Model of the effect of low concentrations of diffusion - mobile hydrogen on the cracks propagation

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Abstract

Small amount of hydrogen concentration impact appears significantly in material fatigue and cracks propagation. Resonant effect is observed at fatigue. This effect was described by a model of bicontinuous medium containing hydrogen [1], [2] and was detected experimentally later [3].

Significant impact of small diffusion - mobile hydrogen concentration to metal fatigue was observed in non-cyclic static and dynamic loading. Hydrogen embrittlement areas were localized. Hydrogen embrittlement sites were formed during metal fracture. Model HELP (Hydrogen-enhanced localized plasticity) is generally used to describe the observed phenomena [4]. The base physical mechanism couldn't be represented in the critical hydrogen concentration, which could be observed experimentally. This and calculation complication are major weak points of the model.

During the testing it had been found that hydrogen was concentrated in a thin boundary layer at the surface of a metal specimen [8]. The result makes it possible to describe new models of hydrogen effect to material mechanical properties.

A boundary layer mechanical properties degradation effect due to accumulation of diffusion - mobile hydrogen was modeled by finite element method.

The cylindrical corset samples with the annular crack were examined because extensive experimental data exist for such cases.

The results of hydrogen concentration from [8] were applied in the model. The bicontinuous model of a boundary layer was chosen as a base model for material properties examination.

A boundary layer thickness and mechanical properties degradation effect on tensile strength, which mostly used in previous studies, was analyzed. Tensile strength dependence on deteriorated layer thickness and level of the properties degradation was plotted.

Degradation of mechanical properties at a depth of the grain size of polycrystalline metal doesn't lead to significant tensile strength change. Only a model of bicontinuous material for the entire specimen could explain experimentally observed effects.

1 Introduction

Hydrogen effect on high strength steel is well known problem due to the degradation of mechanical properties caused by hydrogen accumulation. Moreover, small amount of hydrogen concentration impact appears significantly in material fatigue and cracks propagation.
Resonant effect is observed at fatigue. This effect was described by a model of bicontinuous medium containing hydrogen [1], [2] and was detected experimentally later [3].
Significant influence of small diffusion – mobile hydrogen concentration was observed during the non-cyclic static and dynamic loading. Hydrogen embrittlement areas were localized. Hydrogen embrittlement sites were formed during metal fracture. Model HELP (Hydrogen-enhanced localized plasticity) is generally used for description of the observed phenomena [4]. But the base HELP physical mechanism couldn't be represented, because it is possible only with the hydrogen concentration, which couldn't be observed experimentally. This and calculation complication are major weak points of the model. Model HEDE (hydrogen-enhanced decohesion) [5] doesn't correlate with experimental data about the critical concentrations of hydrogen too. As a result, last articles [6] propose to synergy between HELP and HEDE models. This approach looks universal. However both models consider nonlinear equations and simple linear combination is impossible. Model HELP proposed for description of cracks propagation and it's localized model. HEDE describes grains cohesion and shift. Most likely, they are couldn't be combined in one material without prior linearizing of defining equations [7].
During the testing it had been found that hydrogen was concentrated in a thin boundary layer at the surface of a metal specimen [8]. Testing was performed to observe different specimens fracture under various mechanical loadings. There are a number of studies to describe hydrogen effect in various materials consider condition with or without concentrator, as example [9].
New models are required to describe hydrogen effect to material mechanical properties. And existing independent experimental data create base for models verification.

2 Material and methods

2.1 Hydrogen distribution

The plane corset samples of steel 14HGNDC were examined. Sample size is $900 \times 120 \times 17$ mm^3. Width of the working portion of the sample was 70 mm. Series of tests were performed to study tensile strength, low-cycle and multicycle fatigue. Samples were cutting on pieces with size $6 \times 6 \times 17$ mm^3 after failure for measurement of the hydrogen concentration. Hydrogen analyzer AV-1 was used for measurements.
The half of specimens analyzed without additional polishing. The another half was polished manually in the depth of 0.1 mm layer. Upper and lower specimen edge's had been polished only. Therefore, rolled boundary layer was deleted, which contacts with the environment air during mechanical testing. Specimens were cut also from

unloaded part of sample, as well as from loaded.
Average hydrogen concentration in specimens with removed boundary layer is 0.25 ppm. Unloaded part of corset samples with boundary layer consider 0.42 ppm hydrogen concentration.
Loaded part of samples with boundary layer consider hydrogen concentration in range of 0.42 ppm to 0.95 ppm. Maximum values observed in the main crack, which lead to samples fracture.
Hydrogen concentration could be calculated by subtraction method, considering thickness of boundary layer. Initially boundary layer accumulates approximately 10 ppm hydrogen during rolling stage. Hydrogen are redistributed and accumulated additionally, during tensile phase. Boundary layer around main crack consider up to 60 ppm hydrogen. This means that there is the hydrogen induced fracture during mechanical testing under normal environment conditions.
Nonetheless, this phenomenon should be further analyzed. It would be feasible to use the model for this purpose.

2.2 Hydrogen-induced fracture model

The purpose of this study is the modeling of fracture in cylindrical steel samples, caused by mechanical properties degradation created by diffusion – mobile hydrogen accumulation in the boundary layer.
The simple model of material heterogeneity examined to study impact of mechanical properties degradation. Plasticity is simulated by bilinear material model.
The cylindrical corset samples with the annular crack examined because extensive experimental data exist for such cases (see Fig. 1). ANSYS/LS-DYNA is used for fracture simulation.
The explicit dynamic structural analysis method used for modelling. Axisymmetric 2D model used assumes that a 3D model and its loading can be generated by revolving a 2D section 360° about the y-axis. It reduces number of elements in the model, increases solving time and allows to plot section strain-stress result without additional tools. The geometry has to lie on the positive x-axis of the x-y plane due to symmetry with dimensions shown in the figure 1. Boundary layer thickness is in range of 0..50 Bxm.
2D model are meshed by 2D Solid 162 axisymmetric elements. The Fig. 2 are show 3D revolving a section in 270° with specific mesh in stress concentrations area.
Boundary conditions (loads and constraints) are:

$$y = 0: \quad u_y = 0,$$

$$y = L: \quad u_y = v_y \cdot t,$$

$$x = R: \quad n \cdot \sigma = 0.$$

The lowest edge of section is fixed. The upper edge is moved with constant velocity $v_y = 3$ mm/c. Material properties are based on data from cf. [8] about hydrogen concentration and from cf. [10] about high strength steel AISI 4135 (see table 9).

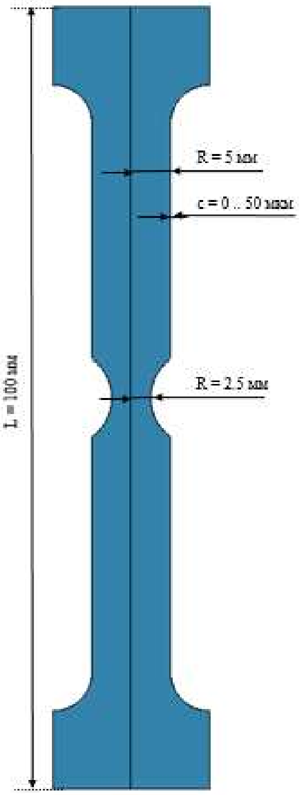

Figure 1: Cylindrical model with concentrator

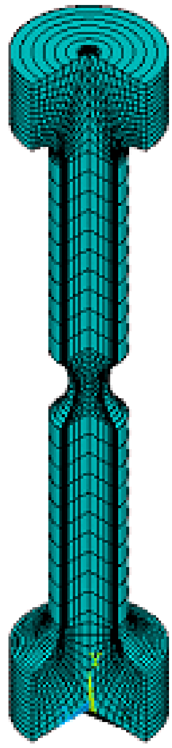

Figure 2: Finite element model revolved in 3/4

Table 9: Material properties

Steel AISI 4135	E	200 GPa
	ν	0.32
	σ_y	1 350 MPa
	E_T	763 MPa
	ρ	7 865 kg/m^3
	$\varepsilon_{failure}$	0.003
Boundary layer	$\sigma_{y\ H\ concentration\ I}$	500 MPa
	$\varepsilon_{failure\ H\ concentration\ I}$	0.00065
	$\sigma_{y\ H\ concentration\ II}$	400 MPa
	$\varepsilon_{failure\ H\ concentration\ II}$	0.0005

3 Results and discussion

Boundary layer thickness and mechanical properties degradation effects on the maximum of the first principal stress were analyzed. The maximum of the first principal stress measured in the point, shown in the Fig. 3. Relation between the maximum stress and boundary layer thickness is plotted in the Fig. 4.

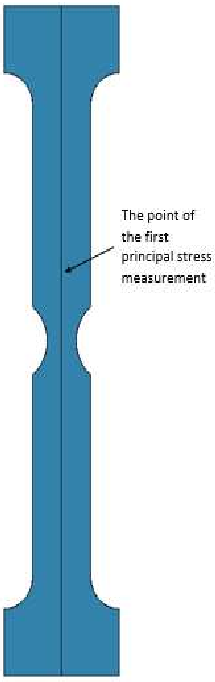

Figure 3: The first principal stress point

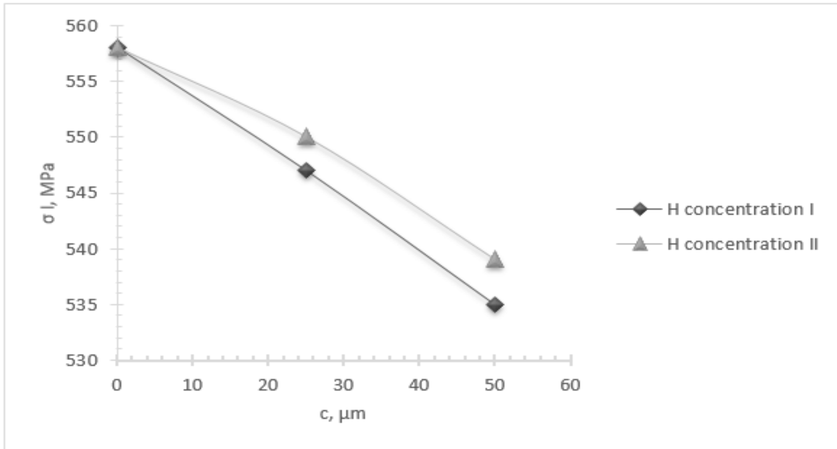

Figure 4: Maximum stress vs boundary layer thickness dependence

The maximum stress decrease is 19 MPa as shown in the graph and it is not more than 4% from decreasing of the initial value. Consequently, degradation of mechanical properties at a depth of the grain size of polycrystalline metal does not lead to significant tensile strength change.
However, effect of the hydrogen accumulation into the boundary layer and hydrogen-induced fracture, which we detected in case of mechanical fracture, was explained in the research [11] for other cases. It may be assumed that surface sorption of hydrogen from environmental is one of the main fracture mechanisms. The model of bicontinuous material, which was developed in [12], has not consider this effect of boundary layer.

4 Conclusions

Experimental data is collected for single-axis tensile loading of corset samples. It shows that leading mechanisms of fracture is hydrogen accumulation in the thin boundary layer with further creation and propagation of cracks.
Hydrogen-induced mechanical properties degradation analyzed on cylindrical corset samples from high strength steel. Degradation of mechanical properties at a depth of the grain size of polycrystalline metal does not lead to significant tensile strength change.

Only a model of bicontinuous material for the entire specimen could explain experimentally observed effects.
This phenomenon should be further analyzed by the model, which explain degradation of boundary layer with high hydrogen concentration during fracture.

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References

[1] V.Polyanskiy, A.Polyanskiy, Y.Yakovlev. The material interaction with the solute hydrogen during fatigue failure //W. Eichlseder, F. Grun, 3rd Fatigue Symposium Leoben. Lightweight design. 18-19 April 2012 Leoben, Austria. Conference transcript. ISBN: 978-3-902544-03-02.-Leoben:Montanauniversitat.-2012.-p.191-201.

[2] A.K. Belyaev, A.M. Polyanskiy, V.A. Polyanskiy and Yu.A. Yakovlev, "Parametric Instability in Cyclic Loading as the Cause of Fracture of Hydrogenous Materials," Mech. Solids. 47 (5), 533-537 (2012)

[3] J. Yamabe, M. Yoshikawa, H. Matsunaga, S. Matsuoka, Effects of hydrogen pressure, test frequency and test temperature on fatigue crack growth properties of low-carbon steel in gaseous hydrogen// Procedia Structural Integrity, Vol. 2, 2016, pp. 525-532.

[4] Birnbaum H.K., Sofronis P. Hydrogen-enhanced localized plasticity – a mechanism for hydrogen-related fracture . Mat. Sci. and Eng.: A. 176(1-2) 1994. -pp. 191–202.

[5] Varias A.G., Massih A.R. Simulation of hydrogen embrittlement in zirconium alloys under stress and temperature gradients. J. of Nuclear Mat. 279(2-3) 2000. -pp. 273–285.

[6] M.B. Djukic, V. Sijacki Zeravcic, G.M. Bakic, A. Sedmak, B. Rajicic, Hydrogen damage of steels: A case study and hydrogen embrittlement model// Engineering Failure Analysis, Vol.58, 2015, pp. 485-498, http://dx.doi.org/10.1016/j.engfailanal.2015.05.017.

[7] Ignatenko A.V., Pokhodnya I.K., Paltsevich A.P., Sinyuk V.S. Dislocation model of hydrogen-enhanced localizing of plasticity in metals with BCC lattice. The Paton Weld J. (3) 2012. -pp. 15–19.

[8] A. K. Belyaev, D. E. Mansyrev, V. A. Polyanskiy, A. M. Polyanskiy, D. A. Tretyakov, Yu. A. Yakovlev, Boundary layer of hydrogen concentration under plastic deformation, Diagnostics, Resource and Mechanics of materials and structures. - 2017. - Iss. 4. - P. 32-43 - DOI: 10.17804/2410-9908.2017.4.032-043

[9] A. Laureysa, T. Depovera, R. Petrova,b, K. Verbekena, Influence of sample geometry and microstructure on the hydrogen induced cracking characteristics under uniaxial load, Materials Science & Engineering, 2017, DOI: 10.1016/j.msea.2017.02.094

[10] Nie, Y., Kimura, Y., Inoue, T., Yin, F., Akiyama, E., & Tsuzaki, K. (2012). Hydrogen embrittlement of a 1500-MPa tensile strength level steel with an ultrafine elongated grain structure. Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science, 43(5), 1670-1687. DOI: 10.1007/s11661-011-0974-7

[11] Garkunov DN, Suranov G.I., Khrustalev Yu.A., Hydrogen wear of parts of machines Ukhta: Ukhta State Technical University 199p. ISBN: 5-88179-319-6

[12] A. K. Belyaev, N.R. Kudinova, V.A. Polyanskiy, Yu. A. Yakovlev, The description of deformation and destruction of materials containing hydrogen by means of rheological model, St. Petersburg Polytechnical University Journal: Physics and Mathematics, Volume 1, Issue 3, 2015, Pages 305-314, ISSN 2405-7223, doi:10.1016/j.spjpm.2015.12.002.

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