HYDROGEN ASSISTED NUCLEATION AND GROWTH OF MACROCRACKS IN METALS

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The model of macrocrack nucleation and growth in metals under sustained loading and action of hydrogenous environment is presented. The model is based on the dislocation-decohesive theory of hydrogen assisted fracture micromechanism and on combined approach of micro- and macromechanics which resulted in equations of hydrogen-induced macrofracture development in time. The model results are in qualitative and quantitative agreement with reported hydrogen embrittlement phenomena.

The effects of hydrogen on the mechanical behaviour of metals are of great importance for structural strength, which in such cases is obviously controlled by initiation and growth of main cracks so that components durability consists of the mentioned periods of process developement up to the exhaustion of their load capability. Accordingly to stresses mean values and gradients any of the two fracture stages may be significant. So it is desired the theory should describe both phases of fracture process in unified way.

The theory of hydrogen-induced fracture ought to be founded on the model of fracture micromechanism which is unique for both process stages. The improved model of dislocational cracks nucleation and growth is adopted (Panasyuk et al (1,2,3)), which takes into account the individual core properties of crack-creating (super)dislocations of pile-ups. Fracture relief in metals is associated with lattice-decohesive effect of hydrogen in dislocational cores. The synthesis of micro-and macromechanics led to failure macrocriterion in material point of elasto-plastic solid in terms of ma-

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ximum shear and tensile stresses τ_{max} and σ_1, equivalent plastic strain ε_i^p, hydrogen concentration C in metal and its structural-mechanical characteristics:

$$(\gamma_p + \varepsilon_i^p)(\tau_{max} - \tau_i)/\hat{f} = \hat{\sigma}(C, \sigma_1), \quad (1)$$

where τ_i is shear stress for the onset of microplastic strains, parameters γ_p, proportional to initial dislocation density, and $\hat{f}$ reflect dislocational nature and inhomogeneity of plastic deformation, the term $\hat{\sigma}$ is given in (3). Analysis of the above criterion fulfilment near structural notch (SN) or main-crack tip (MCT) with peculiar stresses, strain and hydrogen concentration distributions led to equations of hydrogen-induced initiation and growth of crack yielding the time $t=t_c$ for failure nucleation at point $x=x_c$ and the lenth $\Delta\ell$ of fracture increment values:

$$\begin{cases} C(x,t) = C_{cr}[\varepsilon_i^p(x), \sigma_1(x), \tau_{max}(x), \gamma_p(x_c), \hat{f}(x), \tau_i(x)] \\ \partial/\partial x\, C(x,t) = d/dx\, C_{cr}[\varepsilon_i^p(x), \dots] \\ C(x,t) = C_{cr}[\varepsilon_i^{p*}(x, \Delta\ell), \sigma_1^*(x, \Delta\ell), \tau_{max}^*(x, \Delta\ell), \gamma_p^*(\Delta\ell), \dots] \end{cases} \quad (2)$$

where $C(x,t)$ stands for stress-assisted hydrogen diffusion equation solution (4), the critical concentration C_{cr} is determined by eq.(1) and the quantities with asterisk refer to newly created MCT. Eqs.(2) for macroscopically smooth surface of SN give the period of crack initiation $t_c=t_i$, and for the MCT-region - the repetition period $t_c=\Delta t$ of its increments, which together with $\Delta\ell$ gives the crack growth rate (CGR) $v=\Delta\ell/\Delta t$. In the former case the depth x dependence of material parameters γ_p, etc., is used to take into account the surface effects in dislocation behaviour, which may be described by an appropriate model, e.g. by Arsenault and Hsu (5). For the MCT-zone under small- or large-scale yielding the geometrically nonlinear elasto-plastic solutions are to be used. The explicit equations for the crack-growth stage were derived by Kharin (4) earlier.

The qualitative agreement of the theory with hydrogen embrittlement observations is outlined elsewere (1, 3). To give an example of quantitative verification, only the temperature T and hydrogen pressure P dependence of CGR in steels is considered here. From eqs. (2) using known relations for metal-hydrogen systems (Sieverts' law, etc.) it was found

$$v(T,P) = S(\delta)\exp(-E_D/RT)[1 - C_{cr}(\delta)\exp(Q/RT)/(k_S\sqrt{P})]^2, \quad (3)$$

where value $\mathcal{E}$ depends on MCT-zone state, E_D is the diffusion activation energy, δ is the crack opening displacement, k_S is the athermal part of Sieverts' coefficient, Q depends on hydrogen solubility heat, hydrogen-dislocation binding energy, yield stress, etc. The results of calculations using eq. (3) and literary data on metal-hydrogen characteristics are in good agreement with empirical data of Gangloff and Wei (6), and Hudak and Wei

(7). So the theory may be used to develop the strength assesment criteria for engineering purposes.

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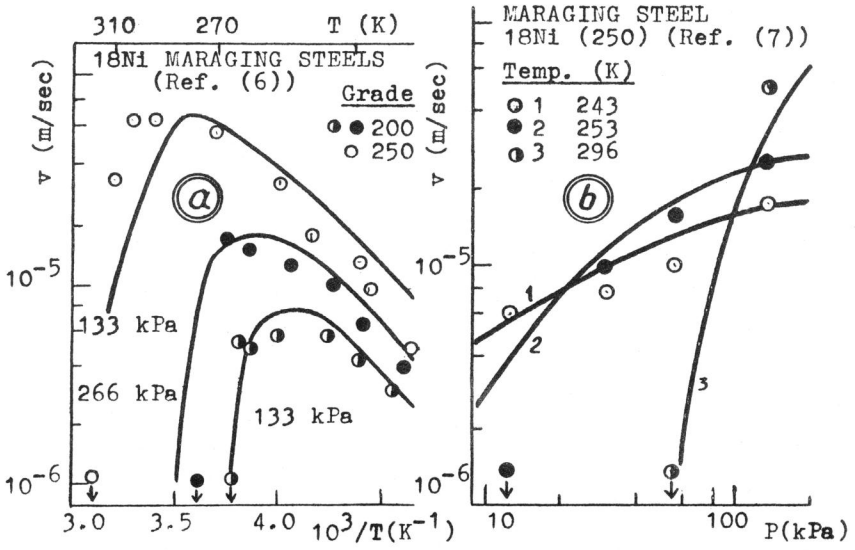

Figure Effect of temperature (a) and pressure (b) on CGR: empirical points (6,7) and calculated curves