Numerical Modelling of Cold Crack Initiation and Propagation in S 1100 QL Steel Root Welds

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ABSTRACT

Although the phenomenon of Hydrogen Assisted Cold Cracking (HACC) and respective avoidance procedures have extensively been investigated in seventies and eighties, the reasons for recent failures are still a lack of knowledge about the basic hydrogen effects on steel microstructures and, in particular, a lack of welding procedure specifications and standards accounting directly and consistently for cold cracking avoidance in modern high strength structural steels with the yield strengths of up to 1100 MPa.

In several previous contributions the consequences of various heat treatment procedures targeted at HACC avoidance have been shown, as for instance their effects on stress-strain build up and on hydrogen diffusion in high strength steel welds. But, the principal interaction of the three local influences on hydrogen assisted cold cracking, i.e. the local microstructure; the local mechanical load and the local hydrogen concentration have not yet been studied in detail for this type of materials. For this, a numerical model for HACC has been developed, accounting particularly for the criteria of crack initiation and propagation, like the hydrogen redistribution during the process of cracking.

The numerical model has been used to investigate HACC in such materials, i.e. in the weld microstructures of an S 1100 QL steel, under severe restraint and various hydrogen levels. The results were achieved by in-dept thermal and structural finite element simulations combined with numerical hydrogen diffusion modelling. By such procedure, HACC in single-layer welded plates with thickness of 20.0 mm at realistic restraints has been studied. As a particular result, it turned out that the location of crack initiation is typically in the center of the weld metal (WM), where only a single crack is initiated at hydrogen concentration levels of up to 10.0 Nml/100g Fe. But, it was evidently shown by such analyses that the crack initiation is shifted into the HAZ and that multiple cracking occurs at higher hydrogen concentration levels of up to 15.0 Nml/100g Fe.

KEY WORDS
Hydrogen assisted cold cracking (HACC); high strength structural steels; numerical simulation; intensity of restraint, single-pass weld; Instrumented Restraint Cracking (IRC) test
1 Introduction
The resistance of welds against Hydrogen Assisted Cold Cracking (HACC) was extensively investigated in the seventies and eighties and the developed welding procedures were successfully applied to avoid HACC in welded low and medium strength structural steel components. However, due to a quite different metallurgical behaviour such procedures cannot be applied and transferred to the recently developed Extra High Strength Structural (EHSS) steels with the yield strengths of up to 1300 MPa. Eliminating HACC-related failure associated with the fabrication and service of welded components is thus becoming again an increasingly challenging task for research and development in joining technology in the near future.

A unique characteristic of hydrogen assisted cold cracking is generally given by three main inter-related factors, i.e. (i) sufficiently high hydrogen concentrations in the weld region, (ii) a crack susceptible microstructure, usually in the Heat Affected Zone (HAZ) and/or in the Weld Metal (WM) and (iii) local mechanical loads in terms of stress or strain acting on the weld and predominantly arising from restraint and thermal contraction during cooling. In order to successfully predict cracking it is necessary to accurately consider all three factors. As a consequence of the previous intensive research to understand the reasons for those cracking phenomena, many metallurgical and physical mechanisms have been developed to explain and describe the Hydrogen Assisted Cracking (HAC) phenomena in metallic materials. However, almost established mechanisms still have not been proven quantitatively and cannot be used individually to clarify HAC phenomena [1]-[8]. Also, a number of models have been developed to quantitatively evaluate HAC. These account predominantly for Hydrogen Assisted Stress Corrosion Cracking (HASCC) and can be divided into two categories.

The first type of models was proposed to evaluate the time required for crack initiation or the stress-strain threshold of cracking, as those reported by Gerberich and Chen [3] as well as by Akhurst and Baker [5]. In additional, other models for predicting the characteristic of crack initiation have further been developed, but they are still based on a same understanding that crack initiation occurs when the instantaneous tensile stress exceeds the critical value suppressed by increasing local hydrogen concentration [8]. However, the adoption of these models for numerical modelling is somewhat difficult due to an unclear interaction of various local factors such as stress-strain intensities interacting with hydrogen and the diffusion of hydrogen into a critical distance ahead of the crack tip. Moreover, such models can only be used to predict the occurrence of cracking and, thus, represent only crack-no-crack models.

The second type is targeted at crack propagation, since any lifetime assessment of a component is usually dependent on duration of stable crack growth (Stage-II). The characteristic of crack propagation must be understood in order to predict how long such components may be used in service, before reaching fracture and failure critical conditions. This is a highly safety relevant value for practical failure control and prevention. As an example for such models, Gerberich [4] studied the effects of hydrogen on the kinetics of crack propagation and investigated the kinetics of crack growth in incubation range, Stage-I, which can simply be described as the average crack jump divided by the average time between jumps. The cracking morphology of intergranular (IG) or quasi-cleavage (QC) corresponding to low stress intensities with time has also been investigated. The authors found out that the main difference between Stage-I and Stage-II is that the hydrostatic stress gradient ahead of the crack tip increases with increasing stress intensities for Stage-I crack growth, whereas that is independent of stress intensities for Stage-II crack growth. Therefore, crack growth rates in Stage-II, showing the fractograph of transgranular (TG) or cleavage-like cracking, can be described in terms of yield stress instead of the hydrostatic stress. Prior to rapid rupture, stress intensities ahead of the crack tip become high enough to produce ductile rupture confirmed by the presence of the fractograph of microvoid coalescence (MVC). Hence, stress intensities are used again for calculating the kinetics of Stage-III crack propagation (Table 1).
As discussed by Gonzalez et al. [8], the model may overestimate the crack growth rates in pipelines after long-term exposure to service environments because of the presence of interconnections, of the reduction of stress intensities and of the relaxation of stress concentration ahead of the crack tip. Failure of components is definitively controlled by the characteristics of continuous crack growth which can obviously be observed during constant slow strain rate tests. Therefore, models which can be adopted to evaluate such continuous crack growth more precisely, are required [2].

It can only be mentioned that the existing analytical HAC models apply to HASCC only and cannot be easily transferred to evaluate the HACC risk in a weld. For this reason, a previously developed numerical model for HASCC has been modified to study the HACC characteristics in extra high strength steel (S 1100 QL) single-pass welds under severe restraint conditions and at various hydrogen concentrations.

### 2 Numerical approach

An original numerical model for hydrogen assisted cracking (HAC) [2] has been developed and successfully been applied to simulate HASCC, covering completely all of the three main inter-related local factors, i.e. microstructure, mechanical load and hydrogen concentration.

The HAC modelling procedure can easily be understood, if a sequence of a number of fictitious tensile specimens is considered alongside a specific crack path (Figure 1). In the numerical model, each tensile specimen is represented by a respective finite element. A fictitious tensile specimen fractures when the hydrogen concentration across the whole specimen or element reaches the critical value the respective microstructure can tolerate at a specific mechanical load. As a crack criterion for a homogeneous microstructure, the reduction of the hydrogen concentration with increasing the true fracture strain has thus been considered. Vice versa, also the respective local strain, the local microstructure can tolerate at a specific hydrogen concentration, can be applied as a crack criterion. In general, failure of a specific finite element or a respective tensile specimen occurs, if a critical combination of hydrogen concentration and mechanical load in terms of strain is exceeded.

By such procedure, the crack growth behaviour can be simulated. For instance, unstable crack propagation occurs when the failure of the first specimen adjacent to the crack tip immediately causes the failure of a large number of subsequent specimens. In contrast, stable crack propagation of the global tensile specimen is simulated, if the failure of the first specimen adjacent to the crack tip does not immediately induce rupture of the subsequent specimen, but requires additional time to build up a respective critical concentration.

### Table 1–Classification of analytical models for hydrogen-assisted cracking [2]

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Mechanisms and Assumption</th>
<th>Equations</th>
</tr>
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<tbody>
<tr>
<td>Crack initiation</td>
<td>Crack initiation is dependent on stress concentration, K, at the notch.[2]</td>
<td>$t_i = \frac{C}{K} \left(1 - \frac{2\sigma_0}{E} \right)^{-1}$</td>
</tr>
<tr>
<td></td>
<td>Cracking occurs if the tensile stress/strain normal to crack plane exceeds the critical fracture value decreased by the presence of hydrogen.[2]</td>
<td></td>
</tr>
<tr>
<td>Crack propagation</td>
<td>Pre-existing crack.[7]</td>
<td>Kinetics of crack growth: $\frac{dH}{dt} = \frac{3}{s} R T \frac{D_{\text{eff}}}{V} \frac{\alpha}{H_D} \sigma$</td>
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<tr>
<td></td>
<td>Crack growth is dependent on K at the crack tip.</td>
<td>Stage-I crack incubation: $\frac{dH}{dt} = \frac{2}{s} R T \frac{D_{\text{eff}}}{V} \frac{\alpha}{H_D} \sigma$</td>
</tr>
<tr>
<td></td>
<td>Consideration of three stages of crack growth: Appearance of intergranular (IG) or quasi-cleavage (QC) during Stage-I.</td>
<td>Stage-II stable crack growth: $\frac{dH}{dt} = \frac{9}{s} R T \frac{D_{\text{eff}}}{V} \frac{\alpha}{H_D} \sigma$</td>
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<tr>
<td></td>
<td>Appearance of transgranular (TG) or cleavage like cracking during Stage-II.</td>
<td>Stage-III rapid rupture: $\frac{dH}{dt} = \frac{9}{s} R T \frac{D_{\text{eff}}}{V} \frac{\alpha}{H_D} \sigma$</td>
</tr>
<tr>
<td></td>
<td>Appearance of microvoid coalescence (MVC) during Stage-III.</td>
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\[1\] E: young’s modulus, \[2\] C: constant containing the s-C term, \[3\] O: notch-root radius, \[4\] s: yield stress, \[5\] D: effective diffusion coefficient, \[6\] V: partial molar hydrogen volume, \[7\] HD: initial hydrogen concentration, \[8\] ys: Young's modulus, \[9\] R: gas constant, T: absolute temperature, \[10\] α: coefficient to consider effects of stress-assisted diffusion, \[11\] HD: critical hydrogen concentration.

As a crack criterion for a homogeneous microstructure, the reduction of the hydrogen concentration with increasing the true fracture strain has thus been considered. Vice versa, also the respective local strain, the local microstructure can tolerate at a specific hydrogen concentration, can be applied as a crack criterion. In general, failure of a specific finite element or a respective tensile specimen occurs, if a critical combination of hydrogen concentration and mechanical load in terms of strain is exceeded.
(a) Crack propagation as a sequence of cracked tensile specimens
(b) Hydrogen redistribution caused by crack propagation demonstrated for the first specimen

Figure 1–Schematic illustration of the concept of fictive tensile specimens to simulate cracking: (a) Crack propagation as a sequence of cracked tensile specimens and (b) Hydrogen redistribution caused by crack propagation demonstrated for the first specimen [2]

In order to transfer the modelling to HACC, a similar procedure has to be developed, also based on the comparison of such crack criteria, i.e. of the critical local hydrogen concentration for the respective local true strain introduced during welding and cooling. The flow chart for the whole modelling procedure is given by Figure 2.

Figure 2–Flow chart of HACC modelling

Critical conditions are given for the investigated S 1100 QL welds by
$$\varepsilon_w = 0.6140 \cdot e^{\text{HD}/0.2296} + 0.0930 \cdot e^{\text{HD}/3.6390}$$

for the weld metal (WM), and

$$\varepsilon_w = 0.8062 \cdot e^{\text{HD}/0.7967} + 0.3390 \cdot e^{\text{HD}/0.8324} + 0.0329$$

for the HAZ and have been determined experimentally ahead of the simulations [9]-[10].

Such modelling can be used for calculating HACC of welded structures, especially crack propagation behaviour by basically thermal and structural modules of such commercial finite element program based on the FORTRAN programming language (Figure 2). The indirectly coupling of the thermal-structural and hydrogen diffusion analysis has been accomplished by Macro-files elaborated by ANSYS Parametric Design Language (APDL). Respective macros have also been utilized in each time step to compare the crack criteria and to delete the respective elements to simulate crack propagation.

In order to better understand the HACC modelling, the conditions during welding and subsequent cooling are elucidated by a Time-Strain-Fracture (TSF) diagram [11], as shown in Figure 3. In this diagram, the calculated temperature, critical strain, local strain and local stress have been plotted versus time for a specific location at the WM centerline in the single-pass weld.

![Figure 3–Time-Strain-Fracture (TSF) diagrams during and after completion of welding](image)

As generally implied by the fictitious tensile specimen concept, cracking will occur, if the local strain exceeds the critical strain. The critical strain is determined by the local hydrogen concentration at this location dependent from the diffusion time and is given by the respective experimentally determined strain-hydrogen relationship. In this case, the local microstructure is represented by the S 1100 QL weld metal and the tolerable strain-hydrogen relation is given by Equation (1). Such conditions are illustrated by Figure 4. During the welding process, hydrogen is introduced via the arc into the weld metal and at the respective location, i.e. at the middle height of the weld metal, this concentration persists over quite a while when hydrogen is diffusing into the adjacent regions and is also effusing at the weld top and bottom surface. Due to Equation (1), the critical strain this microstructure might tolerate is immediately reduced by the respective concentrations traced into the weld metal. With further increasing time the hydrogen concentration is then reduced and thus, the critical strain the microstructure can tolerate is increasing again. However, as a well-known definition HACC can only occur at considerable low temperature levels, i.e. below 200 °C

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1. Equation (1)
2. Equation (2)
[12]-[13] and thus, Equation (1) evaluated from room-temperature experiments fairly well reflects the respective critical conditions.

![Figure 4](image.png)

**Figure 4—Hydrogen concentration with time at the middle height of weld metal centerline and critical strain evolution during welding and cooling process with initial hydrogen concentration of HD = 10 Nm/l/100g Fe in S 1100 QL single-pass weld**

In the TSF diagram, the cooling time for reaching 200 °C is represented by the point T1. From this time on, the weld at this location is evaluated for reaching critical conditions. From the fact that the local strain exceeds the critical strain it can be deduced that HACC occurs at this location. The cracking risk at this location is persisting until the critical value is increasing above the local value again, i.e. hydrogen has been diffused out of the joint and, consequently, no cracking will occur any more.

In some cases, cracking might not occur immediately after completion of welding, but is delayed, i.e. occurs to the long diffusion times and the persisting cracking risk after a welded component has already been subjected to service. As can be drawn from Figure 4, such period is dependent on the hydrogen diffusion time and the critical strain gradually increases again after a cooling period of about 10,000 seconds and then drastically increases after a cooling period of about 90,000 seconds. In order to account also for delayed HACC, a second time T2 of 90,000 seconds has also been selected to evaluate the cracking risk. However, as can be drawn from the TSF diagram, crack safe conditions are only reached, if the critical strain increases above the level of the local strains, i.e. after a very long period of more than 500,000 seconds. This shows that 90,000 seconds, i.e. about one day is probably conservative to evaluate the risk of delayed cracking, because the critical strain increases afterwards. But, the diagram also shows, how long the risk of HACC might persist in certain weld regions.

In the model, such evaluation procedure shown by the TSF diagram is applied to every finite element alongside the predefined crack paths. In order to pinpoint an initial crack location along the predefined crack paths, both in the weld metal centerline and the HAZ, the critical node of that element where the critical conditions are reached first, must first be searched in the model. This means in that case, if the local strain and hydrogen concentration combinations are reached at several nodes at the same time, that node has to be identified where the maximum difference between the local hydrogen concentration and the critical hydrogen concentration dependent on the local strain occurs. The HACC model
for the single-pass weld has been designed with 27 nodes along the predefined crack path in weld metal centerline and thus, the above procedure has been applied to each of these nodes at every time step. In contrast to HASCC, for instance, HACC occurs usually at quite fast crack propagation rates which cannot be represented in numerical analyses by reasonable time step widths. In order to make the crack propagation at least visible, only the failure of one element has been allowed within every time step of 2 seconds.

![Figure 5](image)

(a) Two dimensional finite element model for single-pass weld

(b) Exemplarily ordered node and element performed by using predefined node based on FORTRAN programming language in base material region of model

**Figure 5**– Two dimensional finite element models for HACC analysis of single-pass butt welds: (a) Model with two different predefined crack paths at weld metal centerline and heat affected zone adjacent to fusion line and (b) Exemplarily ordered node and element of model

Cracking is then simulated by deleting the elements both in upward and downward direction from the critical node. Since crack propagation appears either in the upward or downward direction depending on the local hydrogen concentration, local strain and local critical value, it is defined by comparing the local hydrogen concentration both in the downward and upward direction from a specific node. If the local hydrogen concentration in any direction from a specific node is lower than the critical value, crack propagation ceases in that direction, while cracks in other directions continue to propagate if their local hydrogen concentration is higher than the critical value.

Regarding modelling of the specific weld, the following general aspects and boundary conditions have been considered:

(I) As mentioned above, HACC modelling has been performed by indirectly coupled modellings of thermal, structural and hydrogen analyses. For such procedure, all
finite element of such modelings is necessarily performed using the same total nodes and total elements, i.e. the nodes and the elements have to remain precisely at the same location to transfer the data from one analysis to another. For convenience, the same time intervals in the thermal, structural and diffusion analyses should be selected.

(II) Since the material properties for the thermal analyses such as density, heat convection coefficient, enthalpy and thermal conductivity significantly affect the finally calculated hydrogen diffusion, stresses and strains, they have been selected very carefully from Richter’s diagrams [14] for steel with a composition similar to the relatively new S 1100 QL type and have been applied to all microstructures in the respective analyses.

(III) Assuming an inhomogeneous microstructure of weld deposits, i.e. weld metal (WM), coarse grained heat affected zone (CHAZ), fine grained heat affected zone (FHAZ) and base material (BM), the diffusivity depending on time and temperature was provided for each element during the entire hydrogen diffusion analysis. By such procedure, the exact thermal-mechanical properties and temperature-dependent diffusion coefficients at each location in the weld, and for the respective microstructure, is provided [7]. The hydrogen diffusion analyses thus provide quite reliable results and are far more developed than other approaches [16]-[18].

(IV) In order to define precisely the nodes alongside the predefined crack path, the model has been generated by a bottom-up procedure, as shown in Figure 5. The dimension is that of actual IRC tests performed with a total restraint length (L) of 110 mm and a plate thickness (d) of 20 mm. The smallest elements of the predefined crack path mesh are designed to have dimensions of 0.10×0.22 mm and 0.14×0.22 mm for the weld centerline and the heat affected zone adjacent to the fusion line, respectively, to allow for an increase in element size with increasing distance from the weld centerline. For precise two-dimensional analyses, only quadrilaterals have been used in this study and triangular elements have been avoided.

(V) However, in this contribution crack phenomena and hydrogen diffusion with large concentration gradients have been modelled as local microstructural behaviour and thus, finer elements have thus been introduced at the predefined crack paths than originally recommended for thermal stress analyses [19]-[20].

3 Results and Discussions
In order to support real failure cases and to examine effects of an initial hydrogen concentration on the local hydrogen concentration and on HACC susceptibility of the welded component of extra high strength structural steel, various amounts of hydrogen uptake, i.e. 5.0, 10.0 and 15.0 Nml/100g Fe in the weld metal during the welding process were assumed and applied to every finite element node existing in the weld metal.

Simulated HACC in single-pass welds with various hydrogen concentrations picked up by the weld pool during welding, ranging between 5.0 and 15.0 Nml/100g Fe, is shown in Figure 6 to Figure 8, respectively.

At low and medium hydrogen concentration levels, i.e. between 5.0 and 10.0 Nml/100g Fe, respectively, cracks appear only at the weld metal centerline and are initiated in the middle weld height. At high hydrogen concentration levels, i.e. 15.0 Nml/100g Fe, multiple cracks appear both in the weld metal centerline and the HAZ as shown in Figure 8. It can only be emphasized that such changing of the crack initiation location has not been yet reported in the literature.

In order to better understand why the location of cracking is different, the simulated local hydrogen concentrations, critical hydrogen concentrations for crack initiation and local strains along the predefined crack path at the weld metal centerline with an initial hydrogen concentration of 5.0 Nml/100g Fe are exemplarily plotted in Figure 9 and the local values of
the above parameters ahead of the crack tip are plotted in Figure 10 in order to illustrate their effects on the crack area.

(a) Crack initiation at 90,000 seconds

(b) Crack propagation at 90,006 seconds

(c) Final stage of cracking at 90,010 seconds

Figure 6–Simulated HACC in a single-pass S 1100 QL weld after completion of welding and cooling down to room temperature for 90,000 seconds without any heat treatment, with an initial hydrogen concentration introduced into the weld metal of HD = 5.0 Nml/100g Fe

The hydrogen concentration in the bottom part is quite low compared with that in the upper part because hydrogen effuses faster into the surrounding air from regions adjacent to the free surface than from more remote regions. This phenomenon is also found at the free surface where there is no effect of hydrogen diffusion and effusion from neighboring zones like the top surface of the root layer, as shown in Figure 9. Obviously, the local hydrogen concentration accumulates at the middle weld height and the maximum value appears at Node No. 19. In contrast, the maximum local strain is at Node No. 15. This confirms the previously mentioned fact that the initial crack location is not determined by using only the maximum value of local hydrogen or local strain. It is rather necessary to consider the synergistic effect of local hydrogen and local strain in terms of critical hydrogen concentration. Obviously, a number of nodes can be allocated where the critical hydrogen concentration is exceeded and thus, that node has to be identified where cracking probably started first. Accordingly, the maximum difference value between critical and local hydrogen concentration is used to determine the location of crack initiation, i.e. identify that node where the crack first started and then proceeds. For instance, if the hydrogen picked up during welding gives an initial hydrogen concentration of 5.0, 10.0 and 15.0 Nml/100g Fe, the initial crack location is at Node No. 17, Node No. 18 and Node No.19, respectively, as shown in Figure 11. It is remarkable that when a high hydrogen concentration is applied in HACC
calculation; the initial crack location tends to shift towards the upper part where larger amounts of hydrogen have accumulated.

Figure 7–Simulated HACC in a single-pass S 1100 QL weld after completion of welding and cooling down to room temperature for 90,000 seconds without any heat treatment, with an initial hydrogen concentration introduced into the weld metal of HD = 10.0 Nml/100g Fe

In the bottom part of the root layer or in the weld sag, the critical hydrogen concentration is quite high because of lower local hydrogen and local strain (Figure 9). This means that the sag weld metal centerline area is least also sensitive to HACC, although the upper part of the weld represents the most critical area with respect to HACC at high initial hydrogen concentrations.

As another important point, it is clearly demonstrated that in the crack region the local hydrogen concentration gradually increase and accumulates in the direction of the top surface, while the local strain significantly decreases towards the upper part of the weld, as shown in Figure 10. This means that at high deformation only a low level of hydrogen concentration is needed at such locations to produce a crack, while a high hydrogen concentration is necessary for crack initiation at locations with less deformation. Moreover, it is not certain whether cracks propagating in upward and downward direction have the same length. For example, at the initial hydrogen concentration of 5.0 Nml/100g Fe, as shown in Figure 10 the critical node, whose maximum difference value between critical and local hydrogen concentration reaches the critical value, is Node No. 17. Crack propagation in downward direction ceases at Node No. 13, while in upward direction crack propagation stops at Node No. 23. Therefore, the number of the deleted elements is not equal in both directions.
(a) Crack initiation at 90,000 seconds

(b) Crack propagation at 90,006 seconds

(c) Final stage of cracking at 90,008 seconds

Figure 8–Simulated HACC in a single-pass S 1100 QL weld after completion of welding and cooling down to room temperature for 90,000 seconds without any heat treatment, with an initial hydrogen concentration introduced into the weld metal of HD = 15.0 Nml/100g Fe

Up to this point it can be assumed that the preferential crack direction is upwards with increasing hydrogen concentrations, i.e. 10.0 Nml/100g Fe and 15.0 Nml/100g Fe. In contrast, at a lower hydrogen level, i.e. 5.0 Nml/100g Fe, the major factor, i.e. local hydrogen concentration or local mechanical strain, determining the crack propagation stage is not clarified yet. Therefore, in order to clarify which factor determines the crack propagation stage, the preferential crack direction has to be examined again for multi-pass welding in which the cracking behaviour is more complicated, in particular with respect to the strain distribution.
Figure 9–Simulated local hydrogen concentration, critical hydrogen concentration for crack initiation and local strain along the predefined crack path at the weld metal centerline, with an initial hydrogen concentration picked up during welding of HD = 5.0 Nml/100g Fe for single-pass welds.

Figure 10–Local hydrogen concentration and local strain at the crack tip in the weld metal centerline obtained from HACC modelling of single-pass welding, with an initial hydrogen concentration picked up during welding of HD = 5.0 Nml/100g Fe.
Figure 11—Local hydrogen concentration exceeded the critical hydrogen along the crack with various initial hydrogen concentration levels

Figure 12—Total crack length at predefined crack path in S 1100 QL single-pass welds dependent on the initial hydrogen concentration picked up during welding

Above considerations already confirm that the total crack length significantly depends on the hydrogen concentration, as illustrated by the diagram in Figure 12. At the low and medium level of hydrogen concentration, i.e. 5.0 and 10.0 Nml/100g Fe, the crack length ranges between 4.0 and 6.0 mm, respectively, and cracks still appear only at the weld metal centerline. At high hydrogen concentration, i.e. 15.0 Nml/100g Fe, cracks appear not only in
weld metal centerline, but also in the HAZ, and their length is above 6.0 mm and about 5.0 mm, respectively.

4 Conclusions and Perspectives

The following conclusions can be drawn from the present state of HACC modelling in a high strength structural single-pass weld:

1. The originally designed model has successfully been transferred from HASCC to HACC and it is possible to model crack initiation and propagation in a welded component. In contrast to other HACC modelling approaches, such a model accounts also for real crack propagation modelling alongside specific predefined crack paths located at the HAZ adjacent to the fusion line and centerline of the weld metal.

2. Modelling shows that crack critical regions do not necessarily occur at the highest strains and hydrogen concentrations. For the appearance of cracking, simply a critical combination between hydrogen concentration and strain has to be exceeded.

3. At the low hydrogen concentration, i.e.

4. Obviously, crack appearances depend on the hydrogen concentration. At low and medium hydrogen concentration levels, i.e. 5.0 and 10.0 Nm/l/100g Fe, a WM single crack exists. At a high hydrogen concentration level of 15.0 Nm/l/100g Fe, multiple cracks are represented as WM and HAZ single cracks on both the left and right hand side.

As perspectives for further HACC modelling using the described procedure, it will be developed further in a way that the exact time to failure can be determined more conveniently. In addition, it is planned to investigate the chances for modelling without predefined crack paths, i.e. allow changes in crack orientation. The presently existing modelling approach will also be used to investigate the HACC failure risk in welds of other materials and of other joint configurations, if the hydrogen diffusion data and, in particular, the crack critical limits for the respective microstructures have become available.

5 References