

MODELLING HYDROGEN INDUCED CRACKING USING A COUPLED  
DIFFUSION-ELASTO/PLASTIC STRESS ANALYSIS

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A computer program, HICFEM, has been developed to model hydrogen induced cracking. The program is intended to have two functions: determining a fitness-for-future-service criterion for structures with existing HIC-damage and determination of the critical hydrogen conditions for constructions made of new materials designed for sour environments. The influence of plasticity, the fracture toughness, and the crack length on crack growth curves has been investigated. It can be concluded that plasticity delays hydrogen induced cracking.

INTRODUCTION

Hydrogen induced cracking (HIC) is a major problem in the oil and gas industry and is observed mainly at low temperatures ( $< 100$  °C) in ferritic steel environments containing hydrogen sulphide ( $H_2S$ ). It is defined as crack growth resulting from the internal pressure of hydrogen gas collected in internal cracks. Eventually, the linking up of these cracks can lead to failure, as illustrated in Figure 1. The HIC-mechanism is a coupled diffusion/stress problem: the pressure in the crack depends on the hydrogen flux into the crack and vice versa. The HICFEM program calculates the boundary conditions, described in the following section, to be used in a finite element analysis. Plasticity modelling is based on the updated Lagrangian approach. The present model is based on the earlier linear elastic model of Krom and Bakker [1] which is based on the original model presented by Brouwer and Ritchie [2]. They used the finite difference method to solve the diffusion equation. The pressure

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and stress intensity factor were then calculated using an analytical relation.

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In this paper crack growth curves of a penny shaped crack are presented as functions of fracture toughness and crack length. The penny shaped crack geometry is a representation of a flat, circular MnS inclusion, always present in rolled mild steel. The three dimensional crack geometry leading to a two dimensional crack problem and mesh is shown in Figure 2.

### NUMERICAL PROCEDURE

#### Boundary Condition 1: The Hydrogen Concentration on the Crack Flanks

On the surface of the crack the following reaction takes place:  $\frac{1}{2}H_2 \Leftrightarrow H$ . If we assume equilibrium between the hydrogen dissolved in the steel at the surface and the gaseous hydrogen in the crack, the hydrogen concentration in the steel at the surface, C, is related to the hydrogen pressure, p, in crack as follows:

$$C = k\sqrt{(pe^{Bp})} \quad \text{with } B = \frac{z_1}{T} + z_2 \quad (1)$$

where k is the solution coefficient, and  $z_1$  and  $z_2$  are constants which are  $1.51 \cdot 10^{-6} \text{ K/Pa}$  and  $-1.04 \cdot 10^{-11} \text{ 1/Pa}$ , respectively [1], and T the temperature. The variable B is for taking into account the non-ideality of the hydrogen gas. When the temperature is high and/or the pressure low, Eq. 1 reduces to Sieverts' law:  $C = k\sqrt{p}$

#### Boundary Condition 2: The Pressure on the Crack Flanks

The pressure, p, in the crack exerted on the crack flanks depends on the number of hydrogen moles, n, in the crack. The relation used by [2] and [1] is only valid for linear elastic material behaviour where the volume/pressure relation is linear. This is not the valid for cases where plasticity is present. Plastic material behaviour can be accounted by assuming a piecewise linear approach of the volume/pressure relation:  $V = V_1 + (p - p_1)(V_2 - V_1)/(p_2 - p_1) = V_1 + S(p_2 - p_1)$ . In this case we obtain:

$$p = \frac{-(V_1 - Sp_1 - nRTB) + \sqrt{\{(V_1 - Sp_1 - nRTB)^2 + 4nRTS\}}}{2S} \quad (2)$$

when  $V_I$  and  $p_I$  are taken zero, this equation reduces to the one used by [2] and [1].

#### Crack Growth Criterium

The crack growth criterium is based on linear elastic fracture mechanics. We assume that there is only mode I loading, or at least that the mode I loading is much larger than the mode II loading. The mode I stress intensity factor  $K_I$  is used as the critical parameter for crack growth and is derived from the J-integral using the well-known relation (plane strain):  $K_I = \sqrt{\{EJ/(1 - \nu^2)\}}$ . The J-integral is determined using the virtual crack extension method (Delorenzi [5]). When the applied  $K_I$ -factor reaches a critical value (fracture toughness), crack growth occurs by releasing nodes. In the linear elastic case, the  $K_I$ -factor for the penny shaped crack is directly related to the pressure:  $K_I = 2fp\sqrt{(a/\pi)}$  where  $f$  is geometry factor and  $a$  the (half) crack length.

#### Mesh and Material

The investigated geometry is a 22 mm thick and 60 mm long part of a pressure vessel wall made of low-sulphur CMn steel. Young's modulus is 200 GPa, Poisson's ratio is 0.3, and the yield stress is 400 MPa. The operating temperature is 293 K (20 °C). The solution coefficient is  $6.5 \cdot 10^{-6}$  mol/m<sup>3</sup>/Pa<sup>1/2</sup> (Quick and Johnson [3]) and the diffusion coefficient  $1.40 \cdot 10^{-9}$  m<sup>2</sup>/s (Brouwer et al. [4]). The hydrogen concentration on the inner surface of the wall is 20 mol/m<sup>3</sup>. A simple rectangular mesh is used, consisting of 2756, 4-node axi-symmetric elements. The crack is situated in the centre of the wall, parallel to the surfaces. Near the (future) crack flanks the mesh is refined to model the gradients of concentration and stress.

#### RESULTS / DISCUSSION

In Figure 3 the crack length as function of time is shown for  $a = 1$  mm and in Figure 4 for  $a = 3$  mm. All curves show an incubation period, i.e. the time to fill the crack, and an almost constant crack growth rate. For  $K = 400$  N/mm<sup>3/2</sup> the difference between linear elastic and plastic material behaviour is not large. Only the crack growth rate is slightly smaller in the plastic material. This is due to crack tip plastic strains. As a consequence the volume is larger. Therefore, more time is required for filling the crack with gaseous hydrogen to the critical pressure. For  $K = 2000$  N/mm<sup>3/2</sup> the crack in linear elastic material does not grow because the pressure can not reach the critical pressure. The critical pressure depends on the wall thickness and the steady state hydrogen concentration at the crack surface. With plastic material behaviour the J-integral can be higher than with linear elastic behaviour. Hence, the applied  $K_I$ -factor is also higher at a given pressure. In this case the critical stress in-

tensity factor has been reached. It is, however, questionable whether the  $K_I$ -based crack growth criterium is still valid since the plastic zone has become very large compared to the crack length. Furthermore, the J-integral is in fact not valid when there is relatively large crack growth.

For  $a = 3 \text{ mm}$  and  $K = 400 \text{ N/mm}^{3/2}$  the difference between the two types of material behaviour is still small. We see the same trends as with the crack of  $a = 1 \text{ mm}$ . For  $K=2000 \text{ N/mm}^{3/2}$  the crack of  $3 \text{ mm}$  does grow in linear elastic material because the crack length is larger. As a consequence the applied  $K_I$ -factor is larger and the critical  $K$  is reached. At higher critical  $K_I$ -factors the effect of plasticity becomes more pronounced because crack tip stresses are higher. The incubation period is much larger because the volume is larger at given pressure. There is more hydrogen required to fill the crack to the critical pressure and thus more time is required before the crack is filled. After the incubation period the crack growth rate is much smaller than in the linear elastic material. After crack growth, unloading occurs behind the crack tip. Thus the volume of the crack in plastic material remains larger than was the case in linear elastic material. Again, more time is required to fill the new crack volume, and the crack growth rate is less than in the linear elastic material.

The stress distribution around the cracks was also investigated, in particular the hydrostatic stress because positive hydrostatic stresses increase the solubility while negative hydrostatic stresses have the opposite effect. Negative gradients in the hydrostatic stress distribution increase the rate of hydrogen diffusion while positive gradients result in a decrease. The stress distribution around the crack has to be in equilibrium with the pressure in the crack. As a consequence the hydrostatic stresses are relatively low. The influence on the solubility and diffusion of hydrogen should be negligible. However, calculations are necessary to prove this.

#### CONCLUSION

Linear-elastic calculations have shown that the crack growth curves have two distinct features, an incubation period and a constant crack growth rate. These two features are still found if material is modelled allowing for plastic behaviour. However, plasticity decreases the crack growth by increasing incubation period and by decreasing the crack growth rate. The effect of crack tip plasticity is dependent on the fracture toughness and the crack length. It can thus be concluded that plasticity delays hydrogen induced cracking. Hence, modelling linear elastic behaviour leads to conservative and consequently to safe predictions.

Further studies should be carried out to investigate the behaviour of cracks under internal pressure and the J-validity with relatively large crack growth.

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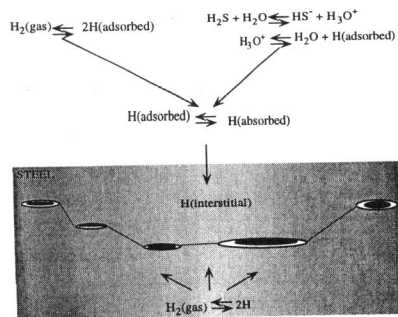


Figure 1 Illustration of the HIC-mechanism

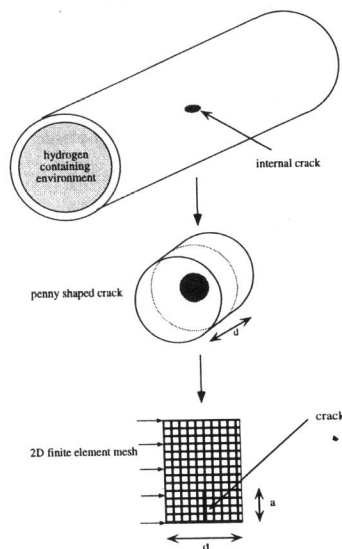


Figure 2 From 3D problem to 2D mesh

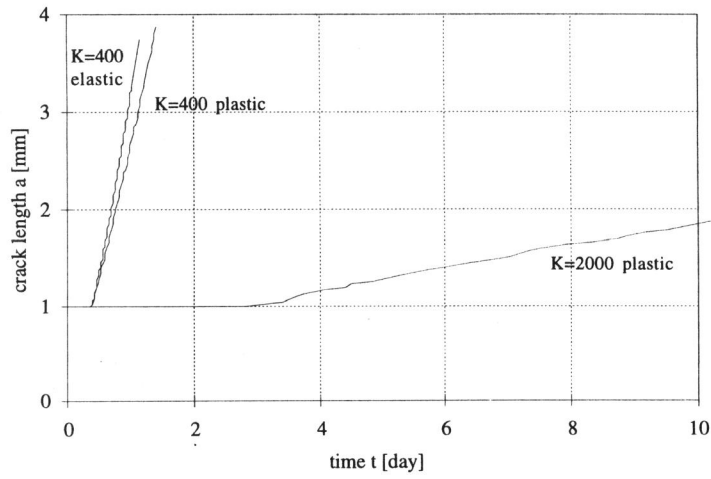


Figure 3 Crack growth curves in steel with linear elastic and plastic material behaviour modelled,  $a=1$  mm,  $K=400$  and  $2000$  N/mm<sup>3/2</sup>

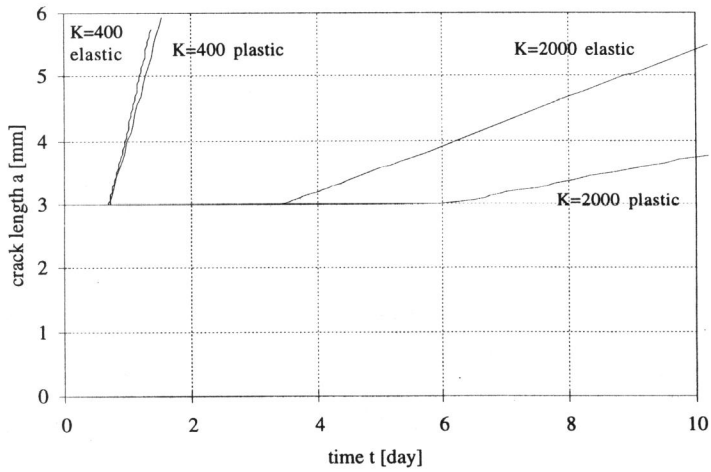


Figure 4 Crack growth curves in steel with linear elastic and plastic material behaviour modelled,  $a=3$  mm,  $K=400$  and  $2000$  N/mm<sup>3/2</sup>