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STRUCTURAL LIFE ASSESSMENT OF OIL RIG PIPES MADE OF API J55 STEEL BY HIGH FREQUENCY WELDING

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Preliminary notes

Structural life of welded pipes made of API J55 steel by high-frequency (HF) welding has been evaluated. Experimental tests of base metal mechanical properties, including fatigue properties, were conducted on pipes after 70 000 hours of service in an oil drilling rig. The fatigue crack growth rate and fatigue threshold is obtained using the pre-cracked Charpy specimens. The number of cycles to the final fracture is then calculated using initial and critical crack depths. Based on the number of cycles to the final fracture and the remaining fatigue lifetime of pipes with axial outer surface crack are determined. It was shown that the remaining fatigue lifetime is more sensitive to the changes in the stress range than to the initial crack depth.

Keywords: *axial surface crack, number of cycles to failure* N_f, *oil rig pipes*

Procjena integriteta bušećih cijevi od API J55 čelika zavarenih VF postupkom

Prethodno priopćenje

Predmet rada je analiza integriteta i procjena preostalog vijeka zaštitnih zavarenih cijevi izrađenih od čelika API J55 visokofrekventnim kontaktnim zavarivanjem (VF). Eksperimentalna ispitivanja mehaničkih svojstava osnovnog materijala i ispitivanja na zamor izvršena su na cijevima povučenim iz naftne bušotine nakon 70 000 sati rada. Ispitivanje brzine rasta zamorne pukotine $\mathrm{d}a/\mathrm{d}N$ i opsega faktora intenzivnosti naprezanja na pragu zamora, ΔK_{th}, izvedeno je na standardnim Charpy epruvetama sa zarezom. Broj ciklusa do loma je izračunat na osnovi početne i krajnje kritične duljine pukotine. Na osnovi broja ciklusa do loma i broja ciklusa opterećenja određen je preostali vijek cijevi s vanjskom aksijalnom površinskom pukotinom. Pokazano je da je preostali vijek osjetljiviji na promjenu opsega opterećenja nego na početnu dubinu pukotine.

Ključne riječi: *aksijalna površinska pukotina, broj ciklusa do loma* N_f, *cijevi za naftne bušotine*

1 Introduction

Pipelines are the most economical and safest way for oil and gas transport. They may consist of welded or seamless pipes. Standard API 5CT generally specifies pipes and fittings dimensions and their mechanical properties. However, majority of failures of welded steel pipelines are due to insufficient resistance to crack initiation and growth, poor quality of welded joints and reduced capacity due to corrosion damage, [1].

The welding parameters selection is very important for obtaining an appropriate weld quality, [2]. Guaranteed quality of welds in welded pipe production is achieved by controlling each operation in production process of every single pipe. During its life cycle, welded casing pipes used for oil rigs are exposed to corrosion effects, augmented with high pressure and high temperature environment. That is why the casing pipes are very sensitive to degradation of the material, which is often preceded by errors in their design and construction, production and installation defects, unforeseen exploitation conditions and working environment conditions.

The reliability of the oil rigs system is very important not only for the continued exploitation, but also for the environmental protection. Therefore, the standards and recommendations for assessing the effect of cracks on the integrity of welded pipes have been developed. Some of them deal with an effect of through-wall cracks on the integrity of the pipes that are loaded by the internal pressure and bending [3]. However, welded casing pipes can also have an axial surface crack on the inside and/or outer surface, and can be subjected to different loads, including external and internal pressure, as well as axial loads (e.g. due to structure weight).

In order to keep pipeline safe and reliable in operation, its integrity assessment is of utmost importance [4 ÷ 9]. The essential part of integrity assessment is to estimate precisely the maximum allowed pressure, as well as to evaluate fracture mechanics parameters, like stress intensity factor and *J*-integral. Contrary to inner circumferential and axial semi-elliptical cracks [4 ÷ 17], there are only a few papers dealing with the outer cracks [13]. So far, there are no detailed 3D finite element analyses of wide spectrum of outer surface cracks.

In recent decades, many studies have been conducted in order to develop a model for residual life assessment in high cyclic fatigue. Previously developed models are based on continuum mechanics [18], many of them using the concept of short crack, but only a few include microstructural parameters [19]. Recently, models for life prediction for low cycle fatigue have been developed, [20, 21]. It is important to notice that environment potentially has a significant detrimental effect on structural integrity [22]. Low-alloyed steels are nowadays widely used for pipelines, due to optimal combination of mechanical properties and weldability, but their application for oil and gas pipelines is still related to failures. Thus, specific models for residual life have been developed, [24]. Many laboratory studies, as well as recent experience, have shown that work environment containing water can significantly increase fatigue crack growth rate in ferrite steels, [25]. There are numerous models for life prediction at the cumulative fatigue damage, none of which is widely accepted. Therefore, further studies of fatigue were conducted, [26], mostly with the constant amplitude cyclic loads in order to simplify the analysis, [27].

This paper presents the integrity analysis and assessment of residual life of welded casing pipes with the axial surface crack, made of API J55 steel. Analysed pipe was in operation at an oil rig and was withdrawn during the process of reparation, after a period of about 70 000 hours (about 8 years). This period is much shorter than the designed service life, which is up to 30 years.

In order to estimate the residual life of pipes with axial surface crack the values of coefficients C_p and m_p are determined, as well as fatigue crack growth rate (da/dN), by testing pre-cracked Charpy specimens in three point bending. The number of cycles to the final fracture is then calculated by using the initial and critical crack depth. Based on the number of cycles to the final fracture and the number of stress cycles (determined by the number of working hours per year), the number of remaining fatigue lifetime years of pipes with the axial surface crack at the outer pipe surface is determined.

2 Experimental procedure for fatigue crack growth

Pressured welded pipes can be very sensitive to cracks and their stable or unstable growth. Therefore, it is important to identify reliable criteria for assessing the remaining life of cracked pressured pipes. In order to understand better crack initiation and growth in casing pipes exposed to high pressures, high temperatures and chemically aggressive work environment, the material fracture resistance should be expressed quantitatively. Therefore, the critical stress intensity factor K_{Ic}, the crack growth resistance curve (J–Δa), the fatigue crack growth rate, da/dN and the stress intensity factor range at the fatigue threshold, ΔK_{th}, are experimentally determined.

The ASTM Standard E647, [28], provides the procedure for fatigue crack growth rate, da/dN, testing and measurement, as well as the procedure for calculation of stress intensity factor range, ΔK. Standard Charpy specimens with fatigue crack in the base material (2 mm long) and with the foil RUMUL RMF A-5 for the continuous monitoring of crack length are used. Tests were conducted at room temperature with three-point bending in load control, using the high-frequency resonant pulsator CRACKTRONIC.

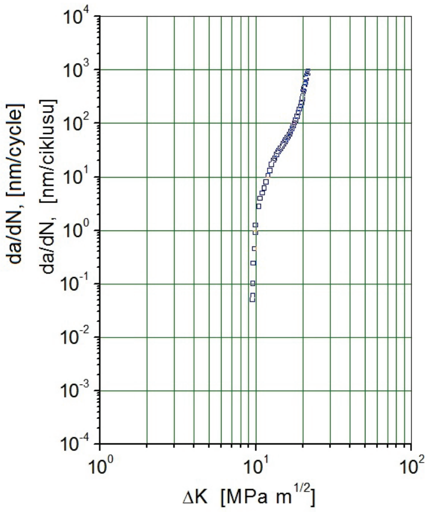

Figure 1 Curve da/dN–ΔK -notch in the base material, pipe from service

The fatigue crack growth rate, da/dN, for specimens taken from the exploited pipe, is shown in Fig. 1, in dependence on the stress intensity factor range, ΔK.

Obtained parameter values from Paris equations are: coefficient C_p=2,11×10^{-15} (m/(cycles·MPa·m$^{1/2}$)), exponent m_p = 6,166, fatigue threshold ΔK_{th} = 9,5 MPa·m$^{1/2}$, and fatigue crack growth rate, da/dN = 3,75×10^{-8} (m/cycles) [29].

3 Assessment of pipeline residual life and integrity

Main technical characteristics of the oil rigs from which the tube was withdrawn after 70 000 hours of exploitation are as follows:

- Layer pressure (Kp-31):
  maximum = 10,01 MPa, minimum = 7,89 MPa.
- layer temperature: ϑ = 65 °C,
- number of strokes of pump rod: n_{PR}= 9,6 min^{-1}.

The test pipes had a diameter of Ø139,7 mm and nominal wall thickness of 6,98 mm. The working stresses and the amplitude in tangential direction were:

$$\sigma_{\max} = \frac{2 p_{\max} \cdot R}{t} = \frac{2 \cdot 10{,}01 \cdot 66{,}36}{6{,}98} = 190\,\text{MPa},$$
$$\sigma_{\min} = \frac{2 p_{\min} R}{t} = \frac{2 \cdot 7{,}89 \cdot 66{,}36}{6{,}98} = 150\ \text{MPa}, \tag{1}$$
$$\Delta\sigma = \sigma_{\max} - \sigma_{\min} = 40\ \text{MPa},$$

where: R is the mean pipe radius, t pipe thickness, p layer pressure, 2 is correction factor due to cross section weakening (crack length 3,5 mm – 50 %).

Crack growth under variable loading has a crucial influence on structural life. Therefore, to estimate the number of cycles to fracture occurrence one should determine the relationship between the stress state at the crack tip, determined by the stress intensity factor range ΔK, and the crack growth rate, da/dN. The crack growth to its critical size primarily depends on external loads and crack growth rate. Paris equation for metals and alloys, defines the relationship between fatigue crack growth da/dN and stress intensity factor range ΔK, using the coefficient C_p and the exponent m_p:

$$\frac{\mathrm{d}a}{\mathrm{d}N} = C_p \cdot (\Delta K)^{m_p} = C_p \cdot \left(1{,}12 \cdot \Delta\sigma \cdot \sqrt{\pi \cdot a}\right)^{m_p}. \tag{2}$$

By the integration of Paris equation from the initial crack length, a_0, to a critical crack length, a_{cr}, the total number of cycles N is obtained, from initiation of a fatigue crack to its critical depth.

$$N = \frac{2}{\left(m_p - 2\right) \cdot C_p \cdot \left(1{,}12 \cdot \Delta\sigma\right)^{m_p} \cdot \pi^{\frac{m_p}{2}}} \cdot \left(\frac{1}{a_0^{\frac{m_p-2}{2}}} - \frac{1}{a_{cr}^{\frac{m_p-2}{2}}} \right), \tag{3}$$

where: a_0 = 2 mm (a/t = 0,285), initial crack length (standard 3PB specimen, Fig. 1), and a_{cr} is the critical crack length:

$$a_{cr} = \frac{1}{\pi} \cdot \left[\frac{K_{Ic}}{1{,}12 \cdot \sigma_c} \right]^2 = \frac{1}{\pi} \cdot \left[\frac{91{,}4}{1{,}12 \cdot 380} \right] = 14{,}4\,\text{mm}, \tag{4}$$

where K_{Ic} is the fracture toughness, and σ_{c} is the critical stress, i.e. the yield strength, [29].

Dependence of stress intensity factor on crack angle φ is given for different crack shapes and crack depths c/t = 0,2 ÷ 0,8 in [30]. For $2a/c = 3$ and $a_{\mathrm{cr}} = 14{,}4$ mm, the critical crack depth is 4,8 mm.

The fracture toughness has been evaluated by using the *J–R* curve, obtained by testing CT specimens, i.e. by using the formula:

$$K_{\mathrm{Ic}} = \sqrt{\frac{J_{\mathrm{Ic}} \cdot E}{1-\nu^2}}. \qquad (3)$$

For $J_{\mathrm{Ic}} = 35{,}8$ kN/m, one gets $K_{\mathrm{Ic}} = 91{,}4\ \mathrm{MPa{\cdot}m^{1/2}}$.

By applying eqn (3) one can get:

$N = 180{,}85 \times 10^6$ cycles.

For annual working hours, T_y = 8760 h, number of cycles is:

$$N_y = 60 \cdot T_y \cdot n = 60 \cdot 8760 \cdot 9{,}6 \approx 5 \times 10^6 \text{ cycles/year.}$$

The remaining fatigue life, n, as given in years of exploitation, depending on the crack depth, and stress amplitude is shown in Fig. 2.

As an example, the remaining fatigue life is given crack depth 2 mm and $\Delta\sigma = 40$ MPa:

$$n = \frac{N}{N_y} = \frac{180{,}85 \times 10^6}{5{,}046 \times 10^6} = 35{,}71 \text{ years.}$$

Fig. 2 provides data (points) for the remaining life depending on the stress amplitude and initial crack depth.

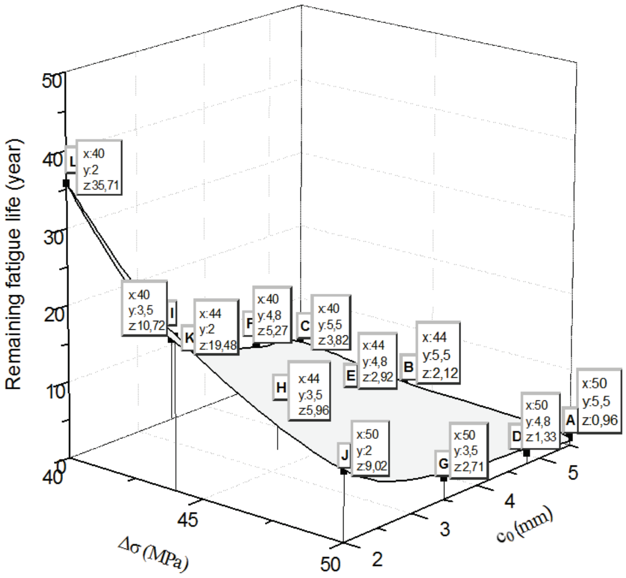

Figure 2 Residual fatigue life dependence on the stress range and initial crack depth. Point coordinates represent (stress range – *x*, initial crack depth – *y*, and residual fatigue life – *z*)

The remaining fatigue life is on the safe side, because it is calculated assuming that welded casing pipes in oil rigs operate in extreme conditions and that the maximum damage made on the outer surface is larger than damage made on the vessel for experimental testing - points in Fig. 2. An analysis of the chart given in Fig. 2, shows that the remaining fatigue life is more sensitive to changes in the stress range than to the reference value of the external damage - compare the curve ABC, DEF, GHI and JKL. Having in mind predicted severe exploitation conditions (high pressure and temperature and chemically aggressive work environment), significantly lower remaining fatigue life of welded casing pipes is expected.

4 Conclusions

Based on results presented here, one can draw the following conclusions:

As predicted by the Paris law, the fatigue crack growth rate increases with increasing service time further reducing the resistance to crack growth, while the fatigue threshold value (ΔK_{th}) remains about the same.

Crack depth under variable loading has a significant influence on structural life. However, by the analysis of the chart given in Fig. 2, it is evident that the remaining fatigue life is more sensitive to the changes in the stress range than to the initial crack depth.

To illustrate this conclusion one can see that for the fixed crack depth, e.g. 2 mm, the increase of stress amplitude of only 25 % reduces remaining life to 25 %. Similar is the case with deeper cracks. Having this in mind, one can also conclude that stress amplitude control is more important for this type of problem than crack depth monitoring.

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