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A FATIGUE INITIATION PARAMETER IN PRESENCE OF HYDROGEN

PARAMETRI INICIJACIJE ZAMORA U PRISUSTVU VODONIKA

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- Notch Stress Intensity (NSI) factor

Abstract

Fatigue initiation resistance has been determined on API 5L X52 gas pipe steel using Roman Tile (RT) specimen and acoustic emission to detect fatigue initiation. Results for intact and hydrogen electrolytically charged specimens are compared. After hydrogen embrittlement fatigue initiation time is reduced for 3 times. Notch Stress Intensity (NSI) factor is applied as parameter of fatigue initiation process. Since hydrogen is localised in the area with high hydrostatic pressure, definitions of local effective stress and distance have been modified when hydrogen is absorbed, what is explained by the effect of hydrogen on the occurrence of a ductile-brittle transition.

Ključne reči

- otpornost prema inicijaciji zamora
- API 5L X52 čelik
- faktor intenziteta napona u zarezu (NSI)

Izvod

Otpornost na inicijaciju zamora je određena za čelik API 5L X52 za cevi za gasovode primenom epruveta lučnog crepa (RT) i akustične emisije za utvrđivanje inicijacije zamora. Upoređeni su rezultati za epruvete netretirane i elektrolitički zasićene vodonikom. Posle vodonične krtosti vreme za inicijaciju zamora smanjeno je za 3 puta. Kao parametar za proces inicijacije zamora je primenjen (NSI) faktor intenziteta napona u zarezu. Kako je vodonik lokalizovan u zoni visokog hidrostatičkog pritiska, definicije lokalnog efektivnog napona i rastojanja su modifikovane zbog prisustva vodonika, što je objašnjeno pojavom plastično-krtog prelaska zbog uticaja vodonika.

INTRODUCTION

In presence of hydrogen, material mechanical properties are degraded, including pipe steels, due to the hydrogen embrittlement phenomenon, /1-3/. This degradation needs to be taken into account for safe design of pipe or tank containing hydrogen submitted to non-stationary stresses induced by daily internal pressure modifications. Mechanical fatigue in presence of hydrogen exhibits a synergistic effect, fatigue crack growth is generally strongly accelerated from 5 to 10 times for the same stress amplitude.

In this paper, we present the influence of hydrogen fatigue crack initiation in an API 5L X52 steel. Crack initiation emanates from a notch which simulates a gouge. Acoustic emission has been used to detect crack initiation. Fatigue resistance to crack initiation is presented as maximum notch stress intensity factor versus number of cycles. Maximum notch stress intensity factor has been modified to take into account hydrogen embrittlement effect, important for fatigue crack initiation, using the idea of specific effective distance in Kim's model. The influence of hydrogen concentration is described by an analytical model presenting hydrogen concentration as function of number of cycles to initiation and its effect on a brittle-ductile transition, /1/.

INFLUENCE OF HYDROGEN ON MECHANICAL PROPERTIES OF STEEL API 5L X52

The object of study is the API 5L X52 grade pipeline steel. Its chemical composition is given in Table 1.

Table 1. Chemical composition of steel API 5L X52, Ø610 mm.
Tabela 1. Hemijski sastav čelika API 5L X52, Ø610 mm

C	Mn	Si	Cr	Ni	Mo	S	Cu	Ti	Nb	Al
0.206	1.257	0.293	0.014	0.017	0.006	0.009	0.011	0.001	<0.03	0.034

Hydrogen absorption in X52 steel by cathodic polarisation

Specimens are hydrogen charged at constant potential of polarisation, which is slightly negative than free corrosion potential for this steel. The hydrogen-charging process is controlled by the cathodic polarisation current.

Hydrogen concentration in metal has been determined based on hydrogen discharging process under anodic polarisation using hydrogen electrochemical oxidation method, /1/, and standard three-electrode electrochemical cell.

Based on experimental results, the increase in hydrogen concentration in metal versus exposition time of specimens in the hydrogenating conditions can be described by:

$$C_H = A \cdot 10^{-6} \cdot \tau^m \quad (\text{mol/cm}^3) \qquad (1)$$

where A and m are constants. They depend on the applied load (Table 2).

Table 2. Meanings of constants in Eq. (1) for steel API 5L X52.
Tabela 2. Veličine konstanti u jedn. (1) za čelik API 5L X52

Without loading	With loading
$C_H = 0.253\cdot10^{-6}\cdot\tau^{0.24}$	$C_H = 0.300\cdot10^{-6}\cdot\tau^{0.57}$

For example, in steels X52 for $t \geq 100$ hours the difference between hydrogen concentration in unloaded and stressed metal can be more than five times, Fig. 1. This fact is important for the development of a reliable procedure of maintenance of pipelines in hydrogen rich environment.

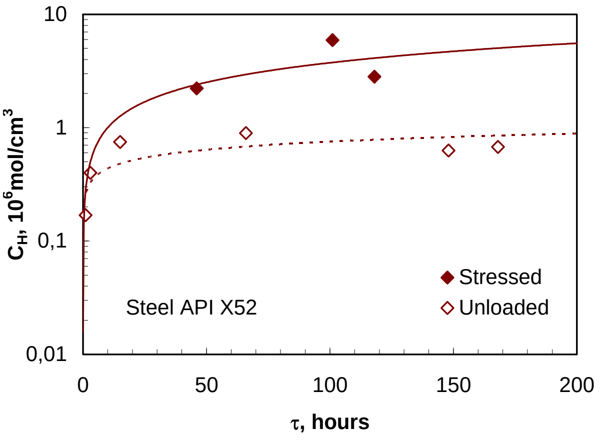

Figure 1. Evolution of hydrogen concentration versus time of hydrogen charging under cathodic polarisation.
Slika 1. Zavisnost koncentracije vodonika od vremena apsorpcije vodonika tokom katodne polarizacije

Influence of hydrogen on tensile properties

Classical tensile properties such as yield stress and ultimate strength increase also when hydrogen is absorbed in steel, Table 3. Increase of yield stress is small (2.5%), but reduction of elongation at fracture is pronounced, 38%.

Table 3. Tensile properties of X52 steel in air and with hydrogen absorbed.
Tabela 3. Zatezne karakteristike čelika X52 na vazduhu i sa apsorbovanim vodonikom

	Yield stress σ_Y, MPa	Ultimate strength σ_{UTS}, MPa	Elongation at failure, A, %
Air	410	528	15.8
Hydrogen	420	570	9.76

Stress-strain is fitted using Ludwik's law:

$$\sigma = K\varepsilon^n \tag{2}$$

Effect of hydrogen on fatigue resistance of X52 steel

The three-point bend test set-up for Roman Tile (RT) specimen, similar to that for static testing, and devices for fatigue initiation tests installed on closed loop hydraulic testing machine of 10 kN are presented in Fig. 2.

The applied load, frequency and fatigue sinusoidal cycle were monitored on the control panel. Hydrogen charging was made using the same cell supplied with NS4 solution. Initiation is detected by acoustic emission by two sensors.

The testing system is presented in Fig. 3. The numbers refer to 1–Roman tile specimen; 2–Actuator; 3–Corrosion cell with NS4 solution; 4–pH electrode; 5–Reference electrode; 6– Platinum auxiliary electrode; 7–AE sensors.

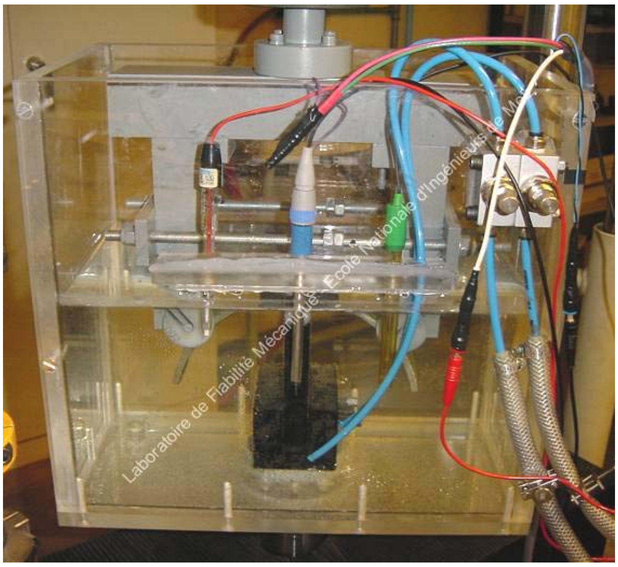

Figure 2. Devices used for fatigue tests under hydrogen presence.
Slika 2. Uređaji za ispitivanje zamora u prisustvu vodonika

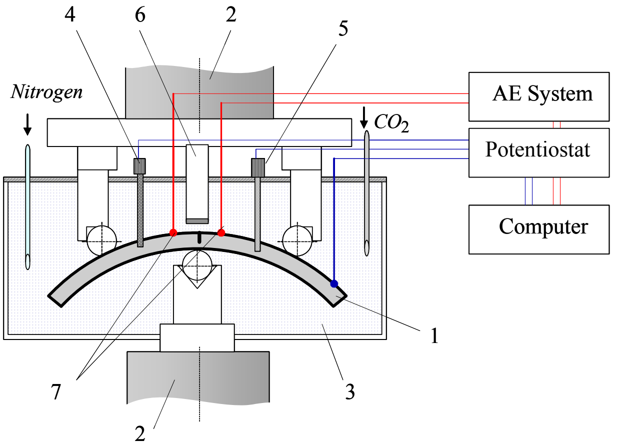

Figure 3. Roman Tile specimen fixture and assembly positions of electrodes for hydrogen charging.
Slika 3. Sklop nosača epruvete tipa lučnog crepa. Položaj epruvete pri izlaganju vodoniku

Specified test conditions are given in Table 4.

Table 4. Fatigue test conditions.
Tabela 4. Uslovi ispitivanja zamorom

Shape of the cycle used	Sinus
Frequency	0.05 Hz
Load ratio	0.5
Working potential	–1 Vsce
Electrolytic solution	Natural Soil 4 (NS4)
Solution pH	between 6.66 and 6.74

Wöhler curves were drawn at both initiation and failure. Results are presented in a bi-logarithmic graph of stress amplitude versus number of cycles to failure (Figs. 4 and 5).

The classical power fit is corresponds to Basquin's law:

$$\Delta\sigma = \sigma'_f (N_R)^b \tag{3}$$

where σ'_f is the fatigue resistance and b the Basquin's exponent.

Table 5. Fatigue endurance parameters at failure, with and without hydrogen charging for X 52.
Table 5. Parametri zamorne čvrstoće pri lomu za X 52 na vazduhu i sa apsorbovanim vodonikom

	Air	H_2
Fatigue resistance σ'_f	336 MPa	301 MPa
Basquin's exponent b	–0.0202	–0.012

We note that fatigue resistance is very sensitive to hydrogen presence. For a stress range of 266 MPa, the life duration is divided by 3.5. This ratio is not constant and decreases when life duration increases.

INFLUENCE OF HYDROGEN ON FATIGUE INITIATION OF STEEL API 5L X52

Fatigue is characterized by two parts, fatigue initiation and crack propagation until failure. The ratio, number of cycles to initiation N_i to number of cycles to failure N_r, vary in range 0.6–0.9. This ratio increases as life duration increases and at endurance limit, test time is spent mostly to initiate fatigue crack. Generally fatigue resistance curves are drawn at failure. Fatigue initiation curves are seldom and need additional devices to detect crack initiation (Fig. 4).

Obtained results obey a power law like the Basquin:

$$\Delta\sigma = \sigma_i'(N_i)^{\beta} \tag{4}$$

where σ'_i is the fatigue initiation resistance and β an exponent (Table 6). $\Delta\sigma$ is the gross stress range.

Evolution of ratio N_i/N_r versus number of cycles to failure is plotted in Fig. 5. We note that fatigue crack propagation is faster in presence of hydrogen because the difference N_r–N_i is strongly reduced. This difference corresponds to number of cycles of propagation. For that the ratio N_i/N_r is higher in presence of hydrogen but exhibits larger scatter.

Table 6. Fatigue initiation resistance and β exponent for steel X52.
Table 6. Otpornost prema inicijaciji zamora i β eksponent za čelik X52

	Fatigue initiation resistance σ'_i, MPa	Exponent β	R^2
Intact	336.05	–0.0202	0.8843
With hydrogen	301.14	–0.0121	0.9502

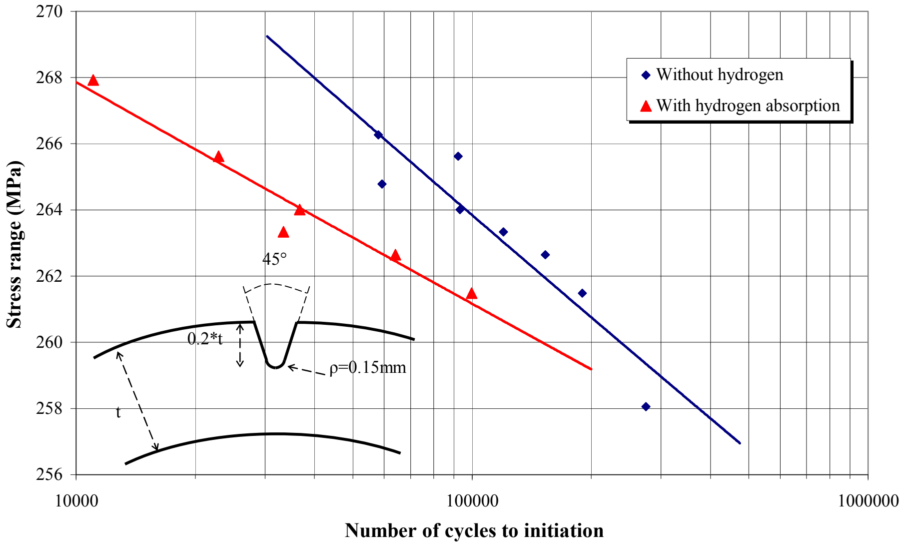

Figure 4. Fatigue initiation resistance curves for X52, with and without hydrogen absorption.
Slika 4. Kriva otpornosti na inicijaciju zamora čelika X52, bez i sa apsorbovanim vodonikom

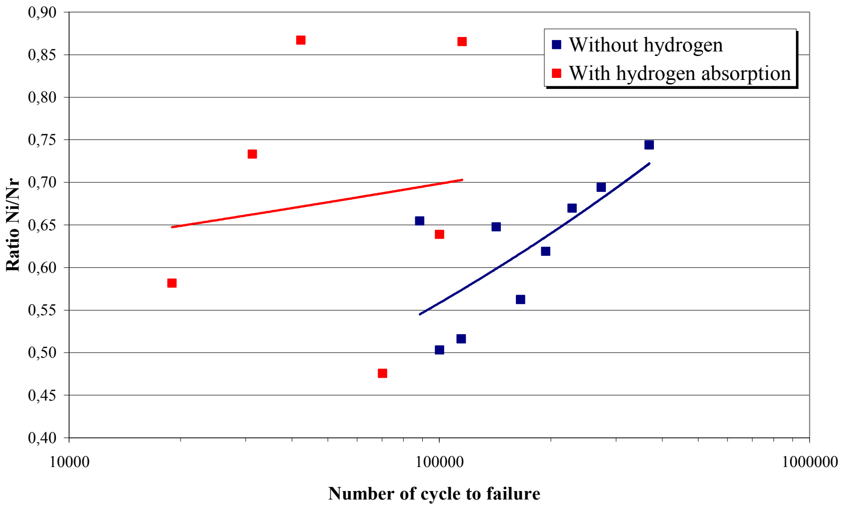

Figure 5. Evolution of ratio N_i/N_r versus number of cycles to failure.
Slika 5. Zavisnost odnosa N_i/N_r od broja ciklusa do loma

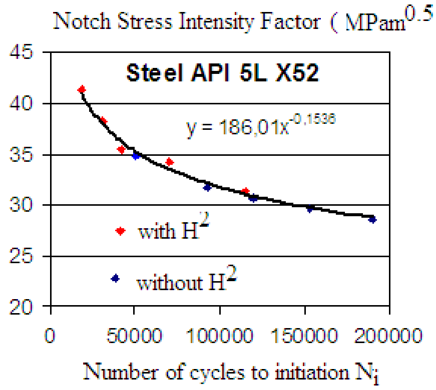

Figure 6. Fatigue initiation curve; Notch Stress Intensity factor at maximum load versus number of cycles to initiation.
Slika 6. Kriva inicijacije zamora, faktor intenziteta napona u zarezu pri maksimalnom opterećenju u zavisnosti od broja ciklusa do inicijacije

Fatigue resistance and fatigue initiation resistance curves in Figs. 4 and 6 are drawn using the gross stress range versus respective number of cycles to failure N_r and number of cycles to fatigue initiation. However, the tested specimens are not smooth but have a notch of radius 0.15 mm in order to simulate a pipe defect such as a gouge. In this case, a local parameter is needed taking into account the stress distribution corresponding to such a stress concentration. We have chosen to use the notch stress intensity (NSI) factor for fatigue initiation parameter based on Volumetric Method and already practically used, /4/.

This assumption is related to the fact that hydrogen concentration is sensitive to the hydrostatic pressure σ_h. The definition of the hydrogen effective distance $X_{ef,H}$ is given also by the minimum of the relative hydrostatic pressure gradient and can be seen in the same figure.

For a fatigue initiation model, we have kept the original idea of Kim et al., /5/, i.e. the existence of a specific hydrogen effective distance, but we have made the assumption that this distance is related to the volume where the hydrostatic stress is high.

This assumption is related to the fact that hydrogen concentration is sensitive to hydrostatic pressure σ_h. The definition of hydrogen effective distance $X_{ef,H}$ is given also by the minimum of the relative hydrostatic pressure gradient and can be seen in the same figure.

Local fatigue criterion needs a second parameter corresponding to the effective stress. The choice has been made on maximum stress of the opening stress distribution $\sigma_{max,H}$ and is based on experimental results of Matvienko, /6/, who detected a hydrogen concentration peak close to the maximal stress. Finally the "hydrogen notch stress intensity factor" is then given by the following formula:

$$K_{\rho,H} = \sigma_{\max,H}\sqrt{2\pi X_{ef,H}} \qquad (5)$$

Values of notch stress intensity factor for test without hydrogen absorption and with hydrogen absorption (Eq. 5) are presented versus the number of cycles to initiation in Fig. 6. Data are fitted with a power function;

$$K_{\rho,i} = R_{f,i}(N_i)^c \qquad (6)$$

where $K_{\rho,i}$ is the Notch Stress Intensity factor at maximum load with $\Delta K_{\rho,i} = \Delta K_{\rho,H}$ for test with hydrogen absorption and $\Delta K_{\rho,i} = \Delta K_{\rho}$ for the test without hydrogen absorption.

$R_{f,i}$ is a new parameter that we named "Resistance to fatigue initiation"; ($R_{f,I} = 186$ MPa√m) and c is an exponent ($c = 0.153$). For a large number of cycles to initiation (one million, for example) we define a conventional fatigue initiation threshold $\Delta K_{\rho,th}$ which is equal in considered case to $K_{\rho,th} = 22.31$ MPa√m.

The fact that according to the presence or not of hydrogen need to change the definition of the notch stress intensity factor as well, we use the value at maximum load, will be discussed later.

The coefficient of correlation of the data fitting is high ($R^2 = 0.973$) and confirms the significance of this approach.

CONCLUSION

Acoustic emission allows to draw fatigue initiation curves. Absorption of hydrogen reduces considerably the time to fatigue initiation in X52 steel (about 3 times). The notch stress intensity factor is a parameter which has been used for describing the fatigue initiation curves. After hydrogen absorption, the concept of notch stress intensity factor has been modified in order to take into account a ductile to brittle transition with hydrogen concentration. Fatigue initiation curves allow to determine a fatigue initiation threshold which is helpful for defect assessment and particularly to define a sleeping defect.

REFERENCES

1. Capelle, J., Gilgert, J., Dmytrakh, I., Pluvinage, G., *Sensitivity of pipelines with steel API 5L X52 to hydrogen embrittlement*, International Journal of Hydrogen Energy 33, Issue 24 (2008), pp.7630-7641.
2. Capelle, J., Dmytrakh, I., Pluvinage, G., *Electrochemical Hydrogen Absorption of API X52 Steel and its Effect on Local Fracture Emanating from Notches*, Structural Integrity and Life, Vol.9, No1 (2009), pp.3-6.
3. Capelle, J., Gilgert, J., Dmytrakh, I., Pluvinage, G., *Hydrogen effect on fatigue and fracture resistance of a pipe steel*, Struc. Int. and Life, Vol.9, No1 (2009), pp.9-14.
4. Boukharouba, T., Tamine, T., Niu, L., Chehimi, C.,.Pluvinage, G., *The Use of Notch Stress Intensity Factor as a Correlating Parameter for Fatigue Crack Initiation*, Engng. Fracture Mechanics, Vol. 52, N°3 (1995), pp.503-512.
5. Kim, Y., Chao, Y., Pechersky, J.M.J., Morgan, M.J., *On the Effect of Hydrogen on the Fracture Toughness of Steel*, International Journal of Fracture (2005), 134:339-347.
6. Matvienko, Yu.G., *The Concept of Damage Evolution in Fracture Mechanics*, Proc. of International Symposium on Chemical Mechanical Polishing, Cheongju, Sough Korea, 27 August 2005: RIIST, 23-32 (2005).