EXAMINATION OF HYDROGEN EMBRITTLEMENT PROCESS OF THE LOADED STRUCTURES

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One of perspective energy sources is hydrogen. However for increase of its power energy output it is necessary to store, carry and pump over of hydrogen under high pressure. At the same time vessels and pipelines are exposed to high mechanical stresses which often lead to undesirable accident.
For a long time mechanical fatigue is assumed as the main cause of the fracture of vessels under high hydrogen pressure. However the detailed study of the hydrogen saturation process shows that mechanical characteristics of metal change strongly. Hydrogen embrittlement takes place which decrease the ultimate strength of metal end leads to the fracture. Hydrogen embrittlement process is intensive increase with the increase of tensile strain.
The model of nonlinear hydrogen saturation is analyzed in the report. Mechanism of gradual hydrogen embrittlement is demonstrated on the flange connection of the pipe line part under high hydrogen pressure. The evolution of hydrogen saturation of tensile parts of the structure which leads to the decrease of ultimate strength is shown.
Analysis of pipe line hydrogen saturation is made by three dimensional model ANSYS code. The reliability of the obtained results is checked by the Lame problem for cylindrical part of the structure.

Keywords: nonlinear hydrogen saturation, hydrogen embrittlement, stress strained structures

Introduction

It is known that hydrogen is one of the dangerous impurities for a large class of metals and their alloys. At the same time hydrogen is one of the most perspective sources of the energy in the future. However for increase of its power energy output it is necessary to store, carry and pump over of hydrogen under high pressure. At the same time vessels and pipelines are exposed to high mechanical stresses which often lead to undesirable accident.
In spite of the fact that influence of the hydrogen on metal properties is described in many of the works, it is a lot of uncertainties in this problem. For example, for a long time mechanical fatigue is assumed as the main cause of the fracture of

vessels under high hydrogen pressure. However the detailed study of the hydrogen saturation process and specially carried tests show that mechanical characteristics of metal change strongly. Hydrogen embrittlement takes place which decrease the ultimate strength of metal end leads to the fracture. Hydrogen embrittlement process is intensive increase with the increase of tensile strain.

The model of nonlinear hydrogen saturation, offered in Ref. [1], is analyzed in this report. The main hypothesis is that during metal tension (and only tension) Hydrogen atoms penetrate to the crystal lattice structure and the interatomic forces of the crystal lattice decrease. At the same time new atomic bonding represent concatenation of elastic connection of the main lattice and penetrated elastic connection of hydrogen particles. Figs 1-2 represent corresponding elastic mass lattice models before and after hydrogen penetration.

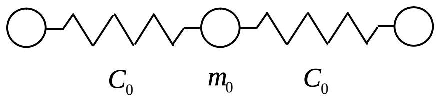


Figure 1: Elastic-mass model of pure metal lattice

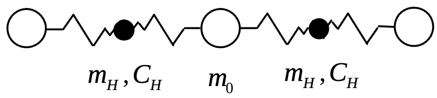


Figure 2: Elastic-mass model of a hydrogen fouled metal lattice

Elastic bonding of hydrogen particles decreases equivalent stiffness of atomic bonding. This decrease grows with hydrogen concentration. At the same time Young's Modulus, Yield strength and Tensile strength decrease. The so called hydrogen embrittlement takes place.

Steel stress strain curve change due to hydrogen saturation is shown in Fig. 3. Fig. 4 represents exponential hydrogen saturation dependence of Yield strength [1].

Hydrogen saturation time depends strongly on the temperature and varies in the range of tens of minutes at temperatures about 900° C up to several months at temperature near 20° C.

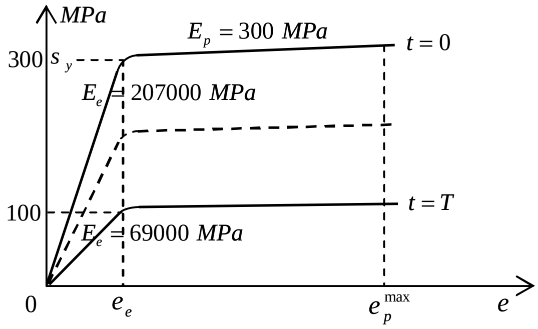


Figure 3: Steel stress strain curve

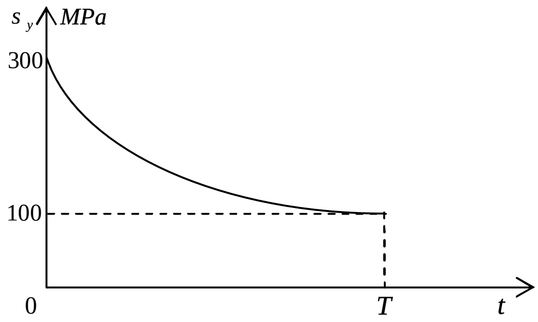


Figure 4: Yield strength decrease at hydrogen saturation

Mechanism of gradual hydrogen embrittlement is demonstrated on the flange connection of the pipe line part under high hydrogen pressure (Fig. 5). Analysis of pipe line hydrogen saturation is made by three dimensional model ANSYS code. Finite element model of the 20° sector is represented in Fig. 6.

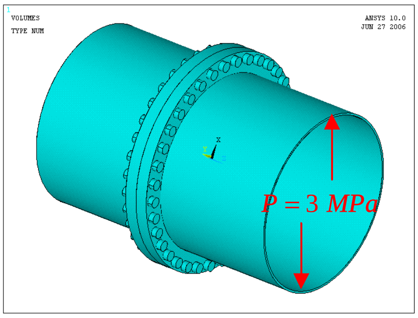


Figure 5: Flange connection of the pipe line

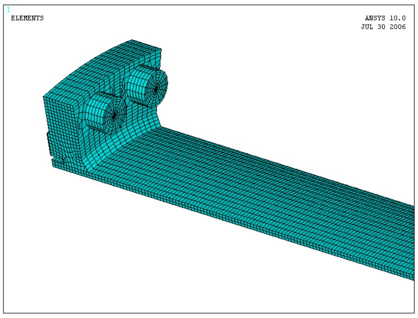


Figure 6: Finite element model of 20° sector

1 Numerical model checking

Calculation by hands of the cylindrical part of the pipe far from it ends has been done to check the mathematical finite element model (Lame problem). Stress distribution is that the maximum stress has been achieved in the inner part of the tube and is equal to:

$$s_r = -P = -3\ MPa, \quad s_q = P\frac{r_2^2/r_1^2+1}{r_2^2/r_1^2-1} = 131.6\ MPa, \quad s_z = P\frac{1}{r_2^2/r_1^2-1} = 64.3\ MPa,$$

where s_r - radial stress, s_q - tangent stress, s_z - axial stress, $r_1 = 694\ mm$ - inner pipe radius, $r_2 = 710\ mm$ - outer pipe radius.

Figs 7-8 demonstrate the results of tangent and axial stresses under inner pressure in the remote part of the pipe obtained by ANSYS mathematical model. Maximum stresses values $s_q = 131.9\ MPa$ and $s_z = 64.6\ MPa$ differ from theoretical ones by 0.2 % and 0.4 % respectively. This fact shows that finite element model reliability.

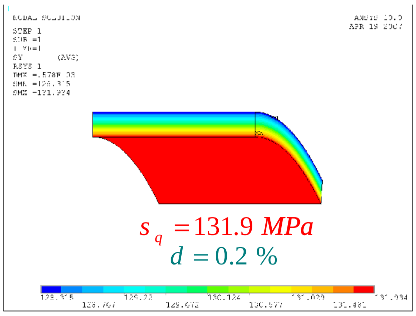


Figure 7: Tangent stress in the remote region of the pipe

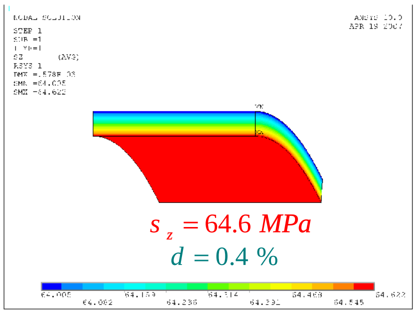
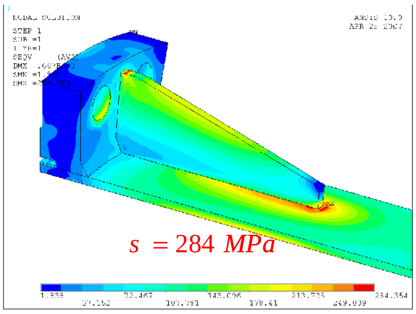


Figure 8: Axial stress in the remote region of the pipe

2 The results of finite element modeling

Fig.9 demonstrates the equivalent stresses in the initial pipe structure (sealing and standard stiffness ribs) before hydrogen saturation. It is seen that that high tension stress arises in the region of the rib fixing to the pipe. Hydrogen will accumulate in this zone and it will lead to decrease of the pipe material mechanical properties and fracture of the pipe. Fig. 10 demonstrates the distribution of the plastic strain in the pipe material at the hydrogen saturation at which plastic strain $e_p = 33.6\ \%$ becomes greater fracture limit strain. Therefore to decrease the tensile stress it is necessary to avoid stress concentrators and take away traditional stiffness ribs.



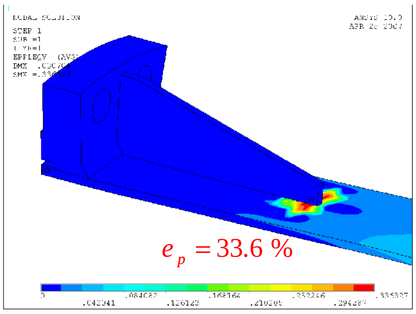
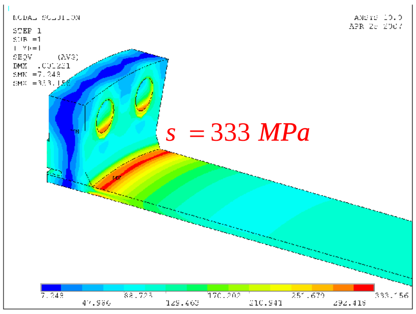


Figure 9: Stress in the pipe line before hydrogen saturation

Figure 10: Plastic strain after hydrogen saturation

Figs 11-12 represents equivalent stresses in the pipe line structure without ribs before and after hydrogen saturation. It is seen that plastic strain without ribs decreases essentially at the hydrogen saturation and achieves the allowable value of $e_p = 4.9\ \%$. But the stress in the pipe connection with the flange becomes greater because of the raised bending stress from $s = 284\ MPa$ to $s = 333\ MPa$. To minimize this stress it is necessary to support flange edges to one another by means of extra sealing at the flange end.



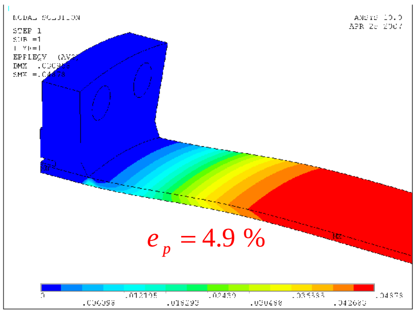


Figure 11: Stress in the pipe line before hydrogen saturation

Figure 12: Plastic strain after hydrogen saturation

Figs 13-14 show the equivalent stress in the pipe line without ribs with two sealings and plastic strain distribution in the pipe line material before and after hydrogen saturation. Such structure will essentially decrease the initial stress in the pipe at the place of flange connection from the value of $s = 333\ MPa$ to $s = 128\ MPa$. Plastic strain is remained at the same value of $e_p = 4.9\ \%$ at the hydrogen saturation.

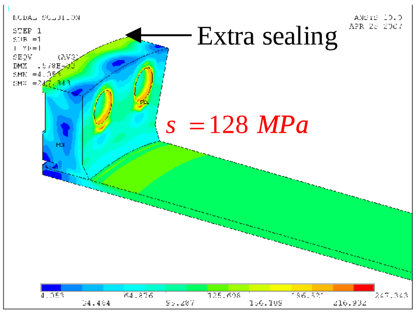


Figure 13: Stress in the pipe line before hydrogen saturation

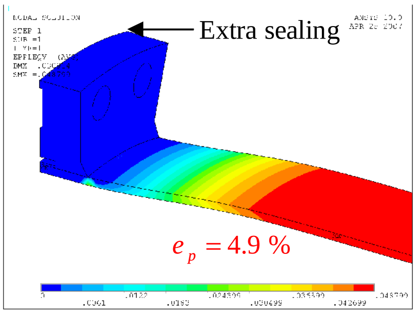


Figure 14: Plastic strain after hydrogen saturation

Another opportunity of stress and plastic strain minimization is the increase of the thickness of the cylindrical part of the pipe. Figs 15-16 demonstrate the equivalent stress in the pipe line without ribs with two sealing disks and increased pipe wall thickness (from 16mm to 20mm) and the distribution of plastic strain of the pipe line material before and after hydrogen saturation respectively. Now after the hydrogen saturation the residual stress in the tube is $s = 95\ MPa$, and plastic strain is $e_p = 0\ \%$.

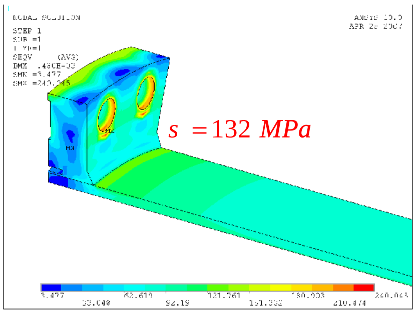


Figure 15: Stress in the pipe line before hydrogen saturation

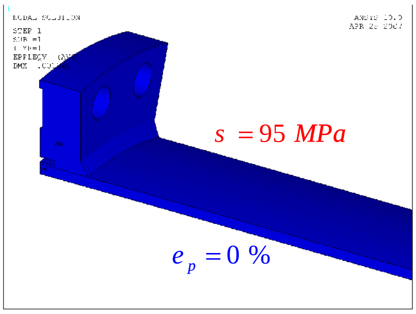


Figure 16: Plastic strain after hydrogen saturation

Conclusions

The demonstrated model of nonlinear hydrogen saturated stress strained metal show the process of gradual decrease of yield strength and ultimate strength up to the material fracture. This model well matches with tests. The detailed computer modeling of hydrogen saturation process made it possible to make optimization of structures working in hydrogen environment. So, to minimize stresses and strains to safe values it is necessary to avoid stress concentrators, to minimize bending moments and to increase thickness of the most loaded elements.

References

[1] Indeitsev, D.A. and Semenov, B.N., "Mathematical Modeling in Solid Mechanics," proceedings, XXI International Conference, October, 2006, pp. 242-253.