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Modeling of hydrogen embrittlement cracking in pipe-lines under high pressures

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Abstract

Hydrogen being accumulated inside the delamination cavity creates pressure which eventually leads to the damage of the pipeline. The focus of this study is the modelling of how the radius of delamination grows with respect to time. The modelling requires the solution of the coupled problem of elasticity theory about the crack opening under gas pressure and diffusion theory of gas diffusion into the crack cavity. The equation of state for the *ideal* gas is first used; however, this is only accurate for low pressures. However, while gas is accumulating inside the crack, its pressure becomes high enough that the gas cannot be considered *ideal* anymore. In this study, we apply the equation of state for *real* gas pressures. While the subsequent calculations are somewhat more cumbersome then for the ideal gas case, they are still straightforward that allow obtaining the close-form solution for the crack size, $a\ (t)$, depending on time.

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Keywords: Hydrogen Induced Cracking, High Pressures, Delamination, Internal Cracks

Introduction

During the transport of oil and hydrocarbons, dissolved hydrogen can penetrate into the walls of pipelines, frequently causing delaminating of the metal (e.g., Elboujdaini, 2006; Rice, 1976). Hydrogen absorbed by a metal is typically dissolved in the lattice in the proton form. Some of the protons reach the surface of a pre-existing or freshly created crack where they recombine with electrons and form molecular hydrogen in the crack cavity. Because the molecular form of hydrogen is usually more thermodynamically stable, this process leads to accumulation of gas hydrogen inside the crack (e.g., Balueva and Dashevski, 1995; Gonzales et. al., 1997; Eliaz et al., 2004). Hydrogen being accumulated inside the delamination cavity creates pressure which eventually leads to the damage of the pipeline (Fig. 1).

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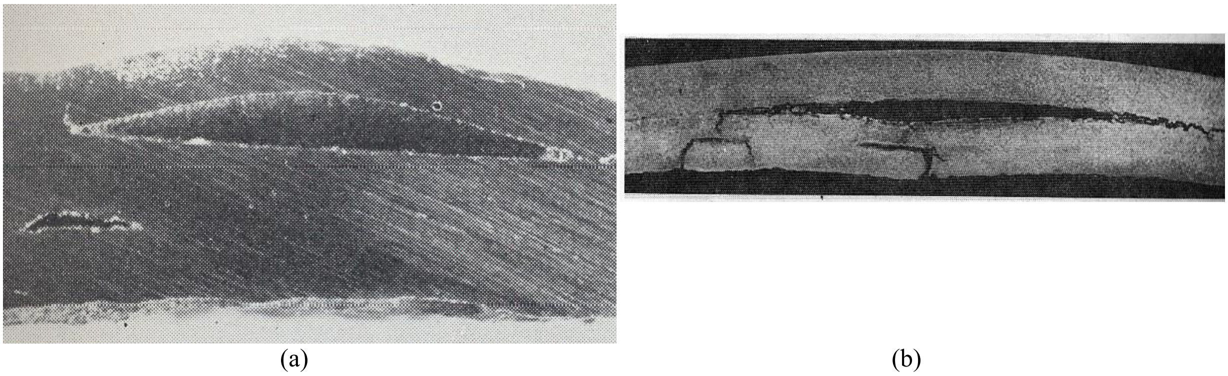

Fig. 1. (a) Hydrogen induced fracture near the external surface of a thick steel pipe (after *Polyakov*, 1996), and (b) hydrogen caused delaminations in a metal plate (after *Gapharov et al.*, 1998).

The focus of this study is the modeling of how the radius of delamination grows with respect to time. In this study, we apply the van der Waals equation, which is valid for high pressures. The results reveal some intriguing features worth checking experimentally. Under high hydrogen pressures inside the cracks, the latter do not grow at the constant speed as for the case of the ideal gas, but accelerate first. However, with time, large pressure driven cracks are slowing down, and in asymptotic approximation, as time is approaching infinity, they also start growing at the constant speed, besides at exactly the same as hydrogen driven cracks under the ideal gas conditions.

1. Main equations for a delamination growth

Suppose that a circular delamination of initial radius a_0, appears in the interface, $z = 0$, at the moment $t = 0$ (Fig. 2). The half space $z < 0$ is saturated uniformly by gas with concentration c_0, and it is covered by a thin layer of thickness h. While the gas is accumulated inside the crack, it keeps growing and the crack radius increases from a_0 to a. The growth of the crack can be analyzed in the framework of fracture mechanics so that the material resistance to the crack development is described by the critical energy release rate, G_c.

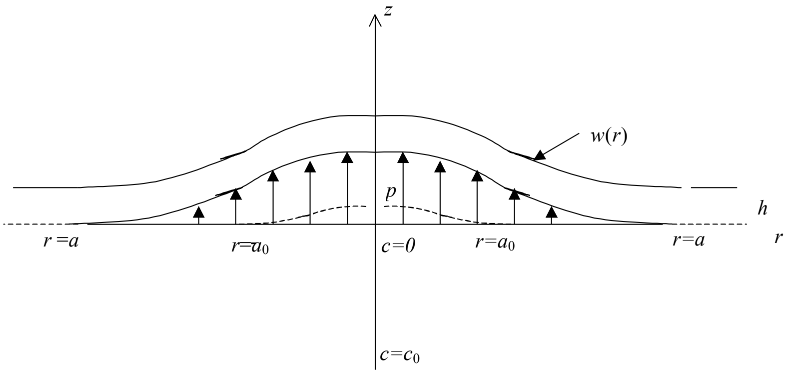

Fig. 2. Delamination growth under the pressure of the fluid accumulated in the crack (a_0 and a are the initial and current radii of the delamination crack).

The delamination opening, w, under the applied load, p, can be determined in the asymptotic approximation of thin plates (e.g., Timoshenko&Goodier, 1970):

$$w(r) = \frac{pa^4}{64D_0}\left(1 - \frac{r^2}{a^2}\right)^2, \tag{1.1}$$

where $D_0 = Eh^3/[12(1-\nu^2)]$, and represents the flexural rigidity. E and ν are the Young modulus and Poisson ratio

of the delaminated material, and r is the radial component of the cylindrical coordinate set (r, z).
The energy release rate, G, is given by the rate of energy absorption by the growing delamination per unit length of the crack front:

$$G = -\frac{1}{2\pi a}\frac{\partial U}{\partial a} = \frac{1}{128}\frac{p^2 a^4}{D_0} \tag{1.2}$$

Then the connection between the critical energy release rate, G_c, the crack radius, a, and the critical gas pressure, p, can be written as:

$$G_c = \frac{p^2 a^4}{128 D_0} \quad \text{or} \quad p^2 = \frac{G_c 128 D_0}{a^4}, \tag{1.3}$$

After integrating the crack aperture (1.1) over the crack area, the equations for the volume for the crack and the pressure applied to it can be written in the following form (Germanovich and Balueva, 2009):

$$V = \frac{\pi}{192}\frac{pa^6}{D} \tag{1.4}$$

In the previous author's paper (Balueva and Dashevski, 1999), the equation for ideal gas was chosen to connect the crack volume, pressure, and mass:

$$pV = nRT$$

While gas is accumulated inside the crack, its pressure becomes big enough that the gas cannot be considered ideal anymore, and the equation for the real gas is considered as (e.g. Eliaz et. al., 2004):

$$\frac{pV}{nRT} = 1 + B_2 p \tag{1.5}$$

where B_2 is the constant of the material (e.g. according to Eliaz et. al. (2004) $B_2 = 5.02\times10^{-9}$ 1/Pa for $T = 300$ °K).
By substituting in equations (1.4) and (1.5) into the equation (1.6), the latter is expressed as follows:

$$\frac{a^4 2\pi G_c}{3(a^2 + 8B_2\sqrt{2G_c D_0})} = nRT \tag{1.6}$$

where $n = \int_0^t Q(t')dt'$ is the mass of gas inside the crack.
From the solution of the problem of gas diffusion into the crack, the expression for the flux density is obtained (e.g., Sneddon, 1972):

$$q(r,t) = \frac{2}{\pi}\frac{c_0 D}{\sqrt{a(t)^2 - r^2}}, \quad r < a(t) \quad \text{or} \quad Q(t) = 4c_0 D a(t) \tag{1.7}$$

and the gas mass

$$n = 4c_0 D\int_0^t a(t')dt' \tag{1.8}$$

After substituting expression (1.10) for the gas mass into equation (1.7), the *integral* equation for the delamination radius can be written as

$$\frac{a^4 2\pi G_c}{3(a^2 + 8B_2\sqrt{2G_c D_0})} = 4c_0 DRT \int_0^t a(t')dt' \qquad (1.9)$$

After differentiating both sides the *integral* equation (1.10) can be reduced to the *differential* equation, and the closed-form solution for the radius of the growing delamination a under high gas pressures over time t was obtained in implicit form:

$$2\alpha\left(a - \frac{1}{2}\frac{\beta a}{a^2+\beta} - \frac{1}{2}\sqrt{\beta}\arctan\left(\frac{a}{\sqrt{\beta}}\right)\right) = t \qquad (1.10)$$

where

$$\beta = 8B_2\sqrt{2G_c D_0} \quad \text{and} \quad \alpha = \frac{\pi G_c}{6RTc_0 D} \qquad (1.11)$$

2. Analysis of results

Expression (1.10) gives the dependence how the radius of the hydrogen driven delamination, $a(t)$, is growing with time, t, when the hydrogen pressure inside the crack is high and we take into account the *real* gas equation. In the approximation that gas can be considered as *ideal*, the delamination radius grows with time at a constant speed as obtained in the previous paper of the author (Germanovich and Balueva, 2009):

$$a(t) = \frac{1}{2\alpha}t \qquad (2.1)$$

where α is given by (1.11).

The developed model will now be used for the analysis of kinetics of near-surface penny-shaped crack growing parallel to the wall of the plate, or delaminating of the external surface of metal exploited in conditions of hydrogen embrittlement. The typical range of K_{Ic} for hydrogen charged steel is 1 to 70 MPa·m$^{1/2}$ (e.g., Strnadel, 1998). Using $2\gamma = K_{Ic}^2/(E/(1-\nu^2))$, we estimate the probable corresponding range for $G_c = 2\gamma$ as 0.01 – 50 kJ/m^2, and in this work, we accept the somewhat intermediate, order-of-magnitude value of $G_c = 2\gamma \approx 10$ kJ/m^2.

Concentration of the atomic hydrogen c_0 in low-carbon alloy steel is observed to vary in the range of 0.38×10^{-7} to 0.78×10^{-7} mol/mm^3 according to Sunami et. al. (1974), which is consistent with 0.145×10^{-7} to 0.7×10^{-7} mol/mm^3 for AISI 430 stainless steel as suggested by Yen and Tsai (1996). Here, for model calculation, we assume c_0 be 10^{-5} mol/mm^3 (e.g., Addach et al., 2005).

The coefficient of proton diffusion, D, for steel varies in the range of 10^{-9} – 10^{-7} mm^2/sec according Beggs and Hahn (1984), can be equal 10^{-10} mm^2/sec according to Thompson (1980) and varies in the range of 10^{-5} to 10^{-4} mm^2/sec according to Yokobori (2004). As described by Sunami et. al. (1974), Goldstein et. al. (1977) and Goldstein et. al. (1985), for low alloy steel, D, can be as high as 10^{-3} mm^2/sec. For this model we assume D = 10^{-9} mm^2/sec.

The graph of radius of the delamnation $a(t)$ on time t is given in Fig. 3 (the *red* curve is for real gas (1.17) and for the initial gas pressure 741MPa; the *blue* curve is for real gas approximation (1.7) and the initial gas pressure inside the crack 70MPa; *black* curve is for the ideal gas approximation (2.1).

One can see that first, under high hydrogen pressures (*red* and *blue* curves in Fig. 3), the cracks do not grow at constant speed as for the case of the ideal gas (*black* curve in Fig. 3), but accelerate first. However, with time, large pressure driven cracks are slowing down, and in asymptotic approximation, as time is approaching infinity, they also start growing at the constant speed (the *red* and *blue* curves become straight lines in Fig.3), besides at the same as delaminations under ideal gas pressures.

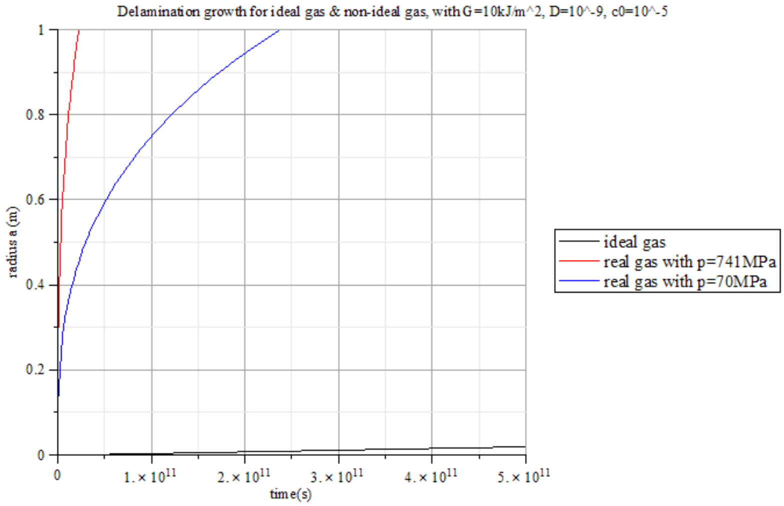

Fig. 3. Dependence of the radius of the delamination, $a(t)$ on time, t, for small times (the *red* curve is for the initial gas pressure 741MPa; the *blue* curve is for the initial gas pressure inside the crack 70MPa; *black* curve is for ideal gas).

Asymptotical approach to steady-state growth for high gas pressure driven cracks can be proved analytically. In extreme as $a \to \infty$, it is easy to see equation (1.17) becomes:

$$2\alpha(a - \frac{1}{4}\pi\sqrt{\beta}) = t \qquad (2.2)$$

or it gives the dependence of $a(t)$ in simple form:

$$a(t) = \frac{1}{2\alpha}t + \frac{1}{4}\pi\sqrt{\beta} \qquad (2.3)$$

which differs from the equation (2.1) only by the constant. Differentiating (2.3) gives that when a is big enough, the delamination radius under high gas pressures starts growing at constant velocity, besides at exactly the same as the delamination radius in conditions of ideal gas (Germanovich and Balueva, 2009), which is easily can be obtained by differentiating (2.1).

It was shown in Germanovich and Balueva (2009) that in case for ideal gas, the solution for the *delamination* crack (Balueva and Dashevski, 1999) coincides with the result of Goldstein et. al. (1985) for the case of *internal* crack. Then, for real gas pressures, the main kinetic equation for the dependence, $a(t)$, of the *internal* crack radius on time, would be the same as the equation (1.12) for the *delamination* up to the constant, similarly to the ideal gas case. Therefore, the solutions obtained in the previous sections for the crack size (1.17) and for the asymptotical velocity (2.4) are equally applicable for *internal* high gas pressure driven cracks if we double the amount of gas inside the fracture.

3. Conclusions

A common feature of HIC (Hydrogen Induced Cracks) in pipes, as observed and reviewed in Gonzales et. al. (1997), is that the fractures propagate in the direction parallel to the pipe wall (as in Fig. 1). In this paper, a near-surface penny-shaped crack growing parallel to the wall of the plate, or delaminating of the external surface, is considered. The driving force for the near-surface cracks is the internal pressure of accumulated hydrogen in the cavity. Delamination also commonly develops at the interface (e.g., Hutchinson and Suo, 1991) and so the developed model can be used for the analysis of fracture kinetics of the protective coating of metal or steel bodies (e.g., Gafarov et. al., 1998; Polyakov, 1996) exploited in the conditions of hydrogen presence.

The known in literature papers considered the HIC growth only under *ideal* gas pressures conditions (e.g. Goldstein et. al., 1985; Goldstein and Balueva, 1997; Balueva and Dashevski, 1995 and 1999; Gonzales et. al, 1997; Altenbach et. al., 1999; Eliaz et. al., 2004; Germanovich and Balueva, 2009). In this paper the analytical solution for hydrogen driven fractures was obtained for *real* gas pressures, and so more exact estimate for longevity of pipelines exposed to hydrogen embrittlement can be calculated on the base of the formula (1.17), or from the graphs in Fig. 3.

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References

Addach, H., Bercot, P., Rezrazi, M., and Wery, M., 2005. Hydrogen Permeability in Iron at Different Temperatures. Materials Letters, 59(11), 1347 – 1351.

Altenbach H., Wahren G. and Nikitine L.V., 1999. Phenomenological Modelling of Deterioration of Metals Resulting from Environmental Influences. Proceeding of the Eighth International Conference on the Mechanical Behaviour of Materials. Victoria, Canada, 586 – 591.

Balueva, A.V., and Dashevski, I.D., 1999. Growth of Hydrogen Delamination in Metal, Mechanics of Solids, 1, 100-104.

Balueva, A.V., and Dashevski, I.D., 1995. Qualitative Estimates of Gas-Filled Crack Growth, Mechanics of Solids, 6, 122-128.

Beggs, D.V., and Hahn, M.T., 1984. Recent Observation on the Propagation of Stress Corrosion Cracks and Their Relevance to Proposed Mechanisms of Stress Corrosion Cracking, In: Hydrogen Embrittlement and Stress Corrosion Cracking, Edited by Gibala, R. and Hehemann, R.F., American Society for Metals, Metal Park, Ohio 44073, 181-205.

Elboujdaini, M., 2006. Initiation of Near Neutral pH Environmentally Assisted Cracking in Line Pipe Steel, Proceedings of the 16th European Conference of Fracture, Alexandroupolis, Greece, July 3 – 7, 2006.

Eliaz, N., Banks-Sills, L., Ashkenazi, D., and Eliasi, R., 2004. Modeling Failure of Metallic Glasses due to Hydrogen Embrittlement in the Absence of External Loads. Acta Materialia, 52, 93 – 105.

Gafarov, N.A., Goncharov, A.A., Kushnarenko, V.M., 1998. Коррозия и защита оборудования на нефтяных и сероводородных месторождениях (Corrosion and Protection of Equipment for Hydrogen Sulfide Oil Deposits). Moscow: Nedra Publishers.

Germanovich, L.N., and Balueva, A.V., 2009. A Transient Model of Hydrogen Induced Delamination, Proceedings of the 12th International Conference of Fracture (ICF12), Ottawa, Ontario, Canada, July 12 – 17, 2009.

Goldstein, R.V. and Balueva, A.V., 1997. Model of Behaviour of Materials with Cracks under Hydrogen Embrittlement Conditions. Fatique & Fracture of Engineering Materials & Structures, v.20, 9, 1269-1277.

Goldstein R.V., Entov V.M., and Pavlovsky B.R., 1977. Model of Development of Hydrogen Cracks in Metal, Academiia nauk SSSR. Doklady. 237, 4, 828-831.

Goldstein R.V., Zazovskii A.F., and Pavlovsky B.R., 1985. Development of Penny-Shaped Layering in a Metal Sheet under Tension and Hydrogenization, Fisiko-Khimicheskaia Mekhanika Materialov. 21, 3, 621-656.

Gonzales, J.L., Ramirez R., Hallen J.M., Guzman R.A., 1997. Hydrogen-Induced Crack Growth Rate in Steel Plates Exposed to Sour Environments. Corrosion 53 (12): 935-943.

Hutchinson, J.W. and Suo, Z., 1991. Mixed Mode Cracking in Layered Materials, Advances in Applied Mechanics, 29, 63-191.

Polyakov, Vadim N., 1996. Катастрофы трубопроводов большого диаметра: роль полей водорода. Влияние водорода в материалах. (Catastrophes of large diameter pipelines: the role of hydrogen fields). Hydrogen Effects in Materials. 991-1000.

Rice, J.R., 1976. "Hydrogen and Interfacial Cohesion", in Effect of Hydrogen on Behavior of Materials (eds. A.W. Thompson and I.M. Bernstein), Metallurgical Society of AIME, 455-466.

Sneddon, I.N., 1972. The Use of Integral Transforms, McGraw-Hill, New York.

Strnadel, B., 1998. Failure of steels caused by hydrogen induced microcracking, Engineering Fracture Mechanics, 61, 299-310.

Sunami, E., Tanimura, M., Tenmyo, G., 1974. Behavior and Thermodynamical Properties of Tantalum-Carbide and -Nitride in Steels, Boshoku Gijutsu, 23, 6, 281-287.

Thompson, A.W., 1980. Current Status of the Role of Hydrogen in Stress Corrosion Cracking, Material Science and Engineering, 43, 41-46.

Timoshenko, S.P. and Goodier, J.N., 1970. Theory of Elasticity, 3rd. Edition. New York: McGraw-Hill.

Yen, S.K. and Tsai, Y.C., 1996. Critical Hydrogen Concentration for the Brittle Fracture of AISI 430 Stainless Steel, J. Electrochem. Soc., 143, 9, 2736-2741.

Yokobori, A.T., 2004. The Mechanism of Hydrogen Embrittlement: the Stress Interaction between a Crack, a Hydrogen Cluster, and Moving Dislocations, International Journal of Fracture, 128(1), 121 – 131.