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Exact analysis of hydrogen induced stress in metal solid sphere

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ABSTRACT

The effect of hydrogen in metals requires a detailed study involving an analysis of the stress-strain tensor field, stemming from the introduction of hydrogen atoms to the system. A model is created, utilizing the strain-stress state generated by the hydrogen atom and the coupling effect between the hydrogen and metal atom. A set of equations are established for a spherical body in the context of theory of elasticity and stress components within the system are determined. The effect of hydrogen concentration along with hydrogenation and dehydrogenation are investigated involving theoretical analysis and analytical ratios. Calculations are obtained for spherical solid systems. The effects of hydrogenation was resulted in intensive compressive stresses near the surface of the sphere, whereas tensile stresses were occurred near its surface during dehydrogenation.

Introduction

The detrimental effects of many elements in various environments for metallic structures has been of question for metallurgists and materials scientists for decades. There are different methods in which these effects can be revealed and analyzed for different elements. Hydrogen is one of the elements that can cause major alterations within the metallic microstructure for different grades of steel that is examined by a number of studies. These studies discuss various aspects of steel degradation and embrittlement due to hydrogen presence the environment and show methods to avoid steel degradation and corrosion [1–3]. The hydrogen embrittlement or hydrogen induced stress can be characterized using different test methods. A recent study by Rosenberg and Sinaiova presents two different samples of steel (X70 and S355) tested under different loading conditions with a correlation drawn between hydrogenation and mechanical properties of the samples [4].

Apart from the characterization methods, modelling of such degradation has been of utmost importance. Starting from the smallest repeating unit itself that is the lattice structure, a mathematical approach for the lattice parameter is established with different studies carried out by Goltshov and Glukhova et al. The output of these studies indicate that the change in lattice parameter manifests itself in the form of an expansion [5–7]. The effects of hydrogen in Niobium is studied using analytical approach and found to be in the form of expansion in lattice parameter, as well [8].

A numerical approach towards the embrittlement due to hydrogen near a crack tip was already established before the

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models proposed by Goltshov and Glukhova. The approach suggests a correlation between the hydrogenation/dehydrogenation process and the stress state of the metals [9]. This correlation can often manifest itself with the inhomogeneous stress state in correlation with a heterogeneous hydrogen concentration [10–12]. It is with little doubt that inhomogeneity of any origin can cause fluctuations in the stress state of area concerned, hence internal stresses in different metals, making hydrogen induced stress an important parameter to be acknowledged given the fact that it can constitute a design issue for numerous application problems and failure to take internal hydrogen stress into account in a design problem may have repercussions of severe nature. There have already been studies concerning the hydrogen stress field and its effects [13–17]. A study in furtherance to the numerical approach of reduced plasticity in the hydrogen interstitial sites is provided by Huang et al. that employs ABAQUS software to compute and examine the stress conditions in these sites [18]. The study yields significant output as the stress states are examined in a triaxial manner with the help of LODE parameter. Another study carried out by Yokobori et al. focuses on the numerical analysis of hydrogen concentration at the crack tip for a steel specimen coupled with the responses to the stress in the concentration field [19]. Evaluation of hydrogen concentration is again studied by Ivanytskyi et al. near the crack tip for the steel material [17]. It is shown in this study that the stress may at or near the crack the tip can lead an increase in the hydrogen concentration. Thermodynamical correlation of hydrogen diffusion is investigated by Di Leo et al. and found to have a great influence on the transition of elastic-plastic deformation [20].

Along with varying numerical methods to analyze hydrogen embrittlement, a composite model is suggested by Feng et al. that combines different aspects such as metal oxide behavior, temperature and metal elastic behavior together [21]. Results of this study reveal that the model can monitor the stress conditions to an adequate degree in terms of the stress distribution and hydrogen concentration. The local influence of hydrogen concentration and stress/strain state can be utilized as main indicators near the stress concentrators using the hydrostatic pressure and these investigations established the hydrogen-induced hydrostatic stress [14–16]. Stashchuk and Dorosh [16] investigate the stress-strain state caused by the concentration of hydrogen on metals. Modelling of the stress-strain state of the metal-hydrogen system was carried out by Stashchuk and Dorosh [13].

It should be noted that the results of the studies mentioned are still in the initial state and the furtherance of the understanding in terms of hydrogen elasticity of the metals is still a curious subject that attracts the attention of scientists. In this study, hydrogenation characteristics of spherical structures and generated stress due to it is investigated.

Governing equations of hydrogen stresses in spherical body

Governing equations of an elastic-deformable sphere of outer radius r_o under the plane stress assumption is considered. It is assumed that the spherical body has hydrogen of $C_H(t,r)$ concentration at a certain time t [13]. Therefore, it is regarded as the elastic waves occur due to time dependent hydrogenation/dehydrogenation. Because of this fact, the linear elasticity equations valid for static case are used as a governing equations. In this case, deformation of sphere is expressed through three stress components $\sigma_r,\sigma_\theta,\sigma_\phi$. The symmetric strain–stress relations using the correlations between hydrogen induced stresses and strain [13] in term of spherical-polar coordinates [22,23] are

$$\begin{aligned}\varepsilon_r &= \frac{1}{E}(\sigma_r - \nu(\sigma_\theta + \sigma_\phi)) + \alpha_{C_H} C_H,\\ \varepsilon_\theta &= \frac{1}{E}(\sigma_\theta - \nu(\sigma_r + \sigma_\phi)) + \alpha_{C_H} C_H,\\ \varepsilon_\phi &= \frac{1}{E}(\sigma_\phi - \nu(\sigma_r + \sigma_\theta)) + \alpha_{C_H} C_H\end{aligned} \tag{1}$$

where E,ν and α_{C_H} are modulus of elasticity, Poisson's ratio and concentration hydrogen expanding ratio, respectively. Under the plane stress and spherical symmetry assumption the strain–stress relations (2) renders in the following form:

$$\begin{aligned}\varepsilon_r &= \frac{1}{E}(\sigma_r - 2\nu\sigma_\theta) + \alpha_{C_H} C_H,\\ \varepsilon_\theta &= \varepsilon_\phi = \frac{1}{E}((1-\nu)\sigma_\theta - \nu\sigma_r) + \alpha_{C_H} C_H.\end{aligned} \tag{2}$$

By solving the strain–stress relations (2) according to the σ_r and σ_θ, stress–strain relations

$$\begin{aligned}\sigma_r &= \frac{E}{(1+\nu)(1-2\nu)}((1-\nu)\varepsilon_r + 2\nu\varepsilon_\theta - (1+\nu)\alpha_{C_H} C_H),\\ \sigma_\theta &= \sigma_\phi = \frac{E}{(1+\nu)(1-2\nu)}(\varepsilon_\theta + \nu\varepsilon_r - (1+\nu)\alpha_{C_H} C_H).\end{aligned} \tag{3}$$

The stresses σ_r and σ_θ fulfill non-trival equilibrium equations [22,23].

$$\frac{d\sigma_r}{dr} + \frac{2(\sigma_r - \sigma_\theta)}{r} = 0. \tag{4}$$

Substituting stress–strain relations (3) into the equilibrium equations gives the governing equation of strain fields

$$r\frac{d}{dr}((1-\nu)\varepsilon_r + 2\nu\varepsilon_\theta) + 2(1-2\nu)(\varepsilon_r - \varepsilon_\theta) = (1+\nu)\alpha_{C_H} r\frac{dC_H}{dr}. \tag{5}$$

The strain–displacement relations in term of radial displacement u outlined as

$$\varepsilon_r = \frac{du}{dr},\ \varepsilon_\theta = \varepsilon_\phi = \frac{u}{r}. \tag{6}$$

Substitute this relations into the (5) and reproduce it

$$r\frac{du}{dr}\left[\frac{du}{dr} + 2\frac{u}{r}\right] = \frac{(1+\nu)}{1-\nu}\alpha_{C_H}\frac{dC_H}{dr}. \tag{7}$$

The radial displacement can be obtained if the last equation is integrated twice. Then

$$u = \frac{(1+\nu)}{1-\nu}\alpha_{C_H}\frac{1}{r^2}\int_0^r dC_H r^2 dr + A_1 r + \frac{A_2}{r^2} \tag{8}$$

Since the radial displacement u must be zero at the center of the sphere ($r = 0$), the constant $A_2 \equiv 0$ is assumed. Therefore, the stresses can be obtained as follows:

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