Influence of hydrogen on stress-strain state of pipeline

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Abstract

An essential present-day engineering problem of pipeline destruction in the result of influence of hydrogen contained in the transported medium is considered. The relevance of this topic is determined by possible environmental and economic issues, in the event of an accident resulting in gas and oil leaks.

Hydrogen affects mechanical properties of the pipe, changing its stress-strain state, which, in turn, changes the distribution of bound hydrogen in the material of the pipe. The hypothesis adopted on the nature of this connection made it possible to explain the reasons for the destruction of pipeline on a simple model.

The problem of the theory of elasticity for a hollow pipe under internal pressure is considered in a plane axisymmetric formulation; stress and strain fields are found. Estimates of stresses according to the Mises criterion have shown the appearance of plastic deformation zone in the pipe that is leading to the delamination of the material in the circumferential direction. This result corresponds to presently known experimental data.

Keywords: influence of hydrogen, stresses in pipeline, hydrogen-affected delamination.

1 Introduction

Many disasters were caused by hydrogen cracking of metals. This phenomenon is especially dangerous for engineering structures operating under high pressure, including oil pipelines. Presence of hydrogen in the transported medium leads to its quick accumulation inside the mass of metal, and, as a result, to a significant deterioration of pipeline mechanical properties [1].

A research by Nie [2] shows, that hydrogen saturation reduces the ultimate stress of metal by a factor of 3 – 5. Studies of Polyanskiy et al [3] have shown that increase of hydrogen concentration by a factor of 2 – 3 with respect to its natural concentration leads to damage of pipe material.

It is well known, that hydrogen causes crack formation inside metal pipes (fig. 1). Usually presence of such cracks is explained by microscopic defects during rolling of metal. However, analysis of experimental data shows that such defects are caused by hydrogen [4].

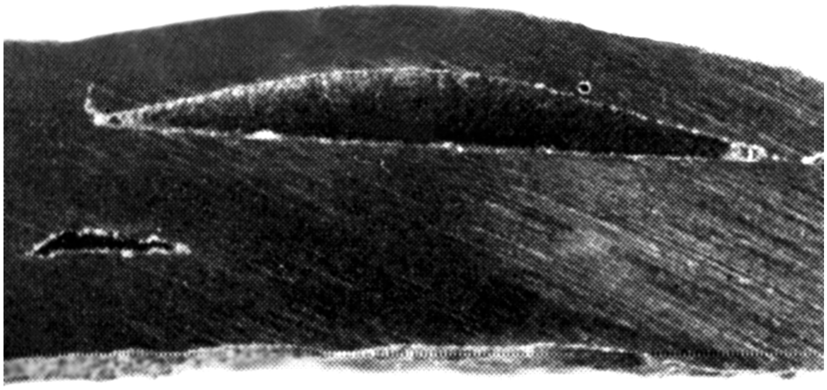


Figure 1: Hydrogen induced fracture near the external surface of a thick steel pipe

Critical reviews of a large number of modern studies on the topic of hydrogen-induced cracking and hydrogen embrittlement are given in [5, 6].
Most studies consider growth condition of a previously-formed crack, without studying of its causes. Mathematical modeling and analysis of causes are still timely issues in studies of cracks. Unfortunately, there are not enough experimental data covering influence of low concentrations of hydrogen onto mechanical properties of materials. The goal of this research is to explain causes of pipe destruction under internal pressure of hydrogen-containing feed with the methods of the theory of elasticity.

2 Prolegomena

Let us first calculate the stress-strain state of a long steel pipeline that experience a pressure onto its internal wall. For that end, let us consider a plane axisymmetric Lame's problem for a hollow pipe under a uniform internal pressure of p.
The overall solution to this problem is known, see [7, 8]:

$$\sigma_r = A - \frac{B}{r^2}, \quad \sigma_\varphi = A + \frac{B}{r^2}, \quad u = \frac{1}{E}\left[A(1-\nu)r + \frac{B(1+\nu)}{r}\right]. \tag{1}$$

Here σ_r and σ_φ are radial and circumferential stress values, u is a radial displacement, A, B are arbitrary constants determined from boundary conditions: on the internal radius (r_0) the stress is $\sigma_r = -p$, on the external radius (r_2) the stress is $\sigma_r = 0$. From that we may find

$$A = \frac{r_0^2}{r_2^2 - r_0^2}p, \quad B = \frac{r_0^2 r_2^2}{r_2^2 - r_0^2}p. \tag{2}$$

Let us determine deformation in the pipe following the formulas

$$\varepsilon_r = u' = \frac{1}{E}\left[A(1-\nu) - \frac{B(1+\nu)}{r^2}\right], \quad \varepsilon_\varphi = \frac{u}{r} = \frac{1}{E}\left[A(1-\nu) + \frac{B(1+\nu)}{r^2}\right], \tag{3}$$

here E is the elasticity modulus and ν is Poisson's ratio of material.

Let us note, that the coefficient of volumetric expansion is constant and positive

$$tr\varepsilon \triangleq \varepsilon_r + \varepsilon_\varphi = \frac{2A(1-\nu)}{E} > 0, \tag{4}$$

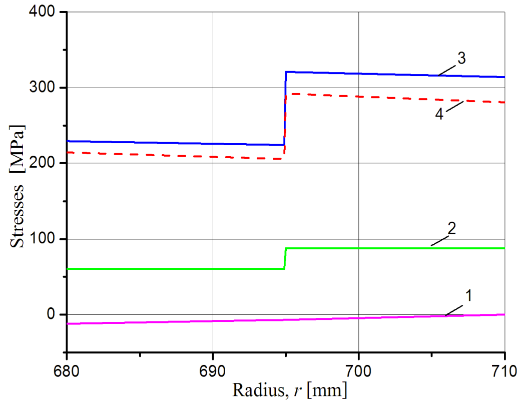
i.e., the pipe material is under conditions of a uniform voluminous expansion.
In this problem, displacements and deformations are two-dimensional, but stress tensor contains the third component in the perpendicular direction:

$$\sigma_z = \nu\left(\sigma_r + \sigma_\varphi\right)\ . \tag{5}$$

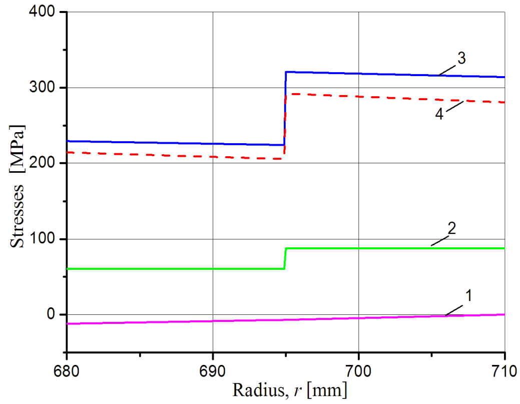
Figure 2a shows the calculation results for stress in the pipe with parameters corresponding to major gas and oil pipelines: internal radius of $r_0 = 680$ mm, outside radius of $r_2 = 710$ mm, working pressure of $p = 12$ MPa, steel properties: $E = 2 \cdot 10^5$ MPa, $\nu = 0.28$.
The maximum of von Mises yield criterion τ_0 is of special interest in determining pipe strength:

$$\tau_0 = \max\sqrt{\left(\sigma_\varphi - \sigma_z\right)^2 + \left(\sigma_z - \sigma_r\right)^2 + \left(\sigma_r - \sigma_\varphi\right)^2/2}, \tag{6}$$

its value shall not exceed the steel tensile yield stress (300 MPa). The distribution of equivalent (von Mises) stress in a pipe is shown on Figure 2a by dotted line. It is evident, that its maximum is located at the internal surface, but the pipe does not have any plastic deformations yet.
Then, it is necessary to take into account presence of hydrogen inside the pipe. It presents in the metal in its natural concentration, but it may also penetrate from medium transported through the pipeline.
Studies [9, 10] stipulate, that diffusion of hydrogen atoms in metal is influenced not only by their concentration and thermal field, but by the stress-strain state of the matrix as well. According to Gorsiy's hypothesis, hydrogen atoms are attracted to areas of tensile stress in metal. High-energy hydrogen is incorporated into crystal lattice of metal. Due to that, mechanical properties of the material undergo changes, in particular, its modulus of elasticity and yield point are reduced [5].
In the problem under consideration, the pipe material is compressed in the radial direction ($\sigma_r < 0$) and stretched out in the circumferential direction ($\sigma_\varphi > 0$); one may assume, that hydrogen will ingress the crystal lattice predominantly in the circumferential direction.
It seems, that a number of condition shall be held for hydrogen intrusion: interatomic bonds in the lattice shall be significantly stretched out, while hydrogen atoms shall have sufficient energy. These conditions are held near the internal surface of the pipe, where both tensile stress and hydrogen concentration are maximal. Thus, there is an internal layer formed in the pipe with weakened mechanical properties.
One may expect, that the properties of metal are changed non-uniformly in different directions. Young's modulus is probably more weakened in the circumferential direction, than in the radial one. For now, let us limit ourselves with analysis of isotropic material with a reduced modulus of elasticity.
The process of hydrogen redistribution through metal is very slow and may take anywhere from several hours to several years [5]. Thus, studies of pipe destruction



(a)



(b)

Figure 1: Figure 2: Stresses in a pipe (a) without weakened layer, (b) with weakened layer of 15 mm: 1 – radial σ_r, 2 – axial σ_z, 3 – circumferential σ_φ, 4 – equivalent stress as function of radius

mechanism under the influence of hydrogen may be considered as a sequence of static problems in the theory of elasticity.

Let us assume, that due to interactions with hydrogen, there is an internal layer of thickness h formed, characterized by weakened mechanical properties. Let us determine the stress-strain state of such a pipe.

3 A pipe with a weakened layer

Let us consider a problem similar to Lame's problem for a circular ring made of two materials. In the internal part $r_0 < r < r_1$ there is a weakened material with a constant Young's modulus of E; in the external part $r_1 < r < r_2$ there is steel with the Young's modulus of E_0. Boundary conditions are the same as in the previous problem, with two additional conditions: on the radius of conjugation (r_1) the values of σ_r and u are continuous.

Formulas (1) are written down for the internal layer with the constants A, B, while for the external layer there are A_0, B_0. Applying boundary conditions, we obtain a linear algebraic system for the four constants. Its solution will give us values of displacement and stress from the formulas (1).

Figure 2b shows diagrams of stresses and deformations for the same parameters as above, the weakened layer thickness is 15 mm ($r_1 = 695$ mm), while the modulus of elasticity is $E = 0.7E_0$.

The calculations show, that radial stress has changed insignificantly, while circumferential and axial stresses have a discontinuity at the boundary between the two layers and there's maximum values increased. The maximum value of the von Mises yield criterion has increased to $\tau_0 = 292$ MPa.

Let us note, that the maximum tensile stress values are now localized in a hydrogen-free layer of steel near the boundary between the layers. As a result, the hydrogen atoms, having ingressed into the crystal lattice in this area, are going to weaken the material. Thus, the thickness of the weakened layer is going to gradually increase.

Obviously, the increase in the thickness of the weakened layer will be accompanied with increasing equivalent stresses. At some critical value of h a yield stress will be attained and plastic deformations appear. The area of such deformations is a circle, marking the boundary of hydrogen-weakened layer of material.

Figure 3 shows maximum equivalent stress as a function of weakened layer thickness; it may be seen that the critical value is h=18 mm.

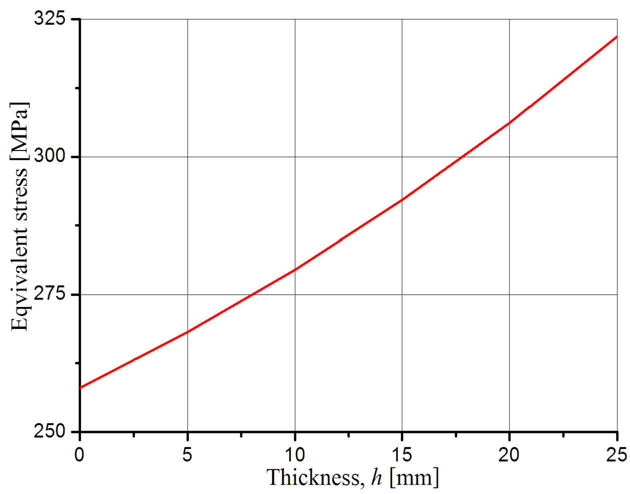


Figure 3: Equivalent stress in a pipe with a weakened layer

The calculation results support the available experimental data, showing that hydrogen damage in pipes happens along a circle.

4 Conclusion

The mathematical modeling study explains the cause of damage of pipeline material as a result of hydrogen impact.
It is shown, that during the transportation of hydrogen-containing feed through the pipeline, a stress-strain state appears that facilitates redistribution of hydrogen through the pipe material. As a result, there is an internal layer formed in the pipe with weakened mechanical properties. Analysis of stress in such a two-layer pipe has shown appearance of a plastic deformation area in the form of a circle along the boundary between layers. This leads to appearance of circular cracks and longitudinal delamination of pipe walls.
Exact quantitative assessment requires new experimental data on influence of small concentrations of hydrogen onto the properties of structural materials.

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