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Rajabipour, Ali; Melchers, Robert E. "Capacity of pitting corroded pipes under hydrogen assisted cracking". Published in International Journal of Hydrogen Energy Vol. 40, Issue 30, p. 9388-9399 (2015)

Available from: <http://dx.doi.org/10.1016/j.ijhydene.2015.05.077>

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Accessed from: <http://hdl.handle.net/1959.13/1339394>

Capacity of pitting corroded pipes under hydrogen assisted cracking

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1 Abstract

Steel pipes used in the oil and gas industry when subject to corrosion pitting may fail as a result of internal pressure and metal cracking influenced by hydrogen embrittlement. The progressive shape of the crack, including at the instant of failure, is predicted under increasing internal pressure. It is proposed that when hydrogen-assisted cracking (HAC) is involved the shape of the crack front may be estimated from a parallel numerical analyses in the absence of HAC. The theory for this is outlined and an example given.

2 Introduction

Cracks along pipes often commence at the sites of corrosion pits [1], although there are other causes of pipe cracking [2]. Cracking from pits may be accelerated by a Hydrogen Assisted Cracking (HAC) mechanism [3]. This has been a challenge for oil and gas industry [4, 5]. Susceptibility to hydrogen assisted cracking has been shown to be greater for some stainless steels when made into pipes [6]. When a contaminant such as H_2S is included in the conveyed fluid, such as in sour gas pipelines [7, 8], hydrogen gas may be in direct contact with the interior metal surface of the pipe. Hydrogen also can be accessible to pits and gouges formed on external surface of pipes, depending on the exposure conditions [9-11]. In aqueous soil environments hydrogen might be generated electrochemically on the external surface of the pipe [12]. It is well-known that hydrogen reduces strength [13-15] and ductility [16-18] of metals by embrittlement and as a result the pressure required within the pipe to cause failure is reduced [1, 12, 19]. The present paper considers pipes pitted by corrosion and the influence on their structural capacity or strength of hydrogen-induced cracking. Numerical modelling is used to develop an improved understanding of the effect of the shape of a corrosion pit on development of cracking, including hydrogen assisted cracking (HAC), starting from the pit.

The loss of structural strength of pipelines operating under pressure and affected by HAC has been much addressed by experimental studies [20-23]. It also has been modelled and analysed numerically using various approaches involving fracture mechanics. One widely used approach employs Linear Elastic Fracture Mechanics (LEFM) to estimate rate of cracking, with

a pre-defined threshold stress intensity factor [24-26] for the embrittled material. The validity of this approach lies largely in evidence provided by fractography that shows that plasticity may be ignored in HAC when the crack has a planar growth pattern [7, 8, 27]. Hydrogen embrittlement also has been modelled as reducing the plasticity of the metal, based on evidence [13-15] showing that plasticity is decreased by embrittlement. This numerical approach has been termed hydrogen-enhanced localized plasticity (HELP) [28, 29]. Finally, so-called hydrogen enhanced decohesion (HEDE) also has been identified as a failure mechanism. The concept of hydrogen causing a degrading cohesive force was first proposed early in 1960s [30] and during the next 20 decades the thermodynamic bases of hydrogen decohesion were investigated [31-35]. Other models, of a more applied nature were proposed subsequently. These aimed at simulating crack propagation [36, 37]. This trend is continuing, aided by more powerful and more robust computational methods and tools [38-41]. In contrast to these latter approaches, the present paper employs the LEFM concept together with the small-scale yield condition [42, 43]. The reason for choosing this approach is that it permits detailed modelling of the effect, on crack properties and on crack propagation, of the reduction in material toughness and plasticity as result of the local presence of hydrogen at and in the neighbourhood of the crack tip.

The overall strength of the pipes themselves, when they are affected by crack propagation from corrosion pits, has been investigated mainly using plastic collapse-based criteria [44]. However, these criteria have been shown to be too conservative for estimating the residual strength of pitted pipes [45]. Codes such as API 579 [46] and BS 7910 [47] provide guidance for evaluating the acceptability of cracking from pipe surface defects. However, in the case of brittle materials it has been proposed that the assessment methods for crack initiation and development need to be further developed [48]. In this regard, a minimum toughness criterion has been proposed [49] when failure is controlled by plastic collapse (plastic flow) [50]. Since HAC inherently involves crack initiation and propagation, it is inevitable that both must be modelled numerically to estimate pipe strength when HAC is involved. Models for this purpose have been developed, coupling hydrogen diffusion and the finite element method [40, 51] but the final goal of estimation the cracking rate and the lifetime of engineering components seems to remain elusive [37]. One of the reasons for this is the need to estimate values for highly uncertain parameters such as the accessibility of pressurized hydrogen pressure to the interior of the crack. The present paper is concerned with this problem and provides a means to estimate the minimum internal pressure that will result in leakage, and therefore failure, of pipes that are pitted and subject to HAC. While the service life of a pipe cannot be estimated using the proposed approach, it does provide a rational tool for decisions on regulating the pressure in pitted pipelines so as to reduce the risk of failure under HAC.

To estimate the strength of pipes with corrosion pits when the pipe metal is subject to HAC several steps must be followed. In the first step it is shown that when a crack has reached the internal surface of the pipe, the strength of the pipe declines rapidly. In the second step, numerical analyses is used together with some common assumptions in Fracture Mechanics to show that the pattern of crack development under HAC is closely similar to that in the

absence of HAC. Finally, in the third step this similarity together with the assumption of the applicability of the Small-Scale Yielding (SSY) condition is invoked to estimate the strength of corrosion pitted pipes affected by HAC, based on the strength of corrosion pitted pipes that are not under the influence of hydrogen embrittlement (i.e. without HAC).

The occurrence of hydrogen embrittlement sets up a condition in the pipe that, from a structural point of view, may be considered to resemble that of cracking in a brittle material. For analytical convenience, to find the properties of cracking in such a condition the approach followed below is to consider first the case for a brittle material (such as cast iron). The analyses and the modelling outcomes then can be generalised to ductile materials. This is discussed in detail in sections 3 and 4. It is shown that the generalization is possible because of (i) planar development of cracking, (ii) small displacement of cracking faces at the instant of formation of a fully penetrating crack and (iii) negligible plasticity at the crack tip.

In the numerical analysis to follow, idealized pits are modelled, for various depth and aspect ratios, to determine crack initiation and crack propagation behaviour under realistic stress conditions. The pits are assumed of semi-ellipsoidal shape as shown in Figure 1 that also shows the assumed orientation and dimensions relative to the pipe wall. In the following the pit geometries are defined by the ratios W/D and D/S .

Figure 1- Shape parameters of an idealised elliptical pits. Axes 1, 2 and 3 show the orientation. These axes are consistent in all figures.

3 Hydrogen assisted cracking from pits

In this section a series of results are presented for the numerical modelling of cracks emanating from the surface of pits such as that shown in Fig. 1. The results together with results from published experimental investigations and several uncontroversial assumptions commonly made in Fracture Mechanics analysis are then used to propose that the crack development pattern under HAC from a pit is closely similar to that in the absence of HAC. This result is then used in Section 4 to consider the capacity of pitted pipes under HAC and under internal pressure.

3.1 Crack development in the absence of HAC

This section considers the initiation and propagation of cracks emanating from corrosion pits without the possibility of HAC of the pipe metal being involved. As noted, the loading on the pipe is internal pressure. For the numerical modelling a quarter slice of pipe is considered in the neighbourhood of a semi-ellipsoidal pit (Figure 2) with symmetry for faces A, B and E. Plane strain conditions are assumed to apply for the faces parallel to the hoop stress - these are A and C in Figure 2. As a result of this symmetry, every section of a pipe has the same radial outward deflection and there is no strain between any two sections perpendicular to axis 1 (Figure 2) (so-called plane strain condition). In the immediate vicinity of a pit, however, this obviously can not be the case. It follows that the plane strain condition can be assigned to the faces perpendicular to direction 2 in Figure 2, but only when these faces are sufficiently far from the pit. A preliminary set of analyses was carried out to ascertain the necessary size of the model for the plane strain condition to be valid. For this and all subsequent numerical analyses the extended finite element method (XFEM) with cohesive behaviour and linear hexahedral elements was employed, using Abaqus 6.11-2.

Figure 2- Pit shape parameters (W, D, S) on a modelled quarter of a pipe slice. Plane strain condition is applied to faces “E” and “B”.

The material properties Young’s modulus, Poisson’s ratio and maximum principal strength, were assigned values of 80 GPa, 0.3 and 80MPa respectively, consistent with references [52, 53]. The maximum principle stress criterion was used for crack initiation. This criterion is widely accepted for brittle materials [54].

The results (Figure 3) show that cracks propagate in a plane perpendicular to axis 2 (Figure 2) and start either from the shoulder or from the bottom of the pits. This planar development is expected due to symmetries in pit shape, pipe shape and axisymmetric loading. After initiation, the crack propagates along the pit wall. Once it reaches the end of

the pit wall, the crack grows with a greater rate at the top, thereby making it more inclined with respect to the pit wall. This behaviour can be tracked in Figure 3-c to Figure 3-g. Eventually, the crack penetrates completely through the wall (Figure 3-g) - let this be termed a fully penetrating crack. As shown in Figure 3-h the crack front tends to become parallel to axis 3. This then facilitates the crack propagating further in an opening or tension mode (which has been termed Mode 1 [31]).

Figure 3- Schematic process of crack initiation and propagation from pit shoulder under monotonically increasing internal pressure based on the analyses $D/S=0.9$, $W/D=0.5$.

When crack initiates from bottom of a pit a generally similar process of crack development is observed. The main difference is the specific location and the precise direction of cracking. Figure 4 shows the propagation of a crack of this type near a pit.

Figure 4- Schematic process of crack initiation and propagation from bottom of a pit under monotonically increasing internal pressure based on the analyses $D/S=0.6$, $W/D=2$.

It should be clear from the above that the type of crack emerging from a pit depends very much on the pit shape. The location from which a crack initiates is dictated by stress field in the vicinity of a pit and this stress field is determined by the pit shape. Both the ratio of W to D and D to S (Figure 2) are important in this regard.

Standard fracture mechanics theory indicates that three modes of cracking are possible, namely [55], mode I (opening mode), mode II (sliding mode) and mode III (tearing mode). For

the present problem several preliminary numerical analyses were conducted and these indicated that only mode I plays a significant role in cracking under pipe internal pressure. This is illustrated in Figure 3 in which the numerical modelling results of the development of the cracked region are compared. Cases (a-e) have all three modes with the same critical energy release rate whereas for cases (f-j) the same critical energy release rate applies only for mode I (G_{Ic}) and zero critical energy release rates for the other modes. Since Figure 3 shows negligible differences between the shapes of the cracked regions for identical applied internal pressures it is clear that crack development from surface pits under internal pressure depends only on G_{Ic} and is independent of G_{IIc} and G_{IIIc} .

Figure 5-Comparison between the crack shapes developed under increasing (monotonic) pipe internal pressure when (i) the critical energy release rates are $G_{Ic} = G_{IIc} = G_{IIIc} = 2500 \text{ J/m}^2$ shown as cases (a) – (e): and (ii) the critical energy release rates are $G_{Ic} = 2500 \text{ J/m}^2$, $G_{IIc} = G_{IIIc} = 0$, shown as cases (f) - (j). In all cases $W/D=2$, $D/S=0.6$ and $S= 15\text{mm}$.

Additional numerical sensitivity studies show that the development of the crack pattern is insensitive under different assigned cohesive strengths and correspondent cohesive energies. Figure 4 shows the results of such analyses under monotonically increasing pipe pressure. Evidently, the cracking pattern is quite similar between cases (a-d) and (e-h) even though the cohesive strengths and cohesive energies are considerably different. From this it can be inferred that when pipe metal has homogeneous toughness the cracking pattern is not strongly influenced by the cohesive strength or the cohesive energy of the metal. Conversely, as has been shown earlier [56], the shape, dimensions and manner in which the crack propagates depends strongly on pit shape.

Figure 6-Comparison between cracked areas under increasing pipe internal pressure. $W/D=0.5$, $D/S=0.9$ and $S=15\text{mm}$.

a-d: $G_{Ic} = G_{IIc} = G_{IIIc} = 1250 \text{ J/m}^2$ and e-h: $G_{Ic} = G_{IIc} = G_{IIIc} = 2500 \text{ J/m}^2$.

3.2 Crack development pattern under HAC

Attention is now turned to the effect of hydrogen on the development of a crack starting at a corrosion pit situated on the surface of a brittle metal when that metal is prone to HAC. There are two potential influences that need to be considered. These are the effect of hydrogen on the elastic modulus of the metal and the effect of hydrogen on the plastic properties of the metal. These are considered in this section.

It has been established that the presence of hydrogen in embrittled regions changes the elastic modulus of the metal in that region by less than 2% [37, 57, 58]. The net result is that compared with a hydrogen-free stress-state, there is negligible effect on the overall stress field and also a negligible effect on the stress field near a crack front. It is known that the stress field in the neighbourhood of a crack front is a direct function of material stiffness [55, 59]. It follows that a decrease in stiffness resulting from hydrogen embrittlement would cause the elastic energy also to decrease. In turn this would cause a decrease in the local stress concentration in the neighbourhood of crack front. However, since hydrogen embrittlement does not change the stiffness considerably this scenario may be neglected and for practical purposes it may be assumed that hydrogen embrittlement has negligible effect on the stress field while the field remains elastic.

On the other hand, hydrogen embrittlement does change the material plasticity [13-15] and by implication changes the stress field around the crack front. Specifically, at a local level hydrogen embrittlement causes a metal to fracture under a lower stress intensity factor. The net effect is a lowering of the available local plasticity compare with that of a virgin (unembrittled) metal. However, this may not be all that important. The reason follows from the observation from numerical analyses that, under uniform internal pipe pressure, the

cracks that develop from pits tend to lie in the 2-3 plane (Fig 2), that is, in the radial direction and along the pipe axis. Moreover, for this scenario it is known that plasticity is negligible in planar cracking [7, 8, 27]. Taken together, these two observations indicate that there is little difference in the overall development of (planar) cracks under uniformly embrittled conditions and for a metal not embrittled.

The above considerations apply to a locally uniformly embrittled material compared to an unembrittled material. However, for metals subject to HAC, embrittlement is unlikely to be uniform. In general it can be expected to vary by distance from the crack front. This is because the pattern of hydrogen concentration within the metal usually is governed by diffusion from the external environment and thus is unlikely to be uniform. There are now two factors that determine the development of the crack front. These are the pattern and the intensity of the stress field in the neighbourhood of the crack front and the local concentration of hydrogen. The direction of growth of the crack at the crack front is dictated by the direction of the greatest net stress intensity factor, that is the difference between the local stress intensity factor, K and the material critical stress intensity factor, K_C that describes the stress intensity for the initiation of cracking ([42]. In the absence of hydrogen, K_C is the same throughout the metal so the medium is homogeneous in terms of critical stress intensity factor (also known as the fracture toughness), K_C . As noted in the previous section, in this case the development of a crack front under increasing pipe internal pressure can be estimated numerically and easily using a commercial finite element software package. Also, for convenience in the exposition to follow, let this be referred to as the homogeneous case, and let the contours of crack fronts that can be computed under the homogeneous conditions be referred to as 'homogenous front contours'.

When hydrogen diffuses from the crack front into the metal, the material critical energy release rate usually is considered to decline [26, 60, 61]. As a result, K_C also decreases, proportionally to the local hydrogen concentration. It follows that when hydrogen is involved in crack development, the crack front itself may not follow the same development pattern as for the homogeneous case, that is, the contours of the crack front development are likely to differ. Figure 5 shows this schematically. It shows that the homogeneous front contours (dashed lines) and hydrogen concentration contours (solid lines) may have different patterns. Thus the crack front development for the homogeneous case is not the same as the development of the crack front when hydrogen assists cracking.

Figure 7- Schematic illustration of crack front, homogeneous front contours and contours of hydrogen concentration, thick rigid line: current crack front, narrow rigid lines: contours of hydrogen concentration, dashed lines: crack fronts in the absence of hydrogen

Although the nonhomogeneous presence of hydrogen causes the crack front contours to deviate from those for the homogeneous case, it can still be expected that for small incremental changes in crack development the difference in the contours for these two cases will be quite similar. This is because when the crack front moves slowly (under the HAC mechanism) every point on the crack front experiences very similar hydrogen pressure. It is therefore reasonable to assume that the hydrogen concentration is identical all along the crack front (Figure 5). Thus the level of hydrogen embrittlement is the same along the whole the crack front. In turn, this means that for every increment the new crack front is very close to the previous crack front, even under overall nonhomogeneous hydrogen concentration conditions and the crack front could be considered as growing as if it were in a uniformly embrittled, locally homogeneous medium. It can be expected, therefore, that the crack front closely follows the crack front contours for the homogeneous case. Figure 5 illustrates this schematically, with the next crack front always close in shape to the immediately previous crack front. Figure 5 also shows that particularly for small increments the contours for the crack front for the homogeneous case and the contours for hydrogen concentration are almost the same. Noting that both the local stress field and the local hydrogen concentration impose the same direction of crack development at any point on the crack front, it follows that the crack front complies with the homogeneous front contours as shown schematically in Figure 6. It shows the current crack front (at 0) and the direction of crack front development as a result of the stress field along the crack front, with an incremental movement to contour marked A. It also shows the contour of localized hydrogen concentration (marked B). These contours are very similar.

Figure 8- Homogeneous front contours and contours of hydrogen concentration in the vicinity of crack front

In summary, the development of the crack pattern from a pit under HAC is closely similar to that of crack development in the absence of HAC. Further, similar front shapes occur under different hydrogen pressures. Because of this similarity the crack development pattern from pits under HAC can be modelled, closely by the analytical tools available for modelling crack development in the absence of HAC. However, it is noted that this approach is valid only when the material (metal) involved has a sufficiently brittle behaviour. This is the state that SSY (Small-Scale Yielding) condition [43] can be considered for that metal. Actually, under condition of Small- Scale Yielding LEFM (Linear Elastic Fracture Mechanics) can be applied [55, 59, 62]. Thus the reasons raised here on similarity of cracking pattern under HAC with homogeneous front contours are valid as LEFM underpins the argument presented here. For brittle materials hydrogen embrittlement acts to make the material 'more brittle' than it otherwise would be and this is the basis for the similarity argument above.

Satisfying SSY condition is the sufficient condition for this similarity and level of embrittlement does not violate the similarity. In an extreme case of no embrittlement by hydrogen diffusion toughness does not change by hydrogen concentration therefore cracking pattern is exactly as the homogeneous fronts. Thus the so called similarity is completely satisfied in this case.

4 Estimating pipe strength under HAC

In the case of surface pits on the brittle pipes under internal pressure it is suggested in this paper that pattern of crack development doesn't change by hydrogen embrittlement. Based on this similarity, the final shape of crack under HAC can be predicted. This shape then is suggested to be used to estimate strength of internally pressurised pipes affected by HAC.

The fully penetrated state of a crack is defined as the condition that a crack has reached the internal surface of the pipe. The full penetration state of cracking is crucial in the study of cracking behaviour of pitted pipes affected by HAC. This is due to the fact that the contents of the pipe can leak out, but of course only after this stage is reached. Moreover, as Figure 7 and Figure 8 illustrate, the area of the cracked region increases rapidly when the crack reaches the internal surface of the pipe (fully penetrating condition). As a practical result it may be assumed that almost negligible pipe resistance can be considered to apply when the crack has become fully penetrating. Finally, a fully penetrating crack is a prerequisite for running crack, due to the fact that a running crack completely penetrates through the pipe wall thickness. In this sense if the existence of a fully penetrating crack is probable on a brittle pipe, then the pipe is likely to be susceptible to running cracks. The pressure that causes full penetration of the crack is discussed in this section.

Herein the pressure needed to initiate and achieving full penetration cracking is termed P_1 . Also, when HAC occurs, P_{1HAC} represents the minimum internal pressure needed to initiate and achieving full penetration cracking respectively. Herein it is suggested that P_{1HAC} is linearly proportional to P_1 . A crack immediately before fully penetrating state is considered. The crack is shown to propagate predominantly in mode one (see section 3.1). As explained in section 3.1, linear elastic fracture mechanics (LEFM) is assumed to be valid due to limited effect of hydrogen embrittlement on planar crack development and also stiffness (see section 3.2). Fracture toughness of virgin material and embrittled material are termed K_{IC} and $K_{IC(HAC)}$, respectively. In absence of HAC and immediately before fully penetrating state when K_I reaches K_{IC} , pipe starts leaking. In the same sense when HAC occurs, and immediately before full penetration state when K_I reaches $K_{IC(HAC)}$, leakage happens. In section 3.2 it is suggested that crack development pattern doesn't change by HAC. Based on this similarity, crack shape immediately before fully penetrating state is the same whether HAC happens or not. Moreover, since LEFM is applicable, there is a linear relation between k , stress intensity factor, and pipe internal pressure. Thus when HAC occurs, the pressure needed to develop a crack is $\frac{K_{IC(HAC)}}{K_{IC}}$ times of the pressure needed to develop the same crack in the virgin material. Especially immediately before full penetration state such a relation between P_{1HAC} and P_1 exists. Equation (1) shows this relation:

$$P_{1HAC} = \frac{K_{IC(HAC)}}{K_{IC}} P_1 \quad \text{Equation (1)}$$

Effect of hydrogen on metals toughness depends on many parameters such as metal composition and microstructure (see for example [63-65]) and also temperature (see for example [5, 66]). However, for limited variation in temperature $\frac{K_{IC(HAC)}}{K_{IC}}$ can be estimated as a function of hydrogen concentration in the environment adjacent to the crack tip. Referring to the results in [67, 68] a quadratic relation is presented between hydrogen coverage and reduction in cohesive energy in [37]. In the presented graph in [37] the relation between hydrogen coverage and reduction in cohesive energy is quite close to a linear relation. Thus a linear relation between hydrogen concentration and cohesive energy reduction is considered in [39, 40, 69]. If LEFM is valid, cohesive energy equals critical energy release rate which has

a linear relation with fracture toughness [55]. Hence a linear relation between fracture toughness, K_{IC} , and hydrogen concentration, u , can be considered, (equation Equation (2)).

$$K_{IC(HAC)} = K_{IC}(1 - \mu \times u) \quad \text{Equation (2)}$$

$K_{IC(HAC)}$: Fracture toughness of the uniformly embrittled metal

K_{IC} : Fracture toughness of the virgin material (not embrittled metal)

u : Relative hydrogen concentration in the metal

μ : Fracture toughness reduction factor by hydrogen concentration

μ depends on metallurgical properties of the material and pressure of hydrogen in the surrounding environment. μ is estimated to be 0.2 for pipeline steel X100 [40].

At the crack tip hydrogen in the environment has direct contact with the metal. Therefore the relative hydrogen concentration at the crack tip can be assumed one (equal to the environment). Hence immediately before reaching to fully penetration state and using equation (2), equation (1) can be simplified to equation (3).

$$P_{1HAC} = (1 - \mu)P_1 \quad \text{Equation (3)}$$

The idea that P_{1HAC} is proportional to P_1 can be generalised to other materials. As explained above, when HAC occurs, the stress field around the crack tip depends on the shape of the crack and increases linearly with internal pressure. In addition, due to negligible plasticity at the crack tip, the shape of the crack is dominated only by pit shape and by internal pressure. Thus the mechanical properties of the material do not influence the crack shape at the fully penetrating state of the crack. However, as discussed above, the internal pressure needed to form a fully penetrating crack depends on material toughness. It follows that when P_1 is known for material A, P_1 for material B can be estimated using equation (4):

$$P_{1HAC,B} = \frac{K_{IC(HAC),B}}{K_{IC(HAC),A}} P_{1HAC,A} = \frac{K_{IC,B}}{K_{IC,A}} (1 - \mu_B) P_{1,A} \quad \text{Equation (4)}$$

where:

$P_{1HAC,B}$: Internal pressure at the instance of fully penetrating crack in material B when HAC occurs

$P_{1HAC,A}$: Internal pressure at the instance of fully penetrating crack in material A when HAC occurs

$K_{IC(HAC),B}$: Fracture toughness of material B when HAC occurs

$K_{IC(HAC),A}$: Fracture toughness of material A when HAC occurs

$P_{1,A}$: Internal pressure at the instance of fully penetrating crack in material B when HAC does not occur

$K_{IC,B}$: Fracture toughness of material B

$K_{IC,A}$: Fracture toughness of material A

μ_B : Fracture toughness reduction factor by hydrogen concentration for material B

Also, it is not helpful to refer to fig 9 when it is further down the text - suggest simply say “ For example, consider the case $K_{IC,A} = 14.5 \text{ MPa} \cdot \sqrt{\text{m}}$. In this case, when $W/D = 1.0$ and $D/S = 0.9$, P_1 has the value $3.6 (1 - \mu) \text{ MPa}$, as discussed in more detail below (see also Fig. 9). For the same pit, but with $K_{IC,A} = 300 \text{ MPa} \cdot \sqrt{\text{m}}$ (as for example for X65 steel) application of equation (4) will give $P_1 = \frac{300}{14.5} \times 3.6 \times (1 - \mu) = 74.5(1 - \mu_{X65}) \text{ MPa}$. This then shows how the base case result is extended to other fracture toughness values. To estimate P_1 in this way clearly requires that plasticity of the material is not involved in the cracking process.

Figure 7 and Figure 8 show the relationship between the area of cracked region, the pipe internal pressure and μ . Evidently, the growth of the area of cracked surfaces depends strongly on pit shape. Crack growth rate increases considerably with parameter W/D , as illustrated in Figure 7. For a constant W/D , shallow pits are more likely to lead to crack growth than do the deeper pits (Figure 8). Analyses show a dramatic growth in the rate of crack propagation after the fully penetrated state has been reached (recall that this is defined above as the condition that a crack has reached the internal surface of the pipe). These observations lead to the general conclusion that pipe strength against internal pressure declines rapidly when the crack has fully penetrated to the internal pipe wall surface. The points at which the fully penetrating state occurs are shown on Figure 7 and Figure 8.

Figure 9- Area of cracked region versus pressure ($D/S=0.6$), when yield stress is 80MPa and fracture toughness is $14 \text{ MPa} \cdot \text{m}^{0.5}$

Figure 10- Area of cracked region versus pressure ($W/D=0.5$), when yield stress is 80MPa and fracture toughness is $14\text{MPa}\cdot\text{m}^{0.5}$

As shown in Figure 9, P_{1HAC} depends both on W/D and D/S . The two plots in Figure 9 tend to approach one point when the geometry of the pits becomes narrow (i.e. smaller W/D) and the plots trend to become more separated when the pits become wider (i.e. larger W/D). Figure 9 also shows that P_{1HAC} decreases with a slightly greater rate when W/D increases, particularly in the case of deeper pits (i.e. those with larger D/S).

Figure 11- Pipe pressure when crack is fully penetrating versus pit shape parameters, when yield stress is 80MPa and fracture toughness is $14\text{MPa}\cdot\text{m}^{0.5}$

A further aspect is that crack initiation depends on pit shape. Let the pressure needed to initiate cracking be termed P_0 . Figure 10 shows the dependence of P_0 on W/D and D/S . It shows that for narrower pits P_0 depends to an increasing extent on pit depth. Figure 10 also shows that for $W/D < 0.3$ then P_0 is almost independent of pit depth. Further, P_0 declines when pits become wider and the rate of decrease is greater when they are deeper.

As discussed above, when HAC occurs, the stress field depends on pits shape and is proportional to internal pressure. Also, since HAC causes a brittle fracture at the crack tip [7, 8, 27], the maximum principal stress criterion (Rankine criterion) is a valid crack initiation

criterion [70]. Using this criterion, crack initiation occurs when the maximum principal stress exceeds the material yield stress. Therefore, for a specific pit shape, at the instant of crack initiation the stress field is proportional to the yield stress of the material. It follows that for a specific pit shape if P_0 is known for material “A”, P_0 can be determined for material “B” by scaling, as follows:

$$P_{0HAC,B} = \frac{\sigma_{y(HAC),B}}{\sigma_{y(HAC),A}} P_{0HAC,A} \quad (5)$$

where:

$P_{0HAC,B}$: Internal pressure at the instance of crack initiation in material B when HAC occurs

$P_{0HAC,A}$: Internal pressure at the instance of crack initiation in material A when HAC occurs

$\sigma_{y(HAC),B}$: Yield stress of material B when HAC occurs

$\sigma_{y(HAC),A}$: Yield stress of material A when HAC occurs

In agreement with the reduction of the cohesive strength while critical separation remains constant [36, 37, 40], it is plausible to assume that ratio of reduction in plasticity is equal to the reduction in fracture toughness. Equation (6) shows this relation:

$$\frac{\sigma_{y,H}}{\sigma_y} = \frac{K_{IC(HAC)}}{K_{IC}} = 1 - \mu \quad (6)$$

in which:

$\sigma_{y,H}$: Yield stress of uniformly embrittled metal

σ_y : Yield stress of the virgin metal (not embrittled)

Therefore, equation (5) can be written as:

$$P_{0HAC,B} = \frac{\sigma_{y,B}}{\sigma_{y,A}} (1 - \mu_B) P_{0,A} \quad (7)$$

where:

$P_{0,A}$: Internal pressure at the instance of crack initiation in material A when HAC doesn't occur

$\sigma_{y,B}$: Yield stress of material B (HAC doesn't occur)

$\sigma_{y,A}$: Yield stress of material A (HAC doesn't occur)

Equation (7) estimates the yield stress of material “B” when hydrogen embrittlement occurs, based on the results obtained for material “A”. For example, based on the analyses

herein, when the yield stress is 80MPa, $P_0 = 2.06\text{MPa}$ for a pit with $W/D = 0.7$ and $D/S = 0.9$ (Figure 10). Thus, using equation (7) for a material with yield stress of 500Mpa (say X65 steel) the value of $P_0 = \frac{500 \times (1 - \mu_{X65})}{80} \times 2.06 = 12.87 \times (1 - \mu_{X65}) \text{MPa}$ for the same pit. Again, it is emphasised that the material plasticity must not be involved in the numerical modelling for estimating $P_{0,A}$ in equation (7).

Figure 12- Pipe internal pressure initiates crack versus W/D, yield stress=80MPa

5 Discussion

Figure 7 and Figure 8 show that in many cases a crack initiating from a pit needs to grow considerably before becoming a critical crack (cf. [71, 72]). This implies that irrespective of whatever other factors might be involved in a practical case of development of crack size, both W/D and D/S need to be sufficient to result in a large cracked area before failure can occur. In this regard, the cracked area at P_1 (or P_{1HAC}) is the minimum area under which the critical cracked condition can occur.

The analysis herein shows that the assumption of the prior existence of critical cracks near the pits will result in a conservative approach for engineering applications. For pipes under internal pressure, under some circumstances a crack may propagate very quickly. This has been termed a 'running crack' or a 'rapidly propagating crack'. In estimating whether a running crack will occur, it is assumed, usually and conservatively, that an initial flaw exists. Methods of checking on the possibility of fracture in pipelines (mostly developed in 70s and 80s) [73-75] check for the possibility of occurrence of a running crack, regardless of whether there exists an initial flaw as needed to trigger the running crack. This attitude is reflected in codified requirements such as, for example, in ASTM E1221 [76]. The analyses presented herein show that occurrence of a fully penetrating crack near a pit, which is a prerequisite to running crack, needs a large internal pressure (typically much more than the pipe design pressure). For example, in the case of the modelled pipe considered above, if $\mu=0.2$ the pressure P_{1HAC} (i.e. the pressure needed for the fully penetrating condition) was shown to be in the range 2.6MPa to 4MPa. These values make the hoop stress 60-80% of the pipe yield

stress (80MPa in the models) and therefore much higher than normally would be considered 'safe'. It follows that the usual assumption of the prior existence of cracks, without considering how these might initiate and develop, is likely to be conservative.

The similarity between cracking pattern from pits in the virgin and embrittled material is true only when the so-called Small-Scale Yielding (SSY) condition is assumed valid. When hydrogen diffuses from the crack tip into the metal, the metal in the neighbourhood of the crack front becomes brittle. Hence if hydrogen embrittlement occurs, the plastic region near the crack front is shorter than that in the virgin material. And, the more of the cracking path is embrittled, the closer is the situation to the SSY condition (in which the plastic region is considered to be small). The cracking pattern when plasticity is not Small-Scale is different from SSY. Two cases of cracks with the same shape and under the same loading are considered. The first one is assumed to satisfy SSY condition. In contrast to the first case, plasticity is assumed to develop considerably in the second one. In the second case less elastic energy can be stored in the plastic region in the neighbourhood of the crack front. Therefore, the stress intensity factor near the crack is less in the second case and also the stress fields are different in the two cases. Since the stress fields are different for cases one and two, the crack shapes for the subsequent steps of loading also will not be the same. Therefore, similarity between cracking pattern in the virgin and embrittled material exists only when SSY condition is considered to apply for the virgin material. However, the analyses herein are considered unlikely to be much affected by ignoring the SSY condition. This is due to the fact that under internal load the analyses herein (see section 3.1) showed that mode one dominates the cracking process and it has been shown previously [7, 8, 27] that plasticity does not change the cracking pattern under HAC when the crack development is planar. It follows that for cracking starting from surface pits and for pipes under internal pressure, with planar crack development under HAC conditions, the SSY criterion is automatically satisfied. Further, it follows that under these circumstances the pattern of cracking can be estimated inexpensively by suppressing the plasticity property of the material and by applying monotonically increasing pressure in the numerical modelling. Even for relatively ductile materials, such as pipe steels, this approach will allow the pattern of cracking and the value of P_{1HAC} to be estimated quickly and reliably.

The relation between P_1 and P_{1HAC} , equation (1), gives a conservative estimate provided there are only subtle decreases in elastic modulus during the HAC process [37, 57, 58]. Slightly decreases in elastic modulus as a result of HAC will cause decreases of the local material stiffness around the crack front. As a result of this declining stiffness, there will be less stress concentration around the crack front. In another words, since HAC reduces the local elastic modulus, the associated elastic energy can be pictured as shifting from the embrittled region to the rest of the medium where the stiffness is higher. As a result, the stress intensity factor decreases at the crack front. This implies that the value of P_{1HAC} estimated using equation (1) underestimates the actual carrying capacity of the pipe. Moreover, as discussed in the previous paragraph, the stress intensity factor is higher than actually is likely to be the case near the crack when the SSY condition is used. As a result, the use of the SSY condition also produces lower estimates for P_1 and P_{1HAC} .

If the growth in pit depth or size with time is known, the pipe capacity can be estimated as a function of time. By comparing the pipe capacity (which changes with time) with the working pressure of the pipe its life-time can be estimated. This framework can be employed in reliability analyses of pipelines. It is noted that a great deal of research has been conducted in modelling pit depth growth from the 1930s onwards when the phenomenon was introduced [77] to recent years [78-80]. The proposed models range from simple models associating pit depth with time using power-law relations, such as in [81], to more sophisticated models, for example [82].

Finally, in most work on corrosion pitting or localized corrosion, the geometry assumed for the pit used for crack analysis has been of a simple form, such as a semi-hemispherical shape. That has also been the starting point for the analyses presented herein. This shows clearly that pit geometry can have an important influence on crack initiation and crack development from such pits. Recent observations and field experience has shown that pit geometries such as those used herein, and in most earlier research [56], are significant idealizations. It follows that an important question for further research is the influence on crack initiation and crack development of pits and localized region of corrosion of more realistic geometry. This will require much more detailed consideration of the development of corrosion pits as pit depth (and size) increase, particularly since there is already some empirical evidence [83] that pit development follows a relatively complex process in time.

6 Conclusion

The present results using detailed finite element modelling show that **when hydrogen embrittlement occurs** the pipe strength depends largely on the pit geometry, as defined by W/D (ratio of mouth size to depth) and by D/S (ratio of depth to pipe thickness). It is not always the case, as often assumed, that depth of pits is the most significant factor in determining the pipe strength.

It is shown that under pipe internal pressure the cracking pattern from pits does not change when HAC (Hydrogen-Induced Cracking) occurs. A simple relationship for estimating pitted pipes strength affected by HAC is obtained based on the strength of pitted pipe in absence of HAC.

The numerical results show that cracks near pits need a very considerable increase in internal pressure to fully penetrate through the pipe wall. As a result, the approaches conventionally used for arrestment of running cracks are likely to be quite conservative as these methods presume the existence of a fully penetrating crack.

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