. Defined stresses were applied in order to simulate the presence of residual stresses in HFI pipes.



$$\sigma = \frac{12 \times E \times t \times y}{3 H^2 - 4 A^2}$$

σ = max. tensile strength

E = Young's modulus

t = sample thickness

y = maximum deflection

H = distance between outer supports

A = distance between inner and outer supports

Figure 7: Sketch of a four point bend test (not correct scale) with deflection *y* to adjust the exact amount of stress with regard to ASTM G39

Table 1
Examined steel grades with increasing yield strength levels

Grade	API	$R_{t0.5\ trans}$ in MPa	$R_{m\ trans}$ in MPa	Sample Geometry LxBxH in mm	C in wt-%	Mn in wt-%
A	Grade B	316	434	140x15x8	0.10	0.46
B	X52	463	535		0.11	1.35
C	X65	532	653		0.13	1.28
D (sour)	X70	510	557		0.04	1.09

Four material strength levels were selected for the tests (Table 1). The first three material strengths (Grade B – X65M) were intentionally produced from non-sour-service material in order to obtain sufficient HIC damage. The highest material strength examined was a HIC resistant steel alternative to ascertain whether under optimal material conditions HIC indications can result solely through high residual stress. For each variation four test pieces as a reference (without residual stress) were prepared. Another set was prepared with 100% simulated residual stress and the HIC triggers in the neutral area (Figure 8 – A). A further set was prepared with 100% simulated residual stress and the HIC triggers located in the area of maximum tension (Figure 8 – B). Finally, the last set was prepared with 100% simulated residual stress and the HIC triggers located in the area of compression (Figure 8 – C).

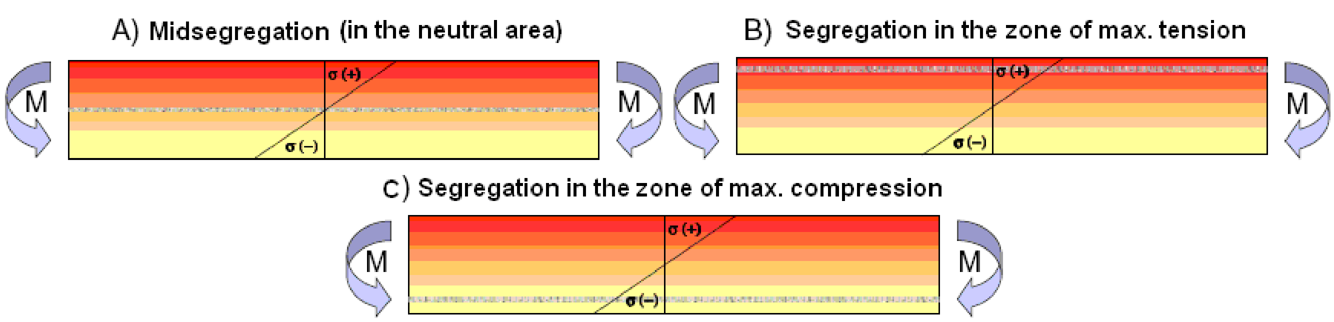


Figure 8: Sketch of samples under 100% load of stress with different areas of H traps (here segregations)

All test sets were immersed for 96 hours in NACE TM0284 solution A and saturated with H_2S. The reference samples without the influence of residual stress (non-sour materials, grade B –

X65) demonstrated the highest CAR value for all material strengths (Figure 9/Table 2). With increasing C and Mn content the CAR values increased significantly. If the simulated residual stress reached 100% of the yield strength, all materials displayed a significant reduction of the CAR values. The samples with HIC triggers in the maximal tension or compression areas tended to have the greatest reduction in the CAR values. No HIC damage was detected for the sample (HIC resistant material) with the highest material strength (X70), even with 100% simulated residual stress (Figure 9/Table 2).

These experimental results strongly supported the assumption that even the maximum possible residual stress in a material cannot trigger HIC, provided the steel is designed for sour service (high cleanliness and limitation of segregation).

Table 2

Comparison of CAR values after 96h exposure to NACE TM0284 solution A for examined steel grades Gr. B – X70MS for reference samples (0% deflection), sample with 100% calculated residual stress in the neutral zone (σ_0), sample with 100% calculated residual stress in the tension zone (σ_+) and with 100% calculated residual stress in the compression zone (σ_-)

	∅ CAR in %			
	Reference Sample (0% load)	**Sample (with 100% Res Stress) Neutral Zone**	**Sample (with 100% Res Stress) Tensile Stress Zone**	**Sample (with 100% Res Stress) Compressive Stress Zone**
Grade B	7	1.6	0.3	0.05
X52N	28.5	20.7	4.9	3.6
X65M	61.8	56	18	3.3
X70MS	0	0	0	0

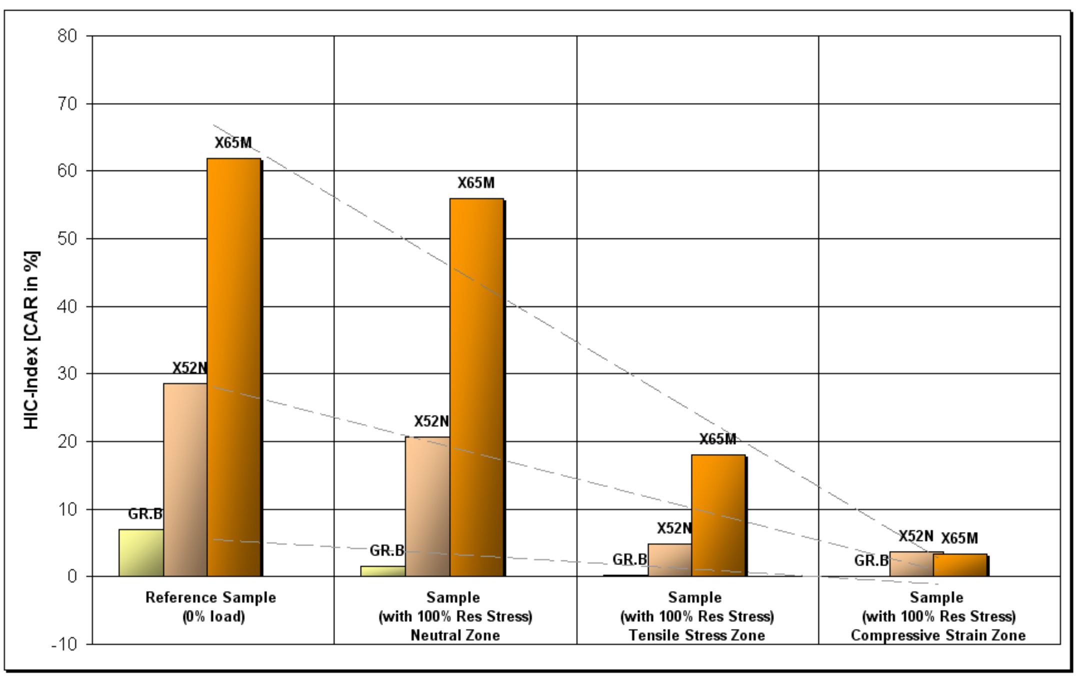
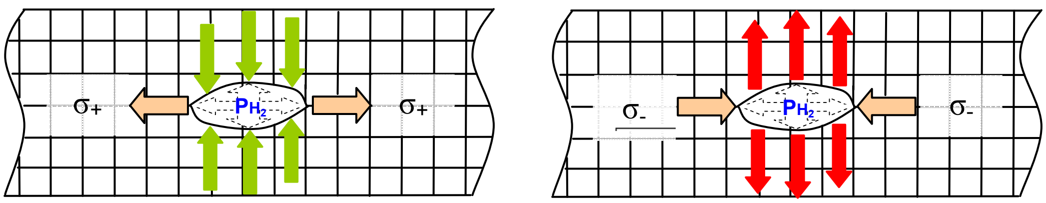


Figure 9: HIC index as a function of material analysis (C, Mn content) and location of residual stress

DISCUSSION

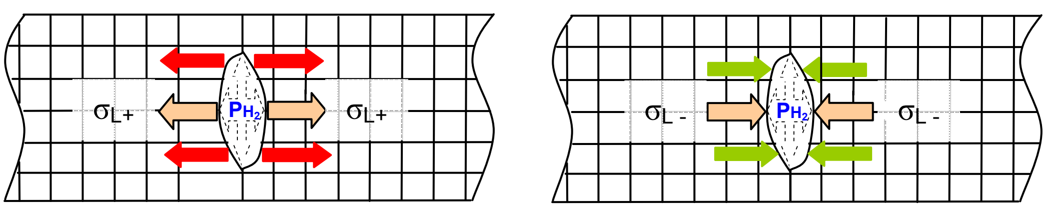
Residual stress tends to have a more positive influence on the HIC damage in steel pipes as assumed so far. The underlying mechanism is proposed as follows: In the region of a H trap (for example a micro crack in the matrix) atomic hydrogen recombines to molecular hydrogen resulting in high H_2 gas pressure which may lead to serious damage in the steel matrix (Figure 2). If this micro crack is placed horizontally to the residual stress (parallel to the coil surface) the resulting forces of a longitudinal residual stress will oppose the gas pressure in the crack (Figure 10a). Under compressive conditions the residual stress supports the forces generated by the internal pressure of the crack and therefore increases the crack propagation (Figure 10b).



a) tensile stress b) compressive stress

Figure 10: Behavior of horizontal HIC cracks under tensile stress (reducing HIC) and compressive stress (increasing HIC)

A converse behaviour of the same level occurs for a vertical crack or H trap. Under tensile stress in horizontal direction the internal pressure of the recombined hydrogen promotes cracking (Figure 11a). Compressive stress in horizontal direction to a vertical crack decreases HIC damage (Figure 11b).



a) tensile stress b) compressive stress

Figure 11: Behavior of vertical HIC cracks under tensile stress (increasing HIC) and compressive stress (reducing HIC)

In the segregation zone of a non-sour steel matrix both kinds of H trap orientation, vertical and horizontal as well as intermediate orientations occur in random distribution. Besides orientation the location within the material and intensity of the H traps plays an important role. With a high intensity of H traps the reduction under residual stress is more significant (X65M) than for only low concentration (Grade B). In an ideal state of elastic stresses the maximum residual stress in longitudinal and transversal direction is reached in the regions near the outer and inner pipe surface. In the middle of the pipe wall, the neutral zone, the stresses are at a minimum level. For that reason the HIC damage will be higher in the middle of the non-sour pipes and decreases in the direction of inner and outer wall, where the maximum tensile stress occurs.

For verification of the proposed model a FEM analysis was processed. A steel beam was modelled and the equivalent stresses (von Mises) for the different cases were calculated (Figure 12):

Orientation:	horizontal / vertical
Location:	neutral zone / outer surface
State of stress:	tensile stress (negative bending moment) / compressive stress (positive bending moment)

The hydrogen gas pressure in the crack is assumed to be 100,000 kPa (14,504 psi).

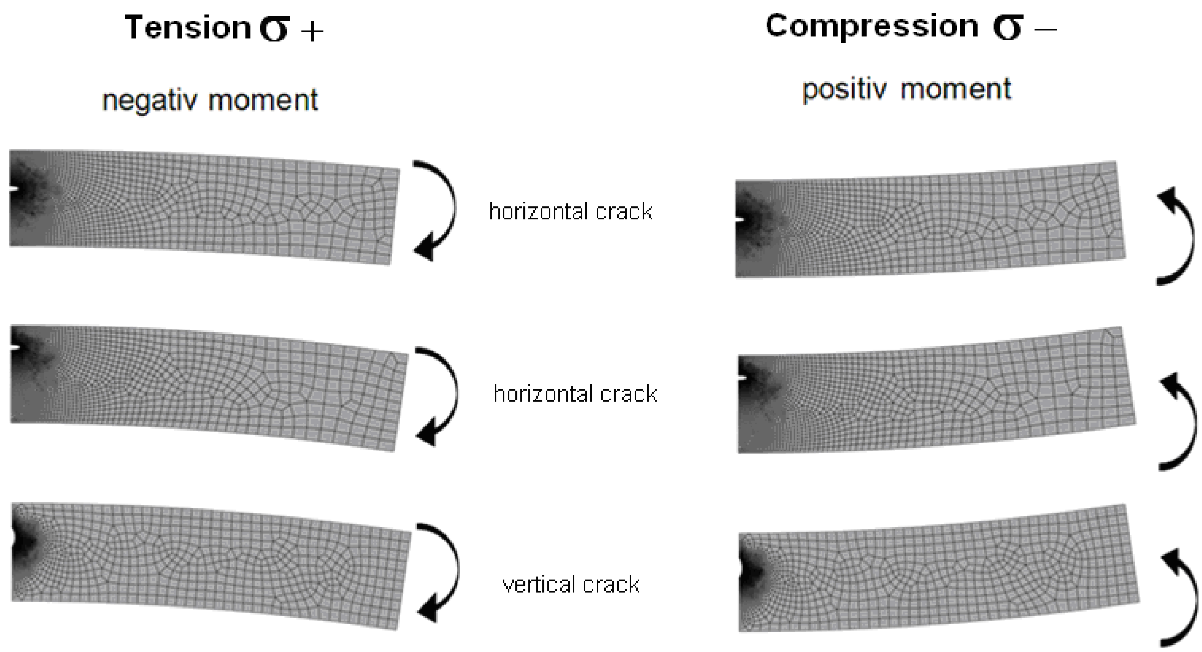


Figure 12: Different cases of residual stress through forming (bending moment) and different crack orientations and locations

The calculation of equivalent stress (von Mises) showed that the tensile stress (negative moment) decreases the equivalent stress on the crack tip (Figure 13). With increasing moment (tensile stress) the equivalent stress decreased linear, which means reducing HIC effects. Turning the moment to the positive (compression) showed a steady increase in the equivalent stress on the crack tip, which means crack growth. As the crack location was moved to the outer region of the wall, the absolute value of the equivalent stress increased (tensile or compressive, depending on the bending moment) more significantly. Changing the crack orientation to vertical position the behaviour changed vice versa (Figure 13). In this specific case the equivalent stress under tension grew steadily with increasing moment. Under compression the equivalent stress for the vertical crack decreased. The FEM calculation confirmed the thesis that location and orientation have a significant influence on the HIC sensitivity of steel (Figure 13).

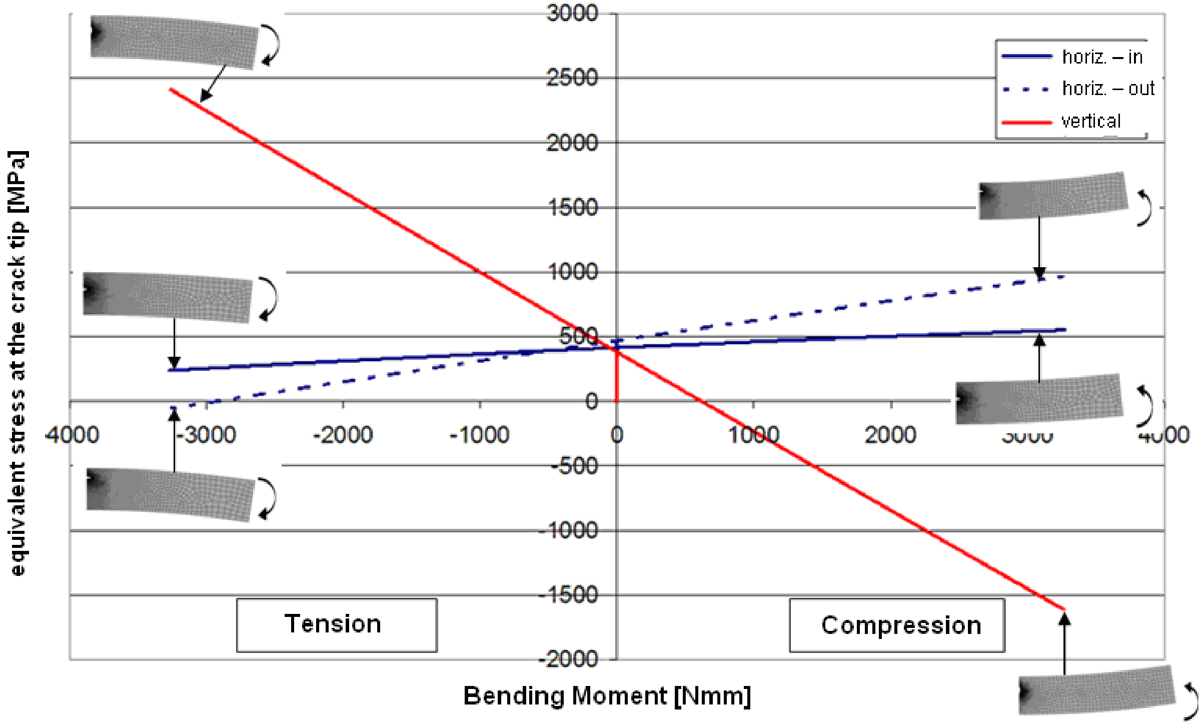


Figure 13: Qualitative FEM calculation for different cases of residual stress (tensile, compressive) on a metal beam with regard to different crack orientations (horizontal, vertical, centered, off-centered) with the help of equivalent stress (von Mises) on the crack tip and a hydrogen pressure of 100,000 kPa (14,503.8 psi)

CONCLUSIONS

Based on the results of this study it can be assumed that both kinds of residual stresses (longitudinal and circumferential) have no negative influence on the system "HFI pipe". With the help of residual stresses the risk of HIC damage can be reduced, depending on the intensity and location of the H traps. Additionally it was shown that even the maximum level of residual stress in a HFI pipe is not able to trigger HIC damage.

During longitudinal welding of the HFI pipe weld care needs to be taken that the weld is free of oxide inclusions, which can lead to HIC damage. HIC damage of the weld could in particular occur when tensile stresses in circumferential direction are present. The fact that HFI welds are locally reduced in carbon and manganese ensures high HIC resistance of the weld itself. Additionally the weld is heat treated after welding, resulting in a strong decrease of residual stresses. Consequently a HFI weld, which is free of inclusions, does not exhibit susceptibility to HIC.

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