MODELLING HYDROGEN INDUCED CRACK GROWTH IN THE WALL OF PIPELINES AND PRESSURE VESSELS

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A finite difference model is presented simulating the growth of hydrogen induced cracking (HIC) defects in the wall of pipelines or pressure vessels due to high internal hydrogen pressures. The model shows that crack growth occurs only for defects larger than a critical size, and that the crack growth rate is proportional to the diffusion coefficient, to the hydrogen concentration in the steel and inversely proportional to the fracture toughness. Although the time to crack initiation is found to depend strongly on defect size, the crack growth rate itself is almost independent of defect size. Crack growth during fluctuations in process conditions has also been modelled.

INTRODUCTION

Hydrogen sulphide (H_2S) present in oil & gas, in the presence of liquid water, causes corrosion reactions with the wall of the pipeline and/or pressure vessel, whereby hydrogen atoms are formed which enter the steel (1). The hydrogen concentration on the inside surface of the wall is determined by the H_2S partial pressure, the local pH, the temperature, the surface condition and the hydrogen solubility of the steel. In the steel, hydrogen atoms diffuse over interstitial lattice sites, and recombine on the outside surface or at inclusions. The hydrogen gas pressure developing around the inclusions is always in equilibrium with the hydrogen concentration in the steel. The relation between the hydrogen pressure and the hydrogen concentration is given by Sieverts law,

$$C = K(T)\sqrt{f} \tag{1}$$

with C the hydrogen concentration in molH/m^3, K(T) the hydrogen solubility in molH/m^3/Pa$^{1/2}$ and f the hydrogen fugacity in Pa. The hydrogen fugacity is related to the hydrogen pressure by the following implicit relationship (2),

$$f = P\, e^{(Q(T)\, P)} \tag{2}$$

with P the pressure in Pa, and Q(T)=A/T+B, T the absolute temperature in Kelvin,

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$A=1.54*10^{-6}\ Pa^{-1}K$ and $B=4.69*10^{-11}\ Pa^{-1}$. At pressures below 200 bar and temperatures above room temperature the fugacity in Eq.1 can be replaced by the hydrogen pressure. At high H_2S partial pressures, high hydrogen concentrations are present in the steel, and high hydrogen gas pressures (up to 10,000 bar) develop around the inclusions. The high hydrogen pressures can result in debonding of the inclusions from the surrounding metal, followed by crack growth (3,4). In Figure 1 an example of this phenomenon called hydrogen induced cracking (HIC) is shown. A typical stepwise cracking pattern has developed due to the growth under high internal hydrogen pressures of rolled out MnS inclusions parallel to the pipeline wall.

Hydrogen induced cracking (HIC) is a phenomenon which is known to affect pipelines and pressure vessels in the oil & gas industry. Although HIC has been studied already for many years, up to now only models have been presented which address the question whether crack growth can occur or not (4-7). No quantitative models are available predicting both the initiation phase and growth phase of HIC. Quantitative models are attractive tools for the fitness for purpose assessment of HIC affected pipelines and pressure vessels in order to estimate residual lifetime, and can be helpful in the selection procedure for steels for new pipelines and pressure vessels e.g. with a view to reduce future maintenance costs. For these reasons a finite difference model was developed enabling a quantitative study of the initiation and growth of HIC defects.

THE FINITE DIFFERENCE MODEL

Geometry

The finite difference mesh (8) which has been used to model in three dimensions the flow of hydrogen into penny shaped defects parallel to the pipeline or pressure vessel wall is shown schematically in Figure 2. It is a two dimensional axisymmetric mesh. The defect is positioned parallel to the wall and is allowed to grow from left to right in discrete steps. The boundary conditions on the inner wall of the pipeline or pressure vessel are determined by the hydrogen concentration, generated by the corrosion reaction. The hydrogen concentration on the outside of the pipeline or pressure vessel is assumed to be zero. The boundary perpendicular to the defect surface, through the centre of the defect, i.e. the y-axis in Figure 2, is an axis of symmetry (rotation axis) and therefore has zero hydrogen flux normal to it. The boundary on the opposite side is assumed to be so far away from the defect, that the defect has no influence on the hydrogen concentration near that boundary, i.e. the hydrogen flux normal to the boundary is also zero.

Crack Growth

Hydrogen accumulates in the penny shaped defects and hydrogen pressures build up until an equilibrium is established with the hydrogen concentration in the surrounding steel, or until crack growth occurs. Analysing the stress fields around a penny shaped defect shows that the volume of a penny shaped defect is given by (9),

$$V = \frac{16\, a^3\, P\, (1-\nu^2)}{3E} \qquad (3)$$

with a the crack radius (in m), P the internal pressure (in Pa), ν the Poisson ratio and E the Young modulus (in Pa). At the temperatures and pressures of interest, hydrogen gas does not behave as an ideal gas, and the following equation for a non-ideal gas has to be used,

$$P V = Z n R T \tag{4}$$

with n the amount of hydrogen gas (in moles H_2), R the ideal gas constant (8.314 J/mol/K) and T the absolute temperature (in K). The compressibility factor Z is given by

$$Z = 1 + P Q(T) \tag{5}$$

with Q(T) the same as in Eq. 2. Combination of Eqs. 3, 4 and 5 leads to a quadratic equation of the pressure P with the following solution,

$$P = \frac{Q(T)\, nRT + \sqrt{(Q(T)\ nRT)^2 + \dfrac{64\, a^3\, (1-\nu^2)}{3E}\, nRT}}{\dfrac{32\, a^3\, (1-\nu^2)}{3\, E}} \tag{6}$$

The relation between the stress intensity at the edges of the penny shaped defect and the internal hydrogen pressure is given by the following simple relationship,

$$K_I = 2\, P \sqrt{\frac{a}{\pi}} \tag{7}$$

with K_I the stress intensity (in $N/m^{3/2}$). The condition for defect growth is that the stress intensity at the edges of the penny shaped defect is larger than the fracture toughness of the steel. The critical pressure above which crack growth will occur is then,

$$P_c = \frac{K_{IH}}{2} \sqrt{\frac{\pi}{a}} \tag{8}$$

with K_{IH} the fracture toughness of the steel (in $N/m^{3/2}$). In the simulations the crack is allowed to grow in small incremental steps. After each increment the hydrogen pressure in the defect drops and hydrogen is supplied from the surrounding steel to the defect until equilibrium is established between the hydrogen concentration in the steel and the hydrogen pressure in the defect, or until P_c is exceeded and crack growth occurs again.

Dimensions and Material Parameters

The calculations were carried out assuming a 22 mm thick wall made of a C-Mn steel and defects located 11 mm from the inner surface, i.e. in the centre band, and parallel to the pipeline or pressure vessel wall. The operating temperature is assumed to be 20 °C and the hydrogen concentration (C) through the pipeline or pressure vessel wall is zero initially. At the start of the simulation C on the inner wall surface is increased in one hour up to 14.1 molH/m^3 (1.75 ppm) and kept constant thereafter. On the outer surface the hydrogen concentration is zero. Relevant material parameters are the Young modulus ($2*10^{-11}$ Pa), Poisson ratio (0.3), the hydrogen diffusion coefficient D(T) = $6.11*10^{-8}$ EXP(-12871/8.314/T) in m^2/s and the hydrogen solubility K(T) = 0.82 EXP(-28577/8.314/T) in molH/m^3/$Pa^{0.5}$.

CRACK GROWTH CALCULATIONS

Crack Size

The first step was to study the crack growth in the wall of the pipeline or pressure vessel as a function of initial crack size (2a). In Fig. 3 growth curves for initial defect sizes ranging from 0.5 mm up to 32 mm are presented for a fracture toughness of 400 $N/mm^{3/2}$ (1 MPa $\sqrt{m}$ = 31.6 $N/mm^{3/2}$). Most defects start to grow after an "incubation period" varying from 58 h for a defect with an initial size of 2 mm up to 275 h for a 32 mm defect. Only the 0.5 mm defect is stable i.e. the stress intensity at the tip of the defect is always smaller than the fracture resistance of the steel. After the incubation time there is an approximately constant crack growth rate for all defects.

Fracture toughness

The time to initiation and the crack growth rate are expected to depend on the fracture toughness. The fracture toughness in a banded X60 steel, charged with hydrogen, and assuming the crack growth to occur in the segregation band of the steel is very low, i.e. the "apparent" K_{IH} is expected to be as low as 400 $N/mm^{3/2}$. Therefore this value was used in most of the calculations. In order to study the dependence of the crack growth rate on fracture toughness, the simulations were carried out for a K_{IH} of 400, 800, 1200 and 1600 $N/mm^{3/2}$. The resulting crack growth curves in Figure 4, for a 2 mm defect, show that for an increasing fracture toughness the time to initiation increases and the crack growth rate decreases. The 2 mm defect does not grow at all in the steel with a K_{IH} of 1600 $N/mm^{3/2}$. With higher fracture toughness values, higher hydrogen pressures are needed for crack growth, more hydrogen has to be supplied to the crack and more time is needed before the critical pressure is reached.

Position in the wall

In Figure 5 the growth curves are compared for 2 mm defects located at three different positions in the wall of the pipeline or pressure vessel: at 5.5 mm, at 11 mm and at 16.5 mm from the inner surface (for a fracture toughness of 400 $N/mm^{3/2}$). The incubation period before the crack starts to grow is increasing with increasing distance to the inner surface. The crack located at 5.5 mm starts to grow first, and after initiation, the growth rate is considerably larger at 5.5 mm than at the other positions. This is due to the higher hydrogen concentration resulting in higher hydrogen fluxes into the defect.

The hydrogen diffusion coefficient

The crack growth rate depends on the flux of hydrogen into the defect and thus on the hydrogen diffusion coefficient. The diffusion coefficient in line pipe and pressure vessel steels depends on the heat treatment and composition of the steel and varies at 20 °C by approximately one order of magnitude. A reasonable average value is $3.1 * 10^{-10}$ m^2/s. Therefore the growth of cracks was studied for diffusion coefficients which were respectively 3 times larger and three times smaller than this average value. In Figure 6 the respective crack growth curves are presented. The time to crack initiation is inversely proportional to the diffusion coefficient, while the crack growth rate is proportional to D(T).

Hydrogen concentration

The hydrogen concentration (C) around the defect increases, with increasing C at the inner surface of the pipeline or pressure vessel. The resulting hydrogen flux into the defect is therefore expected to increase also. In Figure 7 the crack growth curves for three cases are shown. In one case the hydrogen concentration at the inner wall was assumed to be 14 $molH/m^3$, as in the previous calculations. In the two other cases the hydrogen concentration is either a factor two lower, C = 7 $molH/m^3$, or a factor two higher, i.e. 28

molH/m^3. The time to crack initiation is predicted to be inversely proportional to C while the crack growth rate is proportional to the hydrogen concentration.

Fluctuations in process conditions

In Figs. 8 and 9 the growth of a defect due to short fluctuations in operating conditions is simulated. At the inner wall of the pipeline or pressure vessel a hydrogen concentration of 0.32 molH/m^3 during normal service is assumed. During operation the hydrogen concentration increases, every 30 days, in one hour up to 14 molH/m^3 (1.75 ppm) for 48 hours (Fig. 8). The resulting crack growth, for a defect with 2 mm initial size, located at the centre of a 22 mm thick wall, constructed from a steel with a K_{IH} of 400 N/mm$^{3/2}$, is shown in Fig. 9. The crack starts to grow during the first hydrogen pulse and continues to grow for many hours after the hydrogen concentration at the inner surface has reached the normal value. The crack stabilises finally at a size of approximately 3.5 mm. During and after the 2nd pulse the crack grows up to approximately 5 mm. After the third hydrogen pulse the defect continues to grow even during normal operation.

DISCUSSION

Crack Growth Curves

The crack growth curves show two distinct characteristics, an incubation time and an almost constant crack growth rate. The crack growth rate is found to be roughly proportional to the diffusion coefficient, to the hydrogen concentration in the steel, and inversely proportional to the fracture toughness. The time until crack initiation, the "incubation period", is the time it takes to fill the defect with hydrogen until the critical pressure is reached. It is proportional to the fracture toughness, and inversely proportional to the hydrogen concentration and the diffusion coefficient for hydrogen in the steel. The increase in the incubation time with crack size indicates that large defects may not grow during relatively short fluctuations in process conditions.

Fluctuations in process conditions

In the previous sections we studied the growth of cracks for a constant hydrogen concentration on the inner surface of the pipeline or pressure vessel wall. Under these conditions defects are predicted to grow from e.g. 2 mm to 25 mm in approximately 600 h, in agreement with observations of HIC in laboratory (NACE) tests. In general, pipelines or pressure vessels, in which HIC is found, have been in service for many years. HIC could therefore occur during short fluctuations in the normal operating conditions. These fluctuations in process conditions are e.g. a change in the local pH, in the temperature, the concentration of H_2S, or a change in the surface condition of the pipeline or pressure vessel caused by e.g. cleaning, pigging or due to spallation of protecting sulphide films during a shut down. Due to the change in the operating conditions, the hydrogen concentration in the steel increases for a short period and defects start to grow. After establishing normal operating conditions again the defects stabilise. This cycle of a fluctuation in the operating conditions, crack growth and stabilisation can be repeated many times during the life of a pipeline or pressure vessel. The model will be valuable in studying the effects of short term exposure on crack initiation and crack growth rates.

Defect Shape

The penny shaped defects in the model are planar defects with a small volume to surface ratio and with large stress intensities around the edges. These kinds of defects fill relatively fast with hydrogen, and the initiation of cracks starts at relatively low pressures. This is a reasonable representation of the rolled out MnS inclusions in the API 5L grade X60 and X70 steels, which often form the initiation sites for HIC defects.

Fracture toughness

The finite difference hydrogen diffusion model describes the flow of hydrogen through the pipeline or pressure vessel wall in detail. In contrast, the representation of the fracture toughness in the model is rather simple and does not explicitly account for e.g. plasticity at the crack tips, the interaction with stress fields around the crack tip and hydrogen embrittlement. However, because the major driving force is the hydrogen pressure in the defects, the trends predicted in this study will remain valid for more sophisticated fracture mechanics models.

In recent tests designed to validate the model, HIC cracks were observed to initiate and grow in segregation zones with a low fracture toughness. At the end of the segregation zone the HIC defects were observed to arrest due to a much higher fracture toughness in the region in between the segregation zones. The model was used to infer the fracture toughness in the segregation zone in the steel and the crack arrest fracture toughness in the region between the segregation zones. Comparison of the model predictions with the experimental data, showed that the model, in conjunction with accurate measurements of the diffusion properties, hydrogen concentration, defect location and defect size, can be used to study local toughness distributions. The validation tests also demonstrated that the model can predict growth rates of individual cracks. It is our intention to develop this model into a tool for the assessment of HIC damage in pipelines and pressure vessels.

CONCLUSIONS

The finite difference model developed in this report can be used to study the initiation and growth of HIC defects in pipeline or pressures vessel walls, both under constant hydrogen charging conditions, but also under probably more realistic fluctuating operating conditions experienced in service. The following predictions have been made using the model:

- HIC defects larger than a critical size start to grow after an incubation period which increases for cracks with increasing initial size. Larger defects with longer incubation periods can be susceptible to short fluctuations in process conditions, as the critical pressure for defect growth decreases with increasing defect size.
- If defects start to grow this is with a constant crack growth rate independent of crack size.
- Cracks nearer to the inner surface initiate earlier and grow faster than cracks located further away.
- Higher hydrogen concentrations result in shorter incubation periods and higher crack growth rates.
- HIC cracks will grow much slower in steels with lower diffusion coefficients for hydrogen.
- Modelling hydrogen induced crack growth due to short fluctuations in process conditions shows, that cracks stabilise when normal operating conditions are restored. However, after a number of operational fluctuations, cracks can become unstable and will continue to grow also under normal operating conditions.

SYMBOLS USED

a = Crack radius (m)
A = Constant in conversion factor $Q(T)$ ($1.54*10^{-6}$ $Pa^{-1}K$)
B = Constant in conversion factor $Q(T)$ ($4.69*10^{-11}$ Pa^{-1})
C = Hydrogen concentration (molH/m^3)
D = Diffusion coefficient (m^2/s)
E = Young modulus (Pa)
f = Hydrogen fugacity (Pa)
K_I = Stress intensity (N/$m^{3/2}$)
K_{IH} = Fracture toughness (N/$m^{3/2}$)
$K(T)$ = Hydrogen solubility (molH/m^3/$Pa^{1/2}$)
n = Number of moles (moles H_2)
ν = Poisson ratio (0.3)
P = Pressure (Pa)
P_c = Critical pressure for crack growth (Pa)
$Q(T)$ = Conversion factor between pressure and fugacity (Pa^{-1})
R = Ideal gas constant (8.314 J/mol/K)
T = Absolute temperature (K)
V = Volume (m^3)
Z = Compressibility factor

REFERENCES

(1) See e.g. Hydrogen degradation of ferrous alloys, edited by Oriani R.A., Hirth J.P. and Smialowski M., Noyes, Park Ridge, New Jersey 1985.

(2) Brouwer, R.C., Int. J. Pres. Ves. and Piping, 56, 1993, pp.133-148.

(3) Wilde, B.E., Kim, C.D. and Phelps, E.H., NACE, 36, 1980, pp. 625 - 632.

(4) Goldshtein, R.V., Zazovskii, A.F. and Pavlovskii, B.R., Soviet Materials Science, SOMSA4, 21, 1985, pp. 397 - 506.

(5) Gelder, K. van, Erlings, J.G. and Hay, M.G., Int. Conf. on Interaction of Steels with Hydrogen in Petroleum Industry Pressure Vessel Service, Paris, 1989, pp.317-327.

(6) Iino, M., Metallurgical Trans. 9A, 1978, pp. 1581 - 1590.

(7) Ikeda, A., Morita, Y., Terasaki, F. and Takeyama, M., Deuxieme congres international l'hydrogene dans les metaux, Paris, 1977, paper 4A7.

(8) Crank, J., The mathematics of diffusion, Clarendon, Oxford 2nd.ed. 1986, pp.137-159.

(9) Tada, H., Paris, P. and Irwin, G.: Stress Analysis of Cracks Handbook, Del Research Corp. USA, 1985.

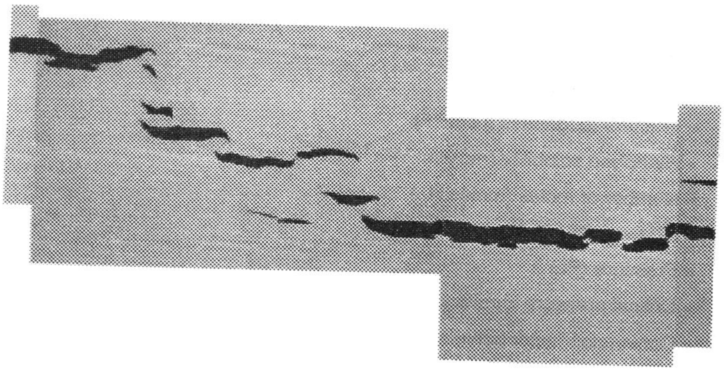

Figure 1. Typical HIC damage in the centre band of an X60 steel (100X).

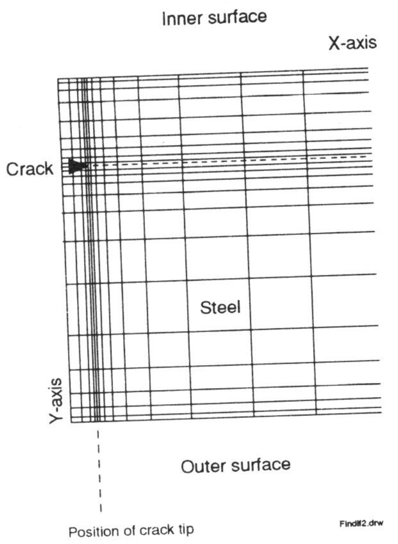

Figure 2. Finite difference mesh of the wall of a pipeline or pressure vessel with a penny shaped defect.

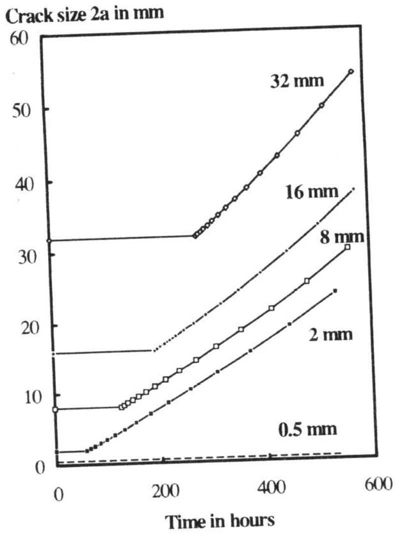

Figure 3. Crack growth curves for defects located at 11 mm from the inner surface (K_{IH}=400 N/mm$^{3/2}$).

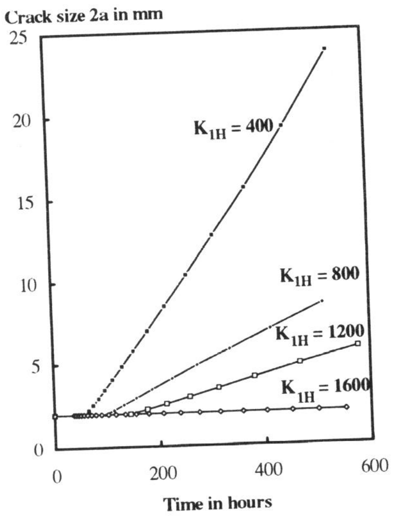

Figure 4. Crack growth curves for defects in steels with different K_{1H} in N/mm$^{3/2}$ (Crack 11 mm from the inner surface)

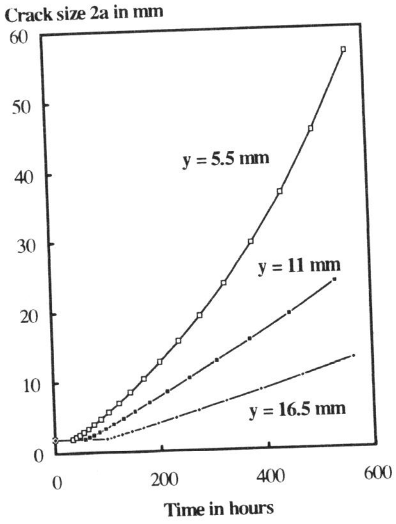

Figure 5. Crack growth curves for defects located at different positions in the wall (K_{IH} = 400 N/mm$^{3/2}$).

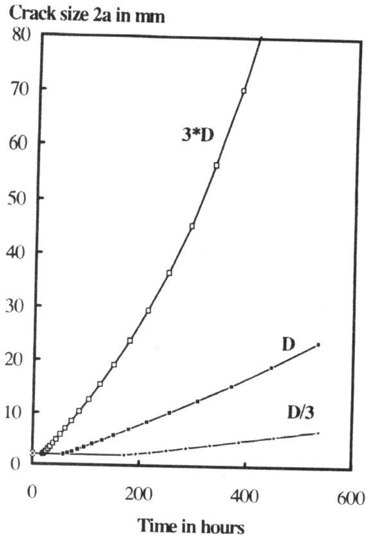

Figure 6. Crack growth curves in steels with different diffusion coefficients ($D=3.1*10^{-10}$ m^2/s, K_{IH} = 400 $N/mm^{3/2}$).

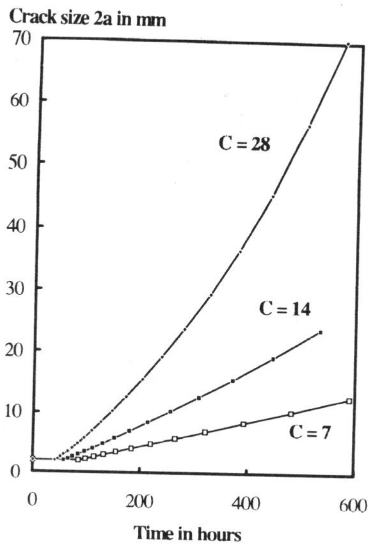

Figure 7. Crack growth curves for different hydrogen concentrations at the inner wall (C in $molH/m^3$, K_{IH} = 400 $N/mm^{3/2}$).

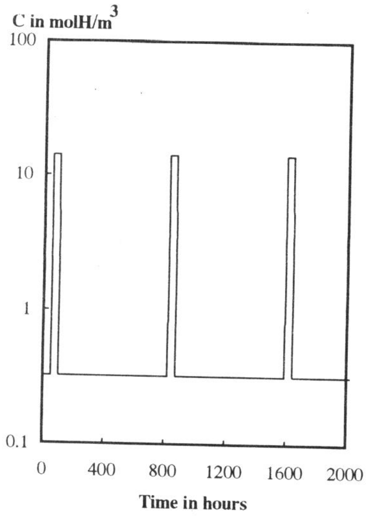

Figure 8. Fluctuating operating conditions: Every 30 days a hydrogen peak is observed lasting 48 h.

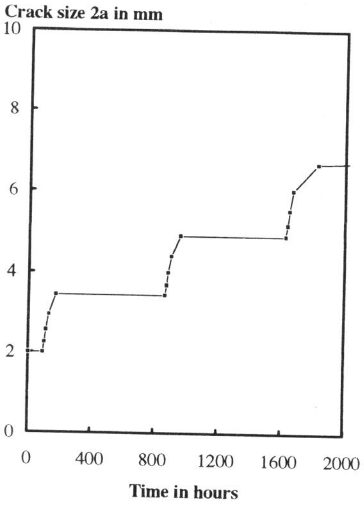

Figure 9. Crack growth due to fluctuations in the operating conditions (K_{IH} = 400 $N/mm^{3/2}$).