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Workability Assessment of Structural Steels of Power Plant Units in Hydrogen Environments

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For estimation of hydrogen influence on the workability of high-stressed parts of power plant unit equipment it is necessary to use the crack growth resistance parameters. The new 18Mn–18Cr steel has higher resistance to hydrogen embrittlement and longer residual life time in hydrogen, than the traditional 8Mn–8Ni–4Cr steel.

Keywords: workability, fracture toughness, hydrogen embrittlement, critical crack size, durability.

1. **Crack Initiation in Modern Power Engineering Structural Components Operating in Gaseous Hydrogen**. Energy units and structural components of fusion power plants (FPP) and nuclear power plants (NPP) operate in contact with gaseous hydrogen. As example, Fig. 1 shows a typical scheme of such structural components. Note that in modern FPP and NPP there exist hydrogen-producing devices (electrolyzers, freezers, separators, condensate accumulators, etc.), wide-branched and long system of hydrogen pipeline, pumps, system of cleaning and drying of hydrogen. The problem of workability assessment of structural steels in gaseous hydrogen environments is critical for modern power engineering.

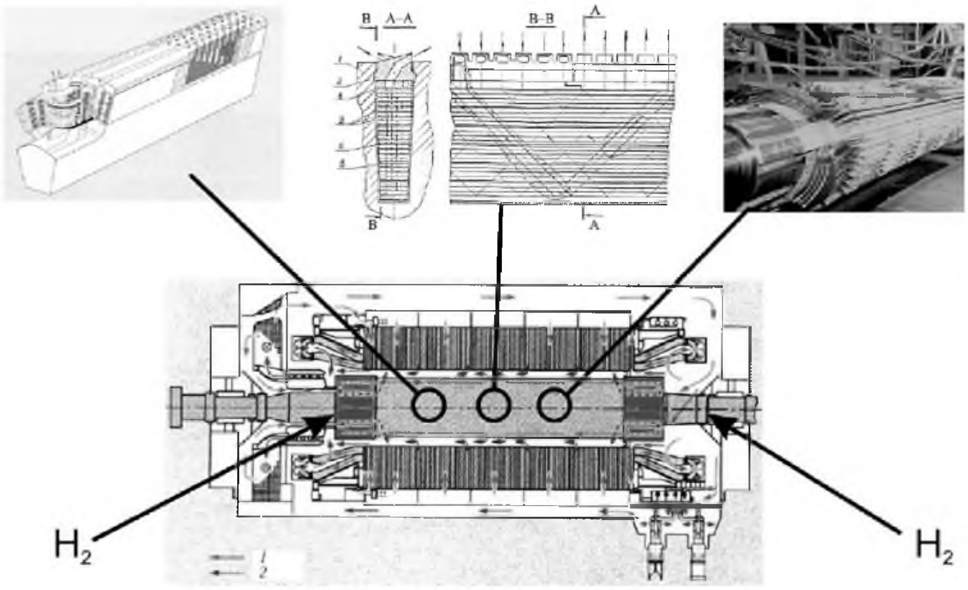


Fig. 1. Hydrogen cooling system of modern turboaggregate.

NPP and FPP structural component long-term service in the hydrogen-containing media is shortened by degradation of physical-mechanical properties (partially, their embrittlement) [1], decrease of the resistance of materials to crack propagation and plasticity, etc. Some examples of such degradation are presented in Fig. 2.

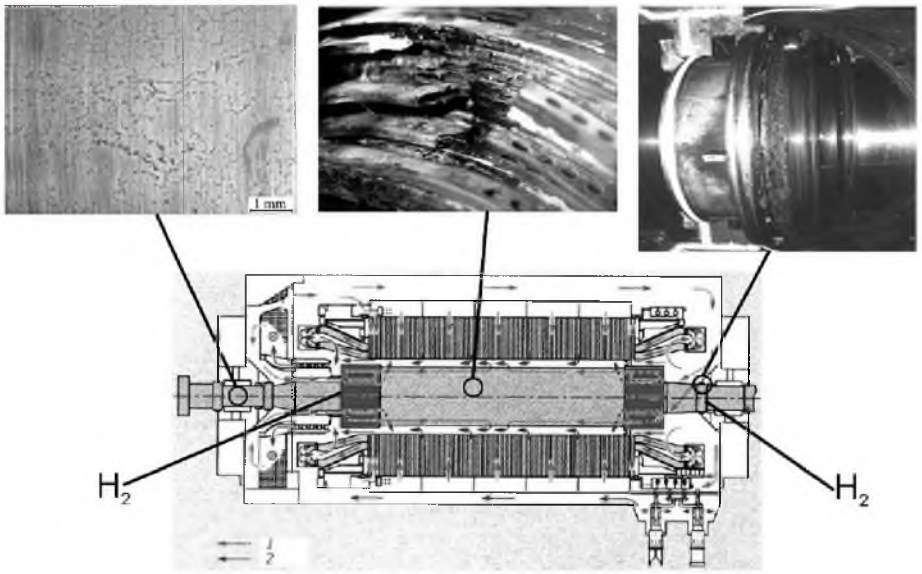


Fig. 2. Hydrogen-induced crack locations in the structural components of modern turboaggregates.

2. **Fracture Mechanics Approaches**. Development of the methods and numerical schemes for material workability estimations taking into account the above hydrogen degradation of physical and mechanical properties is very important. Under the influence of various factors, cracks which exist in the structural components of NPP and FPP propagate during the service.

Crack propagation in the retaining ring or pipe can be estimated by the fracture mechanics criteria equations for cracked solid bodies [2, 3]:

$$\left(\frac{K_{\mathrm{I}\max}(a,\sigma)}{K_{\mathrm{I}c}}\right)^4+\left(\frac{\sigma}{\sigma_Y}\right)^2=1, \tag{1}$$

where σ are operation stresses which arise in the pipe (ring) in the crack plane, $K_{\mathrm{I}\max}=K_{\mathrm{I}\max}(\sigma,a)$ is SIF maximum value for crack with length a in the cyclic load conditions, σ_Y is the yield strength of material, and $K_{\mathrm{I}c}$ is crack growth resistance (plane-strain fracture toughness) of material.

The stress σ is defined by the formula:

$$\sigma=\frac{pR}{t}, \tag{2}$$

where p is pressure, R is inner ring radius, and t is the wall thickness ($a << t$).

For the limit-equilibrium loading $\sigma = \sigma_*$, we can define the critical crack size $a = a_*$, achievement of which results in the spontaneous (catastrophic) fracture [3] using Eq. (1).

Based on Eqs. (1) and (2), crack value $a = a_*$ for particular $\sigma = \sigma_*$ can be written as

$$a_* = \eta \frac{K_{\mathrm{Ic}}^2}{\sigma_*^2}, \tag{3}$$

where η is a constant which depends on the elastic characteristics of materials and body dimensions.

Workability condition of a structure with a crack-like defect of size a is

$$a < a_*. \tag{4}$$

If macrocracks are detected in a pipeline or ring (Fig. 3), the limit-equilibrium state of a pipe (ring) under the internal pressure (or under the action of centrifugal forces) p can be estimated using relations (1)–(3) [3, 4].

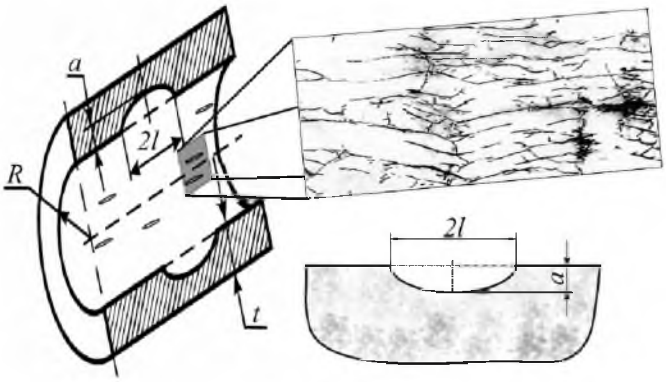


Fig. 3. Typical location and character of crack-like defects in the pipelines walls [4].

3. **Methods of Workability Assessment of Cracked Materials**. For workability assessment of cracked materials or for determination of plant life extension it is necessary to establish the time of microcrack, initiation, which leads to creation of a macrocrack with minimal length and period of its development [3, 4]. The initial damages are formed via dislocations, chemical nonregularities and secondary phases precipitations. By nondestructive control devices (partially by ultrasonic defectoscopy) crack can be detected before the critical size is reached. Crack critical size is estimated by the methods, which are based on the fracture mechanics concepts [2, 3], in particular, on the basis of Eqs. (1)–(3) and fracture toughness values (crack resistance K_{Ic}).

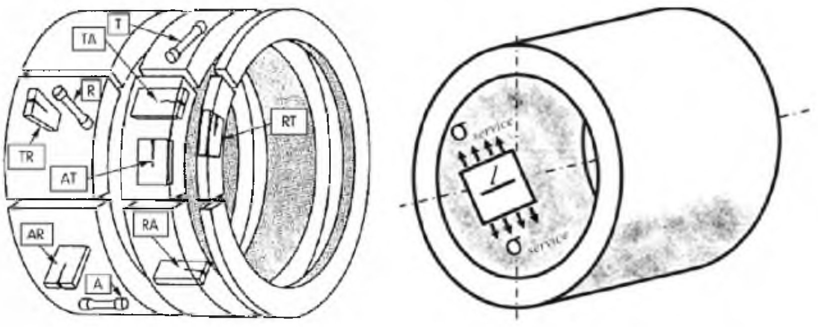
The data on variation of fracture toughness and other characteristics of material in hydrogen-containing environments are very important.

Experimental investigation has been performed in the Karpenko Physico-Mechanical Institute of the National Academy of Sciences of Ukraine. Dimensions of tested specimens are shown in Fig. 4a. Variation of such physical-mechanical characteristics as E (the Young modulus), δ, ψ (macrodeformations), K_{Ic} (fracture toughness) for power engineering purposes in dry air (A) and hydrogen (H) have been studied and the following results were obtained [6, 7] (see Table 1). Young's modulus practically did not change, but fracture toughness changed drastically (in hydrogen-containing environment it decreased). It is known from [5] that the values decrease with the service time or under the hydrogen action due to material embrittlement.

Table 1

Physical and Mechanical Characteristics of Steels for Retaining Rings Units of Turbogenerator in Air (*A*) and in Hydrogen (*H*)

Steel	E, GPa	σ_u, MPa	σ_Y, MPa	δ, %	ψ, %	K_{Ic}, MPa$\sqrt{\mathrm{m}}$
8Mn–8Ni–4Cr	189 (A) 185 (H)	1157 (A) 1002 (H)	925 (A) 800 (H)	30 (A) 22 (H)	60 (A) 55 (H)	200 (A) 160 (H)
18Mn–18Cr	200 (A) 197 (H)	1197 (A) 1152 (H)	1136 (A) 1121 (H)	29 (A) 21 (H)	64 (A) 60 (H)	268 (A) 224 (H)



a b

Fig. 4. Specimen dimensions and crack orientation for crack resistance parameters' dertermination (a) in the retaining ring wall of turbogenerator (TG) rotor made of the 8Mn–8Ni–4Cr and 18Mn–18Cr steels and service stresses which are applied to crack-like defects (b).

Assume that Young's modulus do not change in hydrogen-containing environment, while fracture toughness varies. In a such case, coefficient η in the formula (3) can be assumed independent of environment ($\eta_H \approx \eta_A$).

Then the critical crack size during the materials service in hydrogen (H) and air (A) is determined by formulas:

$$a_*^H = \eta \frac{K_{\mathrm{Ic}(H)}^2}{\sigma_{*(H)}^2}, \qquad (5)$$

$$a_*^A = \eta \frac{K_{\mathrm{Ic}(A)}^2}{\sigma_{*(A)}^2}. \qquad (6)$$

On the basis of formulas (5) and (6), we obtained

$$a_{*(H)} = a_{*(A)} \frac{K^2_{\text{I}c(H)}}{K^2_{\text{I}c(A)}}. \tag{7}$$

Exactly the same approaches are used in some normative documents [8, 9]. Take into account, that in some cases material embrittlement after long-term service (30–40 years) leads to formation of smaller cracks, than predicted by formula (7).

This fact is attributed to calculation errors of coefficient $K_\text{I}(a, \sigma)$, or with phenomena ofl additional ageing of materials (additional decrease of material fracture toughness during long-term operation in service environment) [5, 10]. In this respect, the problem requires additional investigation.

4. **Account of Subcritical Crack Propagation**. Retaining ring workability assessment performed according to normative documents [8, 9] takes into account the existence (extreme case) of a surface defect, which is treated as a plane semielliptical crack with axes a and l, where a is a smaller semiaxis which coincides with crack propagation direction to the depth of the retaining ring wall and characterizes the crack depth, and l is a larger semiaxis which is fixed on the ring surface (see Fig. 3). The most frequent are the following axis relations $a = (0.15–0.35)l$. These relations were established as a results of retaining rings service inspection during long-term operation (Table 2) [1, 5]. The critical crack sizes are established by formula (7) according to the normative documents of power engineering industry [8, 9].

Table 2

Parameters of the Service Defects of Retaining Rings Made of 8Mn–8Ni–4Cr Steel

TG type	Depth (small semiaxis, Fig. 3) of semielliptical crack a, mm	Length (large semiaxis, Fig. 3) of semielliptical crack l, mm	Durability W, cycles	n_j, starts (cold state)	n_i, starts (hot state)
TGV-200	0.5–5.0	1.5–35.0	$9.7 \cdot 10^9$	65	45
	10.0–15.0	28.0–100.0	$8.6 \cdot 10^7$	51	29
TGV-300	0.5–5.0	0.5–5.0	$1.1 \cdot 10^{10}$	55	40
	10.0–15.0	28.0–100.0	$9.0 \cdot 10^7$	48	29

For definition of the critical moment of state, which prevents fracture (durability closing) of retaining ring unit the stress intensity factor (SIF) at plane-strain fracture $K_\text{I}(a, \sigma)$ is used. The critical state is considered such, when the maximum SIF value on the crack contour achieves the fracture toughness $K_{\text{I}c}$.

Using Life Assessment Code EPRI IN-103088, IN-1030887 for life prediction of the retaining ring with defects, we obtain that for the crack depth $a_* = 24$ mm the fracture of retaining ring made from steel 18Mn–18Cr takes place after 5 thousand hours of operation [10, 11]. However, the hydrogen factor can decrease drastically at that time, since the critical crack size in gaseous hydrogen is lower [see Eq. (7)]. Thus, it is necessary to take into account the real value of $K_{\mathrm{I}c(H)}$ for working environment.

Assessment of modern steels has shown that high nitrogen-containing 18Mn–18Cr steel with higher value of fracture toughness (see Table 1) provides safe carrying ability of cracked retaining ring during longer operation time in hydrogen environment than conventional 8Mn–8Ni–4Cr steel [10, 11].

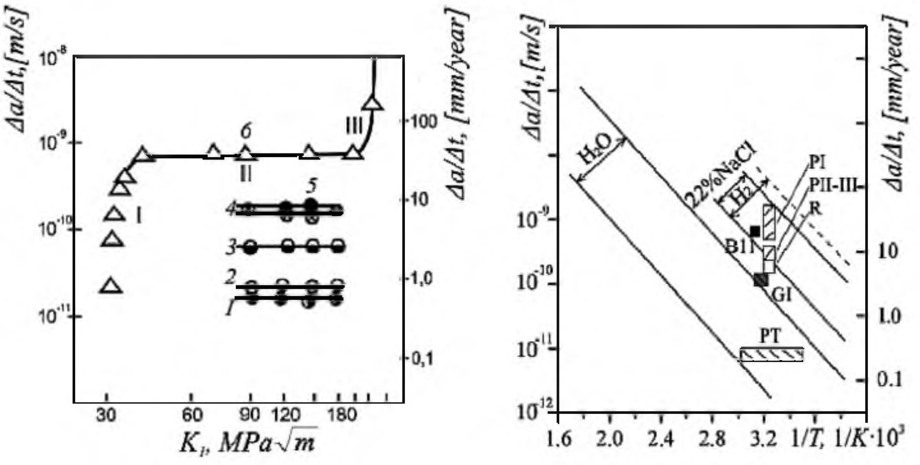


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Fig. 5. (a) Dependence of the crack growth propagation rate on SIF in high-strength 8Mn–8Ni–4Cr steel:(*1*) in air with 15% humidity, $T = 20°$C; (*2*) in hydrogen with 15% humidity, $T = 20°$C; (*3*) in hydrogen with 40% humidity, $T = 20°$C; (*4*) in air with 90% humidity, $T = 65°$C; (*5*) in hydrogen with 90% humidity, $T = 65°$C; (*6*) under electrolytic hydrogenation with current density 1 A/dm^2. (b) Working environments can greatly accelerate the growth rates of SCC in steel 18Mn–18Cr: SCC growth rates estimated by dividing the total crack depth by the total service time of the damaged generator rotor retaining rings: FPP Perm-1 (*PI*), Perm-II (*PII*), Perm-III (*PIII*), Rjazan (*R*), Porto-Tolle (*PT*), Burshtyn-11 (*B11*) (8Mn–8Ni–4Cr), Gacko1 in gaseous hydrogen, pure water and in 22% NaCl solution [1, 5].

As a result of the analysis of cracks detected at the Burshtyn 11 FPP TG retaining rings (Fig. 5) it is established that crack propagation rates are commensurable with crack rates, obtained during experimental testing of specimens made of 8Mn–8Ni–4Cr steel in hydrogen-containing environments. Crack rates in 18Mn–18Cr steel retaining rings at the Perm FPP are equal to 0.10–7.0 mm/year and are lower than those in the retaining rings made of 8Mn–8Ni–4Cr steel (Fig. 5).

Conclusions

1. For estimation of hydrogen influence on the workability and residual life time of high-stressed parts of power engineering equipment it is necessary to use the crack growth resistance parameters (fracture toughness, crack-like defects critical sizes) and their values in the initial and deteriorated states.

2. During operation in hydrogen, the high nitrogen-containing 18Mn–18Cr steel has a higher resistance to hydrogen embrittlement and to stress corrosion cracking, than traditionally used nitrogen-containing 8Mn–8Ni–4Cr steel.

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