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MATERIALS SCIENCE AND CORROSION PROTECTION

A TUBE STEEL BRITTLE FAILURE CRITERION

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A brittle failure mechanism is usually involved in accidents to oil pipelines operated under harsh conditions (temperatures between 40 and –60°C). On prolonged operation, there is a substantial reduction in the resistance to brittle failure, i.e., the cracking resistance.

It is considered that the cracking resistance in tube metal is one of the basic parameters in the reliability of industrial pipelines operated for long periods.

In the Russian pipeline system, the proportion of oilfield pipelines that have been operated for more than 20 years is 30%, while that for over 30 years is 59%. About 40% of oilfield pipelines have been in operation for more than 14 years (in their metal, deformational ageing has already advanced), and of those, 20% of pipelines have exceeded their amortization working life [1].

The safe operation of oilfield pipelines is a complicated problem requiring new approaches to the quantitative evaluation of cracking resistance for metal when these pipes are operated for a long time.

Tube wall failure is characterized by stages of crack nucleation, slow growth to critical dimensions, and rapid growth to complete failure. To prevent rapid nucleation and in some cases to eliminate pipeline failure, one can use hydraulic testing, heat treatment, treatment with high-frequency current, and so on. However, from the practical viewpoint, these technical ways of eliminating the crack nucleation stage are ineffective.

It is best to determine the nucleation conditions by new effective methods of estimating the brittle failure resistance of steels from the structural states. This requires the correct choice of optimum criteria for the cracking resistance of tube steels, which should properly reflect the actual physicomechanical processes in crack nucleation, growth, and propagation causing failure.

Various criteria for mechanical properties are used to estimate metal brittle failure, but most of them are suitable only for comparative analysis, and criteria should be physically based for quantitative estimation of brittleness.

For example, there is the microcleavage conception, which provides physically and experimentally based criteria for brittle failure and enables one to estimate the effects of hydrogen. According to the microscopic failure model, the critical state is the onset of instability in nucleated crack growth, which is characterized by the transition to unstable growth of primary cracks, i.e., submicroscopic ones. The geometrical dimensions of a submicroscopic crack are as follows: length about 100 nm and thickness a few times the lattice period. Such a crack constitutes a superdislocation in elastic equilibrium with the stress pattern produced by a group of dislocations nucleated by a microcrack, and also with the elastic field of the compressive stresses created by the sharp vertex of the microcrack in the surrounding metal. The main difference between a microcrack and a submicroscopic one lies not in the difference in geometrical dimensions but instead in the difference in their relation to the tangential and normal stresses in the metal.

A basic criterion of brittle strength is R_{mc}, the minimum stress at the yield limit for failure in uniaxial stretching. The hydrogen embrittlement is evaluated from δ_H, which is equal to the ratio of the parameter R_{mc}^H for hydrogenated specimens to the parameter R_{mc} for unhydrogenated ones, i.e., $\delta_H = R_{mc}^H / R_{mc}$.

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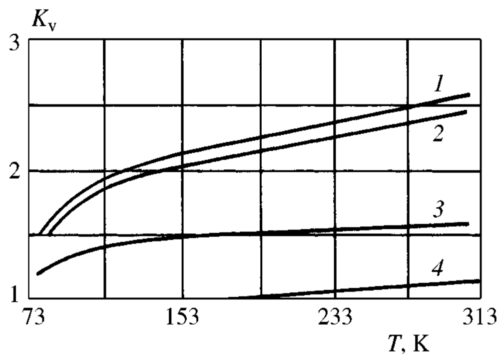

Fig. 1. Temperature dependence of the viscosity $K_v = R_{mce}/\sigma_y$ for steel 20: *1* and *2*) initial structure; *3* and *4*) after heat treatment (860°C, 60 min).

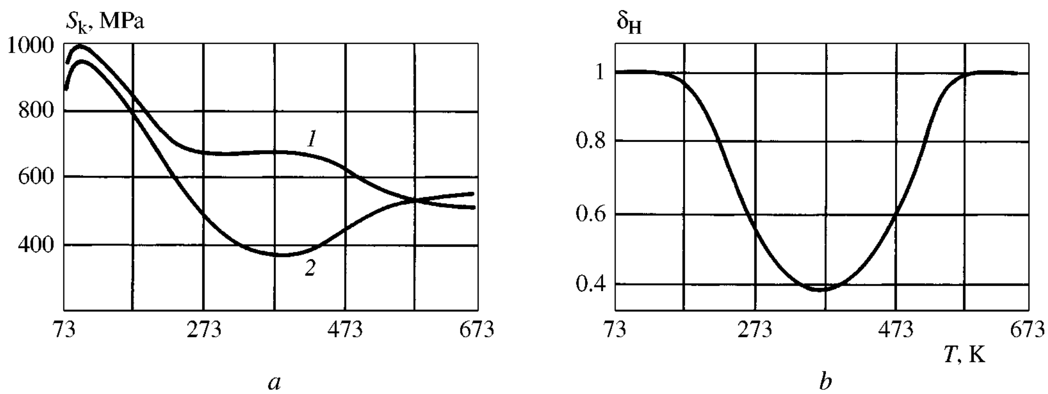

Fig. 2. Temperature dependence of the mean failure stress S_k for steel 20 (*a*) and the degree of hydrogen embrittlement δ_H (*b*): *1*) no hydrogen; *2*) after hydrogenation to 6.3 cm^3/100 g.

One measures R_{mc} at temperatures in the viscous-brittle transition interval. As hydrogen embrittlement occurs at temperatures close to the room value, and because R_{mc} is increased by plastic strain, one uses the failure stress S_k and the relative contraction ψ to determine the deformation analog of R_{mc}, namely R_{mce}, namely the failure stress of metal deformed at a certain step e.

The strain step is calculated from

$$e = \ln(1/(1-\psi)).$$

There exists a typical set of experimental curves from which one can determine R_{mc} and R_{mce}. Figure 1 shows such graphs.

The numerical value of R_{mc} is given by the point of intersection between the temperature dependence of the yield point σ_y and that for the failure stress S_k (Fig. 2), i.e., it can be derived from the graphs. Figure 2 shows that hydrogen does not influence R_{mc} (for steel St3) at low temperatures.

There is [2] the following relation between R_{mc} and R_{mce}:

$$R_{mc} = f(e)R_{mce},$$

where $f(e)$ is a function describing the increase in the brittle strength level because of texture formation.

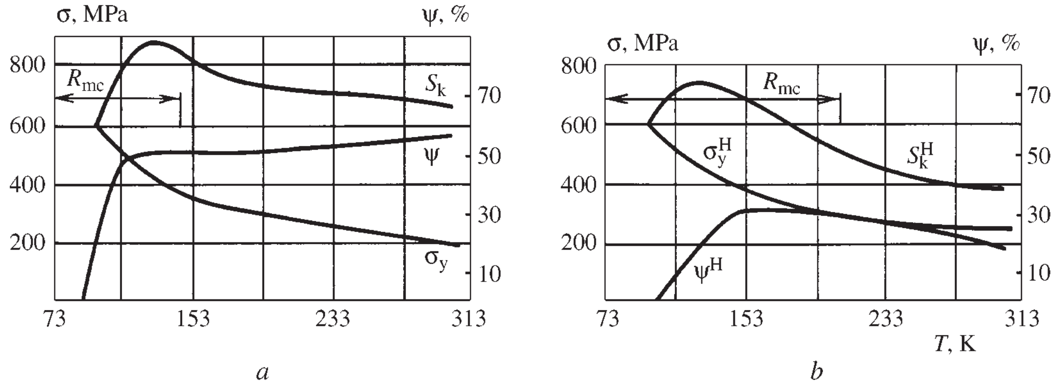

Fig. 3. Typical temperature curves for the mechanical characteristics of steel St3 without hydrogen (*a*) and after hydrogenation to 6.0 cm^3/100 g (*b*).

One assumes that $f(e)$ is invariant with respect to the hydrogen content because it cannot appreciably influence the formation of the metal texture at concentrations not more than 10 cm^3/100 g. On the other hand, R_{mce} is almost the same as the maximum tensile stress σ_{lc} for the failure of a specimen with the same residual strain.

Then the degree of hydrogen embrittlement is

$$\delta_H = \frac{R_{mce}^H}{R_{mce}} = \frac{\sigma_{lc}^H}{\sigma_{lc}},$$

where R_{mce}^H and σ_{lc}^H are the corresponding characteristics of the hydrogenated metal.

The maximal stresses [3] are

$$\sigma_{lc} = S_k \left\{ \frac{\left[1 + \ln\left(1 + \frac{\eta}{2}\right)\right]}{\left(1 + \frac{\eta}{2}\right)\ln\left(1 + \frac{\eta}{2}\right)} \right\},$$

where $\eta = 0.92(e - 0.1)$; S_k is the mean stress at the instant of failure.

Consequently, to determine δ_H characterizing the hydrogen embrittlement one needs to use mechanical tests in order to calculate σ_{lc} for the working temperature range. One divides σ_{lc}^H by σ_{lc} for given strains to get the degree of hydrogen embrittlement.

Although R_{mce} is independent of temperature, the change in δ_H characterizes the effects of hydrogen on this quantity. The temperature dependence of S_k reflects the total action of two embrittlement factors: low temperature and dissolved hydrogen (Fig. 3).

Also, δ_H indicates the temperature range in which hydrogen influences the result and is quantitatively determined by the temperature dependence of the degree of embrittlement (the hydrogen effect is absent for $\delta_H = 1$).

An additional criterion for hydrogen effects is provided by the viscosity K_v, which characterizes the potential scope for the metal to resist microcleavage.

This K_v is directly related to the criterion for the transition to the brittle state: if $K_v > 1$, the metal is viscous; if $K_v < 1$, the metal is brittle.

This method of estimating hydrogen embrittlement has a major advantage: the quantitative criteria are determined from ordinary mechanical tests on smooth cylindrical specimens, which enables one to examine the precise dependence of the hydrogen effect on the composition and structure of the metal, together with the stresses, concentration and distribution of the dissolved hydrogen, temperature, strain rate, and so on.

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