NATURE OF HYDROGEN BRITTLENESS OF STRUCTURAL STEELS

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We generalize the results of investigations performed at the Paton Institute of Electric Welding and aimed at elucidating the nature of the reversible hydrogen brittleness of structural steels. The state of the problem is analyzed, and a methodical approach is proposed for studying the problem at the atomic level. New ideas of the mechanism of reversible hydrogen brittleness are formulated, and their experimental substantiation is presented. It is shown that these ideas are useful for refining the methods of prevention of hydrogen embrittlement in steel structures while they are in production or in operation under conditions of hydrogen adsorption.

When steel structures are in operation, hydrogen, which enters a metal as a result of reactions with the environment or process medium, causes embrittlement, subsurface exfoliation, and corrosion cracking. The repair welding of such structures is complicated by hydrogen dissolved in the metal, and the increased susceptibility of repaired joints to hydrogen embrittlement complicates their use after repair.

To overcome the indicated problems, various methods are used, though they often appear insufficiently efficient. This is explained by the fact that the nature of hydrogen brittleness of steels is not clear [1, 2] and by the absence of detailed ideas of the mechanism of the phenomenon, which hampers its forecast and the improvement of methods of its prevention [3].

Below, we generalize the results of recent investigations [4–12] carried out at the Paton Institute of Electric Welding and aimed at elucidating the nature of the most complex and peculiar manifestation of the negative action of hydrogen, namely, reversible hydrogen brittleness.

Statement of the Problem

The very enumeration of the main regularities of reversible hydrogen brittleness indicates its uniqueness. In general, they are as follows:

(i) hydrogen affects maximally the mechanical characteristics of ferritic steels and, to a much smaller extent, those of austenitic steels;

(ii) susceptibility to hydrogen embrittlement is determined by the microstructure of a steel;

(iii) embrittlement can be caused by extralow (< 1 cm³/100 g of metal) hydrogen concentrations;

(iv) hydrogen brittleness is reversible, i.e., after the removal of hydrogen from a metal, its mechanical characteristics are recovered;

(v) reversible hydrogen brittleness becomes irreversible as a certain critical level of hydrogen concentration is exceeded or as the time of its interaction with the metal increases;

(vi) the degree of embrittlement depends on the value, type, and distribution of stresses;

(vii) the influence of hydrogen decreases as the rate of deformation grows;

(viii) a temperature close to the normal one is most favorable for the manifestation of reversible hydrogen brittleness;

(ix) the degree of embrittlement depends on the carbon content in the metal;

(x) stress concentrators enhance the action of hydrogen.

To explain the regularities detected, numerous hypotheses and theoretical concepts have been proposed, the existence of which by itself indicates the urgency of the problem and the absence of exhaustive knowledge on the nature of the phenomenon.

Let us consider briefly the most extensively used hypotheses for hydrogen brittleness [13]. In the first one, it is assumed that the major factor of embrittlement is the pressure of hydrogen in internal microvoids. Direct experiments confirm that the pressure in microvoids increases while hydrogen evolves from the bulk of the metal. However, this effect cannot explain a number of the well-known features of reversible hydrogen brittleness, in particular, the strong effect of extralow concentrations of dissolved hydrogen when the critical pressure is unattainable.

The second hypothesis is based on the idea of a decrease in the so-called adhesion strength, i.e., the weakening of interatomic bonds in the metal by dissolved hydrogen. However, it is difficult to prove the decohesive effect of hydrogen by direct experiments, and the fact that this hypothesis is unpersuasive becomes apparent if we recall the mean atomic hydrogen concentration over the macrovolume (<1 ppm), at which a catastrophic embrittlement can occur.

The basis of the third theory is the assumption that the specific energy of the internal surface of a crack during hydrogen adsorption decreases, as a result of which the fracture stress decreases. Thermodynamic calculations confirm the strong adsorptive effect of hydrogen. But these ideas have not been developed since it is not clear, for example, why hydrogen embrittles a metal, whereas oxygen, whose adsorptive effect is stronger according to the same calculations, suppresses the action of hydrogen. Moreover, the Griffith’s classical theory, which was successfully used in studies of brittle fracture, assumes the presence of preexisting cracks in a material without any explanation of their origin. That is why a deep gap between the detailed analysis at the atomic level of the possible action of hydrogen and the prediction of the behavior of a macrocrack by the well-developed methods of fracture mechanics arose.

In the fourth hypothesis, hydrogen transport by dislocations is considered to be the major effect: as they pile up near obstacles, the hydrogen concentration can become sufficient to abruptly accelerate fracture by one or another physical mechanism. Some variants of this hypothesis admit a possibility of retardation of dislocations by Cottrell hydrogen atmospheres or, vice versa, acceleration of their movement by hydrogen concentrated in the cores of dislocations. The dislocation hypothesis allows one to explain the temperature and deformation anomalies of the effect of hydrogen but only in the preparatory stage of embrittlement and does not elucidate the mechanism of fracture, which is of prime importance.

The dislocation–decohesion hypothesis admits that the decohesive action of hydrogen is localized in the cores of dislocations, where its higher concentration is possible. Decohesion disturbs the equilibrium of an accumulation of dislocations, which facilitates the nucleation of a crack. On the basis of the aforesaid, one succeeds in overcoming the major objection against the classical variant of the decohesion hypothesis based on the small mean atomic concentration of hydrogen, at which hydrogen embrittlement is possible. However, in contrast to the dislocation hypothesis, the mechanism of hydrogen transfer is believed to play a minor role, since one considers the behavior of a preexisting accumulation of dislocations, which was formed during plastic deformation and was in equilibrium prior to the entrance of hydrogen.

Analysis of the numerous hypotheses implies that they do not reveal the nature of reversible hydrogen brittleness in full measure. It is also seen that the explanation of reversible hydrogen brittleness is complicated by not only the necessity to define the major factors of embrittling action of hydrogen, but, which is of primary importance, by the absence of clear-cut ideas of the micromechanisms of fracture of a metal under the action of hydrogen.