Evaluation of Hydrogen Resistance of 18Mn-18Cr Stainless Steels and its Welding Joining by Fracture Mechanics Approaches

Alexander Balitskii[1*]

[1]Karpenko Physico-Mechanical Institute of National
Academy of Sciences of Ukraine
Naukova str.,5, UA 79601, Lviv, Ukraine
[*]balitski@ipm.lviv.ua

Keywords: hydrogen resistance, fracture toughness, serviceability, subcritical crack length.

Abstract. ***For definition of critical moment of state in gaseous hydrogen, which prevents the fracture (durability closing) of retaining ring unit made from 18Mn-18Cr the stress intensity factor (SIF) at plane-strain fracture*** $K_I(a,\sigma)$ ***has used. The critical state is consider such, when on the crack contour the maximum SIF value achieves the fracture toughness*** K_{1c} ***in hydrogen.***

Introduction

Assessment of the serviceability of advanced structural materials for FPP, NPP and hydrogen energetic equipments in the conditions of their long-term exploitation in gaseous hydrogen with high temperatures, pressure and mechanical stresses required the investigation of the materials physical and mechanical characteristics behavior under such conditions and to establish the fracture mechanics approaches for assessment of durability, reliability and life time extension of modern energetic equipment (electrolyzers, condensate accumulators, steam heaters, dryers, freezers, generators, separators, etc.). NPP and FPP structural elements long-term service in the hydrogen containing elements is assisted with degradation of physical-mechanical properties (partially, their embrittlement), decrease of the resistance of materials to crack propagation and plasticity, etc. So, the crack resistance, hardness, long term strength parameters of high-nitrogen chromium - manganese steels and their welding joining (as a perspective hydrogen resistance materias) has discussed in the several publications [1-3].

Fracture mechanics approaches and methods of materials with cracks workability assessment

Creations of the methods and numerical schemes for materials workability estimations taking into account the described above hydrogen degradation of physical and mechanical properties is very important. Under the influence of various factors cracks (which exist in the construction elements of NPP and FPP) can propagate during the service.

Crack propagation in the ring or in the pipe can be estimate by the fracture mechanics criteria equations for solid states with cracks [4-6]:

$$\left(\frac{K_{\mathrm{Im}ax}(a,\sigma)}{K_{IC}}\right)^4 + \left(\frac{\sigma}{\sigma_T}\right)^2 = 1 \qquad (1)$$

where σ – service stresses, which arise in the pipe (ring) in the crack plane; $K_{\mathrm{Im}ax} = K_{\mathrm{Im}ax}(\sigma, a)$ – SIF maximum value for crack with length a in the cyclic load conditions; σ_T – yield strength of material; K_{Ic} – crack growth resistance (plane-strain fracture toughness) of material.

The stresses σ is defined by the formula:

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

where p – pressure; R – inner ring radius; t – wall thickness ($a \langle\langle t$).

By formula (Eq. 1) we can define for limit-equilibrium loading $\sigma = \sigma_*$ the critical crack size $a = a_*$, with achievement of which begins the spontaneous (catastrophic) fracture [7].

On the base of formula (Eq. 1) and (Eq. 2) crack value $a = a_*$ for definite $\sigma = \sigma_*$ can be written as:

$$a_* = \eta \frac{K^2{}_{IC}}{\sigma_*^2}, \tag{3}$$

where η – constant, which depends of elastic characteristics of materials and body sizes.

Workability condition of construction with a crack-like defect of size a is:

$$a \langle a_* \tag{4}$$

If in the ring the macrocracks are detected, than limit-equilibrium state of a ring under the inner pressure (or under the actions of centrifugal forces) p can be estimate on the base of the relations (Eq. 1) - (Eq. 3) [4].

For workability assessment of materials with cracks or for determination of plant life extension it is necessary to establish the time (period) of microcracks initiation, which leads to the creation of macro crack with minimal length and period of its development. The initial damages are formed on the dislocations, chemical nonregularities and secondary phases precipitations. By non-destructive control devices (partially by ultrasonic defectoscopy) crack can be detected before critical sizes evaluation. Crack critical size is estimated by the methods, which are based on the fracture mechanics concepts [4], in particular, on the basis of (Eq. 1) – (Eq. 3) and fracture toughness values (crack resistance K_{Ic}).

Very important are the data about changing fracture toughness and other characteristics of material in the conditions of hydrogen containing environments action.

Results of experimental investigation of 18Mn-18Cr steel for retaining rings (specimen dimensions and crack orientation are shown in Fig. 1*a*) deals with the study of change of such physical-mechanical characteristics as E (Young modulus), δ, ψ (macrodeformations), K_{Ic} (fracture toughness) for power engineering purposes in dry air (A) and hydrogen (H), were characterized by the following results [4] (see Table 1): Young modulus practically was not changed, but fracture toughness changed (in hydrogen containing environment it decreased).

It is known also [3], that K_{Ic} (fracture toughness) value for 18Mn–18Cr steel (with σ_B up to 1000 MPa) decrease with the service time (Fig.2) under the hydrogen action due to materials embrittlement. On the other hand - dependence of *Cromanite* steel (another type of high nitrogen steel) plasticity and impact energy of service time in hydrogen is more drastically (Fig.3).

Note the fact (in the first iteration), that Young modulus do not change in hydrogen containing environment, but only fracture toughness changes. In such a case coefficient η in the (Eq. 3) can be assumed independent of hydrogen containing environment ($\eta_H \approx \eta_A$).

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

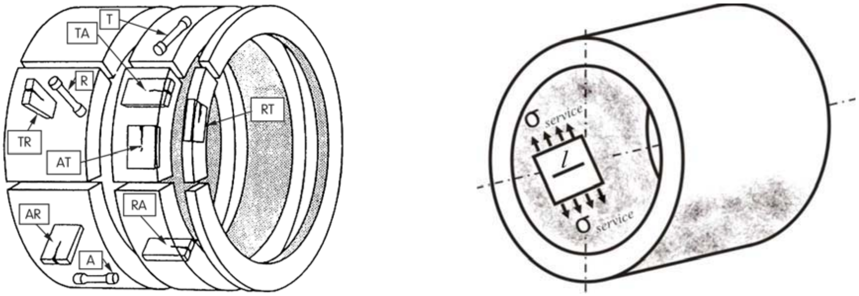
$$a^H{}_* = \eta \frac{K^2{}_{IC(H)}}{\sigma^2_{*(H)}}, \tag{5}$$

$$a^{A}{}_{*} = \eta \frac{K^{2}{}_{IC(A)}}{\sigma^{2}_{*(A)}}, \qquad (6)$$

Table 1.

Physical and mechanical characteristics of 18Mn–18Cr steel air (*A*) and in hydrogen (*H*).

Steel	E (Young modulus) [GPa]	σ_B [MPa]	σ_T [MPa]	δ [%]	Ψ [%]	K_{Ic} [MPa√m]
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. 1. Specimen dimensions and crack orientation for crack resistance parameters measuring (*a*) in the retaining ring wall of turbogenerator (TG) rotor made of the 18Mn–18Cr steels and service stresses, which applied to crack-like defects (*b*).

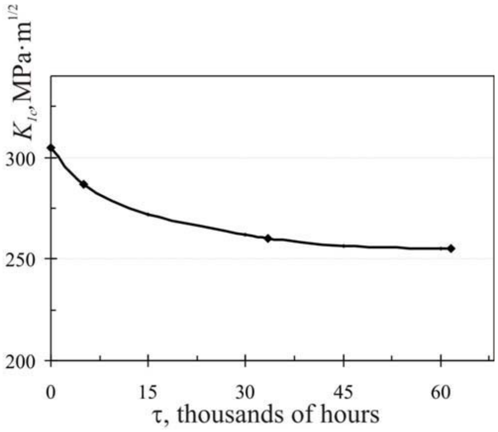


Fig. 2. Changing of 18Mn18Cr steel K_{Ic} (fracture toughness) during long term service in gaseous hydrogen.

Exactly the same approaches are used in some normative documents [8, 9]. Take in to account, that in some cases materials embrittlement after long-term service leads to the cracks appearance with size less, than predicted formula (Eq. 5, 6).

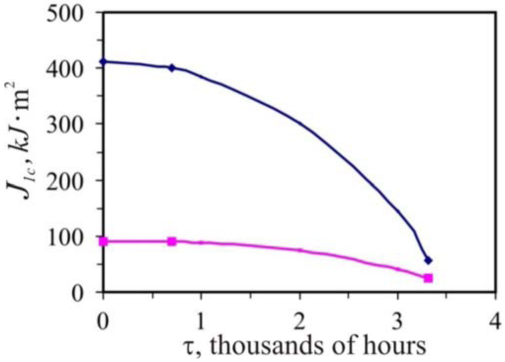


Fig. 3. Changing of 21Cr-6Ni-9Mn-0,37N (♦) and 22Cr-13Ni-5Mn-0,28N (■) steels welding joining J_{Ic} during long term service in gaseous hydrogen.

Thus, changing of K_{IC} value under the hydrogen environment action must be account in the possible crack length (Eq. 9) due to next circumstances (Eq. 7, 8)

$$\frac{K_{IC(H)}}{\sqrt{a_*}(H)} = \frac{K_{IC(A)}}{\sqrt{a_*}(A)} \tag{7}$$

$$\frac{K^2_{IC(H)}}{a_{*(H)}} = \frac{K^2_{IC(A)}}{a_{*(A)}} \tag{8}$$

$$a_{*(H)} = a_{*(A)} \bullet \frac{K^2_{IC(H)}}{K^2_{IC(A)}} \tag{9}$$

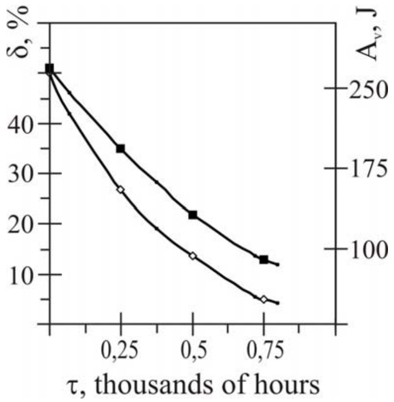


Fig. 4. Dependence of Cromanite steel plasticity (◊) and impact energy (■) of service time in hydrogen.

Beside that

$$P_* = \eta_1 \frac{K^A{}_{IC}}{\sqrt{a_*}}, \qquad P_* \langle \eta_2 \frac{K^H_{ICH}}{\sqrt{a_*}} \tag{10}$$

Various factors can accelerated crack extension with decreasing the time to failure and failure stresses:

$$\sigma_{\max} = P = F(R, l, E, ...) \tag{11}$$

Stresses, which are necessary for crack extension in hydrogen are less than in inert environment

$$P_*^{(H)} \langle P_* \tag{12}$$

$$\frac{K^2_{IC(H)}}{\sigma^2_{service(H)}} = \frac{K^2_{IC(A)}}{\sigma^2_{service(A)}} \tag{13}$$

$$\sigma_{service(H)} = \sigma_{service(A)} \bullet \frac{K_{IC(A)}}{K_{IC(H)}} \tag{14}$$

$$P_*^{(H)} = P_*^{(A)} \bullet \frac{K_{IC(H)}}{K_{IC(A)}} \tag{15}$$

Account of the subcritical crack propagation

Retaining rings workability assessment performed according to normative documents [8, 9], take into account existence (extreme case) of the surface defect, which are considered as plane semielliptical crack with axes a and l, where a - small semiaxes, which coincides with crack propagation direction to the depth of the retaining ring wall and characterizes the crack depth, and l – big semiaxes, which is fixed on the ring surface. 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 exploitation [3]. The critical crack sizes are established according the normative documents of power engineering industry [8, 9].

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

Using Life Assessment Code EPRI IN-103088, IN-1030887 for calculation of retaining ring life with defects we can predict, that with crack depth a_*= 24 *mm* the fracture of retaining ring made from steel 18Mn-18Cr take place after 5 thousand hours of the service [10, 11]. In spite of that, hydrogen factor can decrease drastically at that time, because critical crack size in gaseous hydrogen is less. Thus, it is necessary to take into account the real value of $K_{Ic(H)}$ for working environment.

Assessment of modern steels has shown, that high nitrogen 18Mn-18Cr steel with higher value of fracture toughness enable the safe carrying ability of retaining ring with crack during the higher service time in hydrogen environment, than traditional 8Mn–8Ni–4Cr and 18Mn–4Cr steels [12].

Changing of 21Cr–6Ni–9Mn–0,37N and 22Cr–13Ni–5Mn–0,28N steels welding joining J_{Ic} during long term service in gaseous hydrogen is drastically (Fig.3) [13-15].

In the electrical engineering normative documents for cycled loaded parts has established, that for each a the maximum SIF amplitude ΔK_{1imax} at i–type regime by the kinetic diagrams and Paris equations to determine the actual crack propagation rate

$$V_i(a) = \frac{da}{dN_i} = C\cdot\left(\frac{\Delta K_{1_i}(a)}{\sqrt{1-R}}\right)^m , \tag{16}$$

where N_i – number of cyclic loading by *i*- type, *C* and *m* – constants, *R* – cycles stress ratio, which is equal $K_{1\min}/K_{1\max}$ at $K_{1\min}/K_{1\max} \geq -1$ or – -1 at $|K_{1\min}/K_{1\max}| > 1$.

Number of loading *G(a)* (cycles), during which cracks propagated from initial depth a_0 up to critical a_C at mixed influence of cyclic loading of *k*-type has determined from next relation

$$G(a) = \int_{a_0}^{a_C} \frac{da}{\sum_{i=1}^{k} V_i(a)\cdot n_i^y} a \ , \tag{17}$$

де *Vi(a)* – crack rate t cyclic loading and *i*-type regime, m/cycles; n_i^y - cycles number of *i*-type per year.

Conclusions

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 initial and degradated states. During the exploitation in hydrogen the high nitrogen 18Mn-18Cr steel have higher resistance to hydrogen embrittlement and to stress corrosion cracking, than traditional used nitrogen containing 8Mn–8Ni–4Cr and 18Mn–4Cr steels.

Summary

As under action of hydrogen the cracks initiation and its propagation takes place as a result of imposition of applied and residual stresses, constructions and details counted on work at the high levels of tensions can turn out unreliable, as at extreme operating terms a subcritical crack, that arose up at low tensions, can grow up to the critical size.

Retaining rings workability assessment made from the new 18Mn-18Cr steel performed according to normative documents, take into account existence (extreme case) of the surface defect, which are considered as plane semielliptical crack with axes *a* and *l*, where *a* - small semiaxes, which coincides with crack propagation direction to the depth of the retaining ring wall and characterizes the crack depth, and *l* – big semiaxes, which is fixed on the ring surface. The most frequent are the following axis relations *a*=(0,15–0,35)*l.* A clear fracture mode transition occurred from microvoid coalescence to cleavage with hydrogen additions. For hydrogen embrittlement in the range of 60…150 MPa· $m^{1/2}$ values a plateau crack extension rate in high nitrogen steels can arise of about 1…7 nm/s. For definition of critical moment of state in gaseous hydrogen, which prevents the fracture (durability closing) of retaining ring unit made from 18Mn-18Cr the stress intensity factor (SIF) at plane-strain fracture $K_I(a,\sigma)$ has used. The critical state is consider such, when on the crack contour the maximum SIF value achieves the fracture toughness K_{Ic} in hydrogen. Thus, for estimation of hydrogen influence on the workability of high stressed parts of power plant unit equipment with welding joining it is necessary to use the crack growth resistance parameters.

References

[1] A.I. Balitskii: Mater. Sci. Forum Vol. 318-320 (1992), p. 539.

[2] A.I. Balitskii, M.Diener, R.M Magdowski., V.I. Pokhmurski, M.O Speidel: Mater. Sci. Forum Vol. 318-320 (1992), p. 401.

[3] *Fracture mechanics and strength of materials: Reference book* / Editor-in-chief V. V. Panasyuk. *Vol. 8: Strength of materials and durability of structural elements of nuclear power plants*/ A.I.Balitskii, O.V.Makhnenko, O.A.Balitskii, V.A.Grabovskii, D.M.Zaverbnyi, B.T.Timofeev. Editor A. I. Balitskii – Kyiv: PH "Akademperiodyka"(2005).

[4] A.I. Balitskii, V.V. Panasyuk: Problems of Strength (2008), in press.

[5] A.Neimitz *Ocena wytrzymałości elementów konstrukcyjnych zawierających pęknięcia (podstawowe elementy procedur SINTAP).* – Kielce: Politechnika Swiętokrzyska, (2004).

[6] V.V. Panasyuk *Strength and fracture of solids with cracks.* – Lviv: National Academy of Sciences of Ukraine, Karpenko Physico-Mechanical Institute.(2002).

[7] Fracture mechanics and strength of materials: Reference book / Editor-in-chief V. V. Panasyuk. Vol. 7: Reliability and durability of structural elements for heat-and-power engineering equipment / I.M. Dmytrakh, A.B. Vainman, M.H. Stashchuk, L. Toth / Editor of the volume I.M. Dmytrakh – Kyiv: PH "Academperiodyka"(2005).

[8] Methodical recommendations of technical state evaluation of turbogenerator rotor retaining rings (normative document SNOU-N EE 45.301:2006)/ Loshak O.S., Balitskii A.I., Pulkas L.G., Lizunov S.O., Ripey I.V., Gurina O.V. // Ministry of fuel and energetic of Ukraine.- Decision of Minister N 432, 9.11.2006.- Kyiv, Ukraine, GRIFRE.- 32 P.

[9] Methodical recommendations of technical state diagnostic and evaluation of life time of steam turbine cast vessel details (normative document SNOU-N EE 30.304:2007)/ Loshak O.S., Balitskii A.I., Pulkas L.G., Lizunov S.O., Ripey I.V., Gurina O.V. // Ministry of fuel and energetic of Ukraine.- Decision of Minister N 124, 1.03.2007.- Kyiv, Ukraine, GRIFRE.- 39 P.

[10] *Recommendation for Stress Corrosion Testing Using Pre-Cracked Specimens.* – ESIS-Procedures. – P 4–92 D.(1992).

[11] A. Balitskii: *Zeszyty Naukove Politechniki Opolskiej.- Seria: Mechanika*, z.79, Nr kol. 300/ (2005), s.33.

[12] A. Balitskii. Hydrogen embrittlement and cracking of 18Mn-4Cr steels// Fracture of nano and engineering Materials.- Edited by E.E.Gdoutos.- Springer.-Dordrecht.-(2006).- p.981.

[13] B.P. Somerday, D.K. Balch, P. Novak, P. Sofronis: Abstract Book of 11th International Conference on Fracture.- Turin, Italy, March 20–25 (2005). – p. 672.

[14] *S.L. Robinson,* B.P. Somerday, N.R. Moody: Abstract Book of 11th International Conference on Fracture.- Turin, Italy, March 20–25 (2005). – p. 669.

[15] *K.A. Nibur*, D.F. Bahr, B.P. Somerday. Deformation behavior in materials susceptible to hydrogen embrittlement // Abstract Book of 11th International Conference on Fracture.- Turin, Italy, March 20–25 (2005). – p. 663.