DOI 10.1007/s11003-017-0049-z

Materials Science, Vol. 53, No. 1, July, 2017 (Ukrainian Original Vol. 53, No. 1, January–February, 2017)

APPLICATION OF THE ENERGY APPROACH TO THE EVALUATION OF THE SERVICEABILITY OF THE DRUM OF A STEAM BOILER SUBJECTED TO THERMAL CYCLING AND HYDROGENATION

O. V. Hembara,[1] **O. Ya. Chepil',**[1] **and T. V. Hembara**[2,3]

UDC 620.197.5: 669.788

We develop a method for the evaluation of the influence of hydrogen on the strength and durability of the drum of a high-pressure steam boiler subjected to thermal cycling and hydrogenation. We analyze the influence of hydrogen on the accumulation of damage to the metal and the duration of operation of the drum for different modes of damage. It is established that hydrogen accelerates the accumulation of damage and reduces the period of operation of metals by 25–30% for planned shutdowns of the boilers and by 40–50% for their emergency shutdowns.

Keywords: hydrogen concentration, strain energy, damage, service life, drum of steam boiler.

Standard branch methods [1] used to estimate the service life of power-generating equipment are usually constructed on the basis of simple engineering formulas deduced for shells and rods. As follows from the literature data and, in particular, from the results presented in [2, 3], the numerical analyses of structural strength carried out according to the indicated approaches give overestimated values of the characteristics of stress-strain state (SSS) with, in some cases, severalfold difference. Moreover, the effect of working media is taken into account only by the introduction of additional safety factors compensating the heavier conditions of operation of metals in hydrogen-containing media.

However, the analysis carried out in [4] demonstrates that this approach is incorrect. Thus, in particular, it was established that the long-term strength of cylindrical specimens under the action of internal pressure becomes several times lower in the presence of hydrogen. It is also known that the thermomechanical loading of metals leads to the redistribution of hydrogen over the volume. In particular, as shown in [5–10], its concentration in the process zone is several times higher than the average values.

Hence, in estimating the serviceability of elements of the power-generating equipment, it is necessary to take into account this aspect.

Therefore, it is important to determine the SSS of elements of the power-generating equipment under the operating conditions with regard for their actual geometric shapes, hydrogen degradation of the metal, and local defects. These data should be then used to estimate the remaining service life of these elements and the possibility of temporary prolongation of their service life or the necessity of replacement of the damaged units and elements of the power-generating equipment, as well as to develop recommendations concerning the repair works required for subsequent operation.

---

[1] Karpenko Physicomechanical Institute, Ukrainian National Academy of Sciences, Lviv, Ukraine.

[2] Lviv State University of Safety of the Vital Activity, Lviv, Ukraine.

[3] Corresponding author; e-mail: hembara@ipm.lviv.ua.

Translated from Fizyko-Khimichna Mekhanika Materialiv, Vol. 53, No. 1, pp. 90–95, January–February, 2017. Original article submitted March 27, 2016.

1068-820X/17/5301–0102

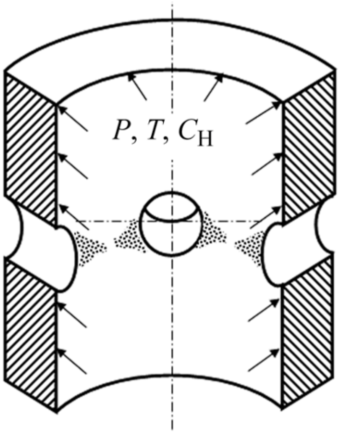

Fig. 1. Loading scheme of a three-dimensional body with stress concentrators in hydrogen.

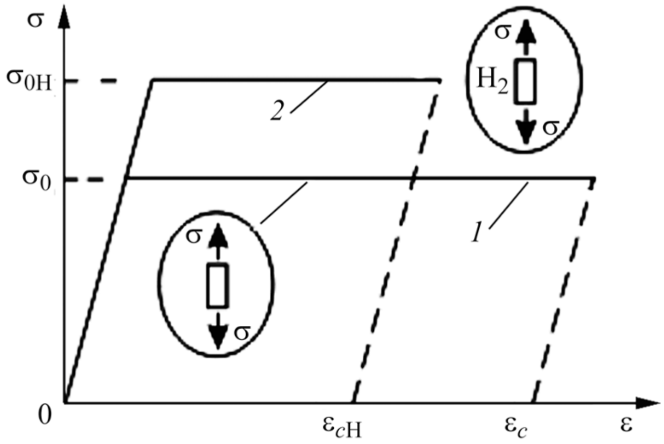

Fig. 2. Tensile stress-strain diagrams of the material in air (1) and in hydrogen (2) [9].

Statement of the Problem

We consider a metal body with stress concentrators (Fig. 1) subjected to the action of a hydrogen-containing medium and the force and thermal loads variable as functions of time. As a result of these actions, the body is deformed and process zones are formed near the stress concentrators. The defects appear just in these zones.

It is known [9, 11, 12] that the process of hydrogenation affects the mechanical properties of materials, which usually leads to an increase in strength and a decrease in plasticity (Fig. 2). Hence, the energy accumulated in the material changes, which must lead to changes in the characteristics of its fracture resistance. It is difficult to predict how exactly this affects the accumulation of defects in hydrogenated materials but one can estimate this phenomenon by analyzing the changes in the energy balance for the characteristic element.

Thus, to estimate the degree of damage to the material of an elastoplastic body under cyclic deformation, we can use the energy criterion of fracture of a local volume of the element [9]:

$$W(P_*, T_*, C_{\mathrm{H}*}) = W_C^{\mathrm{H}}, \tag{1}$$

where

W is the strain energy of a local volume of the element,

P_*, T_*, and $C_{\mathrm{H}*}$ are the pressure, temperature, and hydrogen concentration for which the strain energy takes its critical value,

and

W_C^{H} is the characteristic of fracture resistance of the material for given loading conditions, temperature, and working medium.

As the measure of energy damage, we use the ratio of the elastoplastic strain energy for a local volume to its critical value [7]:

$$\omega = \frac{W(x,y,z,t)}{W_C^{\mathrm{H}}}. \tag{2}$$

The elastoplastic strain energy is given by the following Palmgren–Miner formula:

$$W(x,y,z,t) = \sum_{i=1}^{N} \Delta W_i(x,y,z,t), \tag{3}$$

where

N is the number of cycles

and

ΔW_i is the increment of strain energy in a local volume of the element in a single loading cycle.

An element of volume of the material fails as soon as the following equality is attained:

$$\omega(x_*, y_*, z_*, t_*) = 1. \tag{4}$$

The strain energy is determined via the distribution of equivalent stresses and strains as follows:

$$W(x,y,z,t) = \iiint\limits_V \sigma_e(x,y,z,t)\,\varepsilon_e(x,y,z,t)dV, \tag{5}$$

where σ_e and ε_e are the equivalent stresses and strains in a local volume of the element depending on mechanical loads, temperature field, and hydrogen concentration:

$$\varepsilon(x,y,z,t) = \varepsilon_p(x,y,z,t) + \varepsilon_T(x,y,z,t,T) + \varepsilon_{\mathrm{H}}(x,y,z,t,C_{\mathrm{H}},\sigma_h,T). \tag{6}$$

In view of the Gorsky effect and the experimental results obtained in [9], we approximate the dependence of strain on the hydrogen concentration by a linear law

$$\varepsilon_{\mathrm{H}} = AC_{\mathrm{H}}, \tag{7}$$

where A is the coefficient of concentration hydrogen expansion.

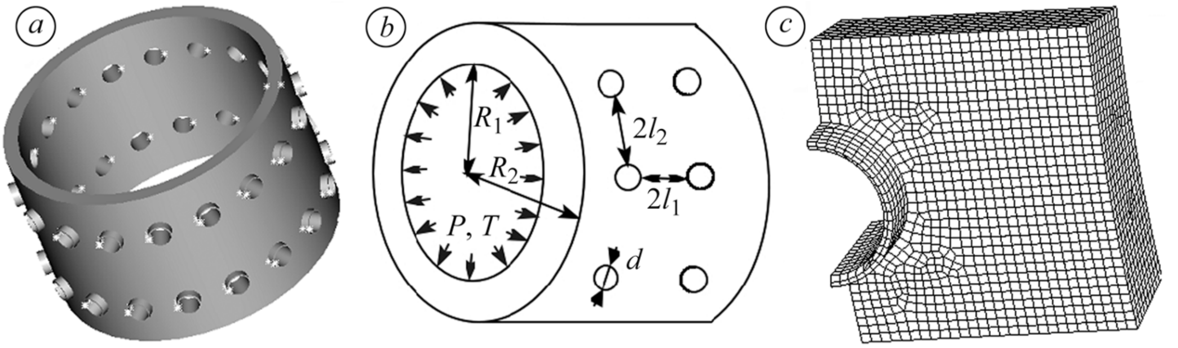

Fig. 3. Fragment of the boiler drum (a), its computational scheme (b), and partition into finite elements (c).

The possibility, conditions, and period of prolongation of the operation of high-temperature elements of the equipment are determined according to expression (1) by comparing the computed values of the current strain energy of the process zone with its ultimate value, which is established according to the results of experimental investigations of the specimens made of structural alloyed steels in the corresponding media at operating temperatures.

Modeling of the Stress-Strain State of a Fragment of the Drum of High-Pressure Steam Boiler

The main causes of the appearance of cracks in drums in the process of their operation are as follows: high levels of the acting stresses, significant time-dependent temperature stresses caused by shutdowns (and, especially, by the emergency shutdowns) and startups of the boilers, and hydrogen degradation and low deformation ability of the drum metal.

In what follows, we present the main results obtained by the computer simulation of deformation of a boiler drum with holes under conditions of its operation.

As a computational model, we used a three-dimensional hollow cylinder with holes chosen according to the actual sizes of the boiler drum: $R_1 = 0.805$ m, $R_2 = 0.9$ m, $d = 0.13$ m, $l_1 = 0.26$ m, and $l_2 = 0.5$ m (Fig. 3) and loaded by time-dependent internal pressure and temperature ($T = 400 \pm 20°\mathrm{C}$, $P = 16 \pm 1.7$ MPa). In the course of finite-element simulation of the grid, a fragment of the drum was split into 216,000 elements in the form of parallelepipeds.

We performed calculations for the following modes of operation:

(I) with planned cooling at a rate of 5°C/h once a year;

(II) steady-state mode of thermal cycling with planned cooling at a rate of 5°C/h ten times per year;

(III) with emergency cooling at a rate of 90°C/h ten times per year.

The problem of determination of the stressed state of the analyzed cylinder under the operating conditions is connected with the determination of the space-and-time distributions of temperature, displacements, strains, and stresses from the nonstationary three-dimensional heat-conduction equation and the complete system of equations of nonisothermal thermoelastoplasticity under the corresponding initial and boundary conditions. The influence of hydrogen on the accumulation of damage in the metal is taken into account by changes in the

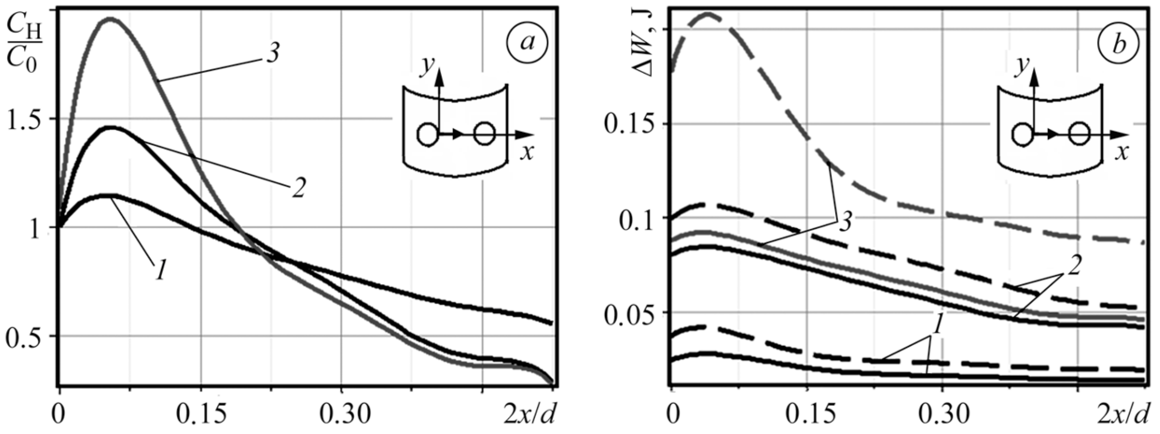

Fig. 4. Distributions of the relative hydrogen concentration (a) and the increment of the strain energy (b) from the hole to the middle of the distance between the contours with (dashed line) and without (solid) the influence of hydrogen-containing media for different loading modes for two cycles: (1) mode I, (2) mode II, (3) mode III.

hydrogen concentration determined from the nonstationary three-dimensional equation of hydrogen diffusion depending on the temperature field and the SSS [5–7]. To solve these problems, we developed the corresponding software based on the finite-element method.

As a result, we plotted the distributions of relative hydrogen concentration (Fig. 4a) and the increment of the strain energy in a single loading cycle (Fig. 4b) near the stress concentrator and on the line from the contour to the point located in the middle of the line between the contours of the holes in air and hydrogen for different modes of operation.

It was shown that the hydrogenation of the drum wall increases the level of strains in the material. The highest strains are formed in the mode of operation with emergency cooling.

As follows from Fig. 4a, thermal cycling is accompanied by the redistribution of hydrogen with its accumulation near the stress concentrator. In the case of operation with emergency cooling, the maximal value of the relative concentration of hydrogen is twice higher than the corresponding value for scheduled shutdowns.

Note that, in the vicinity of the hole (at a certain distance from it), the maximal value of energy is twice higher than the energy between the holes (Fig. 4b). In addition, hydrogen diffusing into the metal of steam-generating tubes of boilers as a result the reaction of steam with this metal increases the elastoplastic strain energy of the metal by 20–40% for scheduled shutdowns and almost doubles for the emergency shutdowns.

Influence of the Hydrogenation of the Metal on the Accumulation of Damage and the Time of Operation of the Drum

We assume that the damage is initiated in the local volume of the material, where the elastoplastic strain energies ΔW_p and ΔW_{p_H} are maximum.

In Fig. 5, we present the dependence of the accumulated damage on the time of operation with regard for the influence of the hydrogen medium (ω_{p_H}) and in the absence of hydrogen (ω_p) for different operating modes.

As follows from Fig. 5, the cooling rate and the number of shutdowns strongly affect the accumulated degree of damage to the metal and the service life of the drum as a whole.

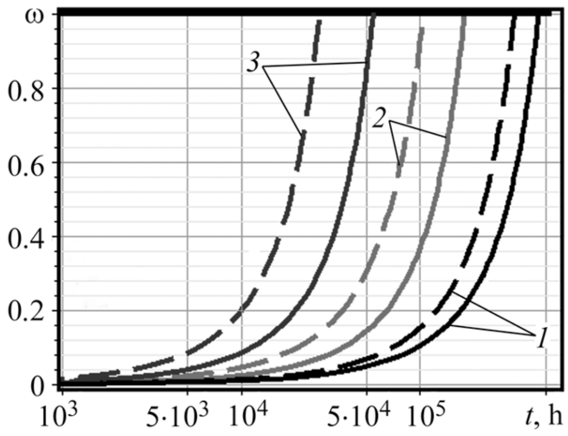

Fig. 5. Time dependences of the degree of damage accumulation in the vicinity of the stress concentrator with regard for the influence of hydrogen-containing media (ω_{p_H}, dashed line) and in the absence of hydrogen (ω_p, solid line) for different modes of operation: (1) mode I, (2) mode II, (3) mode III.

Table 1. Number of Cycles to Fracture for the Boiler Drum in Air and in Hydrogen for Different Modes of Operation

Mode	Duration of a single cycle, h	Number of cycles to fracture		Decrease in the service life under the action of hydrogen, %
		under the action of hydrogen	without hydrogen	
I	876	92	130	29
II	8760	39	52	25
III	876	20	37	48

Thus, the realization of ten scheduled shutdowns per year (Fig. 5) decreases the service life of the boiler drum by a factor of 2.5 as compared with a single scheduled shutdown. Emergency shutdowns additionally decrease the service life of the drum by 15%.

It is worth noting that there is one more significant factor that affects the service life, namely, the working hydrogen-containing medium, which accelerates the process of accumulation of damage and decreases the period of operation of the metal (Table 1) by 25–30% in the case of scheduled shutdowns of the boiler and by 40–50% in the case of its emergency shutdowns.

CONCLUSIONS

By using the energy approach, we propose a method for the evaluation of the influence of hydrogen on the service life of the drum of a high-pressure steam boiler subjected to thermal cycling and hydrogenation. The algorithms and programs created on the basis of the finite-element method enable us to model and analyze the variations of the temperature field, stress-strain state, hydrogen concentration, and the degree of damage accumulation in the fragment of a boiler drum made of 22K steel for different modes of operation with regard for the hydrogenation of the wall and the actual geometry of the drum. It is shown that hydrogen accelerates the process of damage accumulation and decreases the period of operation of the metal by $25–30\%$ in the case of scheduled shutdowns of the boiler and by $40–50\%$ in the case of its emergency shutdowns.

REFERENCES

1. *Instruction SOU 40.1-21677681-02:2009. Procedure of Prolongation of the Service Life of the Drums of High-Pressure Boilers* [in Ukrainian], Haluzevyi Rezervno-Investytsiinyi Fond Rozvytku Enerhetyky, Kyiv (2009).
2. H. M. Nykyforchyn, O. Z. Student, H. V. Krechkovs'ka, and A. D. Markov, "Evaluation of the influence of shutdowns of a technological process on changes in the in-service state of the metal of main steam pipelines of thermal power plants," *Fiz.-Khim. Mekh. Mater.,* **46**, No. 2, 42–54 (2010); ***English translation:*** *Mater. Sci.,* **46**, No. 2, 177–189 (2010).
3. B. Drobenko and O. Buryk, "Mathematical modeling of the processes of deformation of structural element under thermal-and-force loading," *Fiz.-Mat. Model. Inform. Tekhnol.,* Issue 20, 117–126 (2014).
4. I. I. Ovchinnikov, "Influence of hydrogen-containing media at high temperatures and pressures on the behavior of metals and metal structures," *Internet J. Naukovedenie,* No. 4, 1–28 (2012).
5. V. Panasyuk, Ya. Ivanytskyi, and O. Hembara, "Assessment of hydrogen effect on fracture resistance under complex-mode loading," *Eng. Fract. Mech.,* **83,** 54–61 (2012).
6. V. V. Panasyuk, Ya. L. Ivanyts'kyi, O. V. Hembara, and V. M. Boiko, "Influence of the stress-strain state on the distribution of hydrogen concentration in the process zone," *Fiz.-Khim. Mekh. Mater.,* **50**, No. 3, 7–14 (2014); ***English translation:*** *Mater. Sci.,* **50**, No. 3, 315–323 (2014).
7. Ya. L. Ivanyts'kyi, O. V. Hembara, and O. Ya. Chepil', "Determination of the durability of elements of power-generating equipment with regard for the influence of working media," *Fiz.-Khim. Mekh. Mater.,* **51**, No. 1, 93–101 (2015); ***English translation:*** *Mater. Sci.,* **51**, No. 1, 104–113 (2015).
8. M. Stashchuk and M. Dorosh, "Evaluation of hydrogen stresses in metal and redistribution of hydrogen around cracklike defects," *Int. J. Hydrogen Energy,* **37,** 14687–14696 (2012).
9. Ya. L. Ivanyts'kyi, P. S. Kun', S. T. Shtayura, and V. M. Mochul's'kyi, "Theoretical-experimental approach to the analysis of fatigue crack propagation in hydrogenated materials," *Fiz.-Khim. Mekh. Mater.,* **46**, No. 2, 77–82 (2010); ***English translation:*** *Mater. Sci.,* **46**, No. 2, 213–220 (2010).
10. O. E. Andreikiv and O. V. Hembara, *Fracture Mechanics and Durability of Metallic Materials in Hydrogen-Containing Media* [in Ukrainian], Naukova Dumka, Kyiv (2008).
11. Ya. L. Ivanyts'kyi, S. T. Shtayura, Yu. V. Mol'kov, and T. M. Lenkovs'kyi, "Influence of hydrogen on the fracture resistance of 65G sheet steel," *Fiz.-Khim. Mekh. Mater.,* **47**, No. 4, 36–40 (2011); ***English translation:*** *Mater. Sci.,* **47**, No. 4, 457–461 (2012).
12. Y. Ivanytskyj, S. Shtayura, Y. Molkov, and T. Lenkovskyi, "Hydrogen influence on fracture of sheet carbon steel," *Int. J. Fracture,* **176**, No. 1, 17–23 (2012).