Prediction of corrosion fatigue crack propagation life for welded joints under cathodic potentials

Marek Jakubowski
Gdańsk University of Technology

ABSTRACT

Enhancement of corrosion fatigue crack growth rates by cathodic protection is observed below the optimum applied potential of the protection. An empirical formula for the effect of the protective potential below -0.8 V ($Ag/AgCl_2$) on the crack growth rates for some classes of shipbuilding steels tested in salt water has been derived for medium and high value ranges of the stress intensity factor. For the lower value range the formula reflects a relatively steep decrease of the crack growth rates (against the same values in air) along with decreasing the stress intensity factor range. A simple formula for the corrosion fatigue crack propagation life under cathodic potential has been derived for fillet welded joints in bending by integrating the corrosion fatigue kinetic characteristics. The new formula for the stress intensity factor range has been used for the bent joint. The predicted "S-Np" curves have been compared with experimental data, taken from literature, for two different values of both applied potential and the plate thickness. The predicted curves correspond approximately to lower bounds of the test results. The presented procedure can be applied to joints of higher strength steels (of the yield strength σ_Y = 315 and 355 MPa) fatigued at any applied cathodic potential below -0.8 V under sea loading of (0.05÷0.2 Hz) frequency at (0÷0.2) stress ratios.

Keywords : corrosion fatigue, shipbuilding steel joints, cathodic protection

INTRODUCTION

One of the main aims of fatigue investigations is to create fatigue life calculation procedures for structural members. In the paper [1] this author presented a simple procedure for joints fatigued in air and verified it by using fatigue test results for notched steel specimens. The specimen geometry in the notch region simulated that of fillet welded joint. In the author's paper [2] the "S-N_p" curves calculated by using the procedure were compared with the fatigue test results for real fillet welded joints. The procedure gave rather conservative prediction of the total fatigue life, except for the largest values of the stress concentration factor K_t , and the longest life region (above $1{\div}3{\times}10^6$ cycles), hence it can be recommended for approximate fatigue life predictions. However, real fatigue life of ship and offshore structures is usually affected by marine environment. A prediction procedure of corrosion fatigue crack initiation life and total life for welded joints under free corrosion conditions was presented elsewhere [3].

There is a common opinion that cathodic protection increases corrosion fatigue strength and restores true fatigue limit, although the real magnitude of this effect is not certain. Some tests of notched steel specimens [4 ÷ 6] have shown that the strength in salt water under cathodic protection is higher than in air, however, other tests [7 , 8] have shown that the strength is lower than in air. Therefore the "S-N_p" curve in air cannot be always considered as conservative one for cathodically protected structures in salt water. Hartt and Hooper [5 , 6] have asserted that the fatigue limit for the protected specimens is controlled by hydrogen embrittlement and the cathodic-deposit-induced crack closure effect. Hydrogen embrittlement is well known as a crack-growth-rate accelerating process. Crack closure phenomenon leads to reduction of the crack growth rate by reduction of an effective value of the stress intensity factor that is considered to be the true crack-driving parameter. Thus they are competitive processes. However, the deposits formation process within the crack and their interaction with the crack walls is complex and practically unpredictable. The kind of the mentioned crack closure affects especially propagation of short cracks that is usually considered as a dominating part of a conventional crack initiation period. It makes the prediction of the crack initiation life for cathodically protected joints practically impossible at present. Therefore this paper deals only with the prediction of the corrosion fatigue crack propagation life N_p for welded joints under cathodic protection. The predicted "S-N_p" curves were compared with experimental data evaluated by Vosikovsky *at al.* [8] for the welded fillet joints schematically shown in Fig.1.

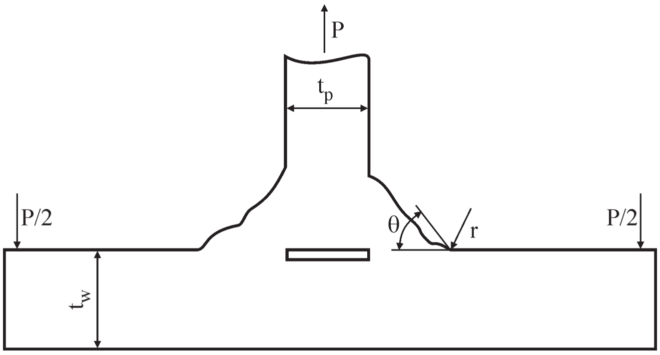

Fig. 1. *Geometry of the analyzed welded joints*

CORROSION FATIGUE CRACK GROWTH RATE CHARACTERISTICS

Fig.2 shows the effect of the applied cathodic potential Φ on the ratio β_{cat} (at $\Delta K = 20 \div 40$ MPa$\sqrt{m}$) of the crack growth rate $(da/dN)_\Phi$ at the applied potential Φ, and the crack growth rate $(da/dN)_{air}$ in air for BS4360-50D steel (σ_Y=360 MPa) [9], as well as for St41U5 steel (σ_Y = 316 MPa) and St41E-TF32 steel (σ_Y = 318 MPa)[10, 11].

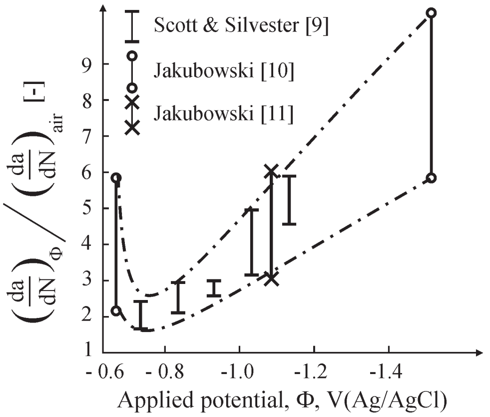

Fig. 2. *The ratio* $\beta_{cat} = (da/dN)_\Phi/(da/dN)_{air}$ *versus the applied potential* Φ *for BS4360-50D steel, acc.to [9], and for St41U5 steel and St41E-TF32 steel, acc. to [10,11]*

For $\Phi \leq -0.8$ V (Ag/AgCl) the crack growth rate $(da/dN)_\Phi$ can be approximated by the following formula [10] :

$$\left(\frac{da}{dN}\right)_\Phi = \beta_{cat}\left(\frac{da}{dN}\right)_{air} = A\left(\frac{da}{dN}\right)_{air} \cdot (E_{free} - \Phi) \quad (1)$$

where :

E_{free} - free corrosion potential

A - coefficient of the applied cathodic potential effect.

A equals 12.2 V^{-1} for the upper envelope of the results, and 7 V^{-1} for their lower envelope; and the mean value – about 9.6 V^{-1}. Approximate values of A, evaluated by this author for a higher strength steel (σ_Y=370 MPa) at $\Delta K = 25 \div 35$ MPa$\sqrt{m}$ on the basis of the test results [12] are $3 \div 14$ V^{-1}, i.e. they are of the same order as the above mentioned values.

Some tests results [9 ÷ 14] showed that the strongest enhancement of the crack growth rate by hydrogen embrittlement for steels under cathodic protection occurs approximately for ΔK above 20 MPa$\sqrt{m}$. Another set of data [7] leads to the same conclusion. The above is true for the loading frequencies f = = 0.1 ÷ 0.2 Hz and the stress ratios R = 0 ÷ 0.2. Therefore it is assumed that the crack growth rate at any applied potential $\Phi \leq -0.8$ V and for $\Delta K \geq 20$ MPa$\sqrt{m}$ is given by the equation (1) with A = 9.6 V^{-1}. For ΔK < 20 MPa$\sqrt{m}$ hydrogen embrittlement is not so dangerous as for ΔK values greater than 20 MPa$\sqrt{m}$, and in this case the crack growth rate quickly drops to the values observed in air, or below them. It is *ad hoc* assumed that $(da/dN)_{air}=(da/dN)_\Phi$ for $\Delta K = \Delta K_0$. Value of ΔK_0 corresponds to the end of conventional crack initiation stage and to the beginning of conventional propagation stage [1 ÷ 3]. Fig.3 schematically shows the assumed corrosion fatigue crack propagation characteristics.

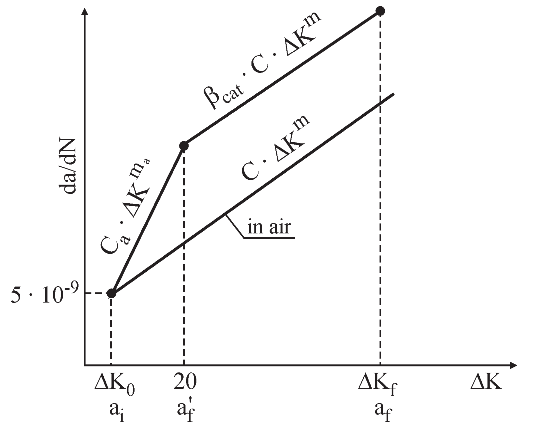

Fig. 3. *Schematic diagram of the assumed corrosion fatigue crack growth characteristics under cathodic potentials*

STRESS INTENSITY FACTOR

The stress intensity factor range ΔK was evaluated by using the formula :

$$\Delta K = \Delta S\sqrt{\pi a} \cdot Y(a/t_w) \quad (2)$$

In the present calculations, and in [1 , 2] as well, the following form of the correction function Y was assumed :

$$Y = \gamma \cdot (a/t_w)^{-\delta} \quad (3)$$

For smooth beam in bending : Y = 1.12 for $a/t_w \approx 0$ and $a/t_w = 0.305$. For notched beam the following values were assumed : Y(0.000305) = 1.12K_t and Y(0.305) = 1.12, that led to the following equations :

$$\delta = \frac{\log(K_t)}{3} \quad (4)$$

$$\gamma = 1.12\ (0.305)^\delta \quad (5)$$

The stress concentration factor for the joint shown in Fig.1 was calculated by the following formula [15] :

$$K_t = 1 + 0.512\ \theta^{\,0.572}\ (t_w/r)^{0.469} \quad (6)$$

The values of Y calculated by using the above given formulae are comparable [2] to those evaluated by Niu and Glinka [15] by means of the finite element method.

THE ASSUMED CHARACTERISTIC CRACK LENGTHS

Values of a_i are usually – by a convention – assumed equal to 0.5 ÷ 1mm. In this paper, as well as in [1 , 2], a_i values – by another convention – correspond to a fixed value of $\Delta K = \Delta K_0$, where ΔK_0 corresponds – by an *ad hoc* assumption – to the end of the near threshold propagation rate (da/dN=5×10^{-9}m/c). Values of a_i were calculated by means of the formula :

$$a_i = \left(\frac{\Delta K_0}{\pi^{1/2}\gamma \cdot (t_w)^\delta \Delta S}\right)^{1/0.5-\delta} \quad (7a)$$

$$a_i \leq 0.0014\ \text{m} \tag{7b}$$

The final crack length is assumed $a_f = 0.4t_w$, i.e. the same as in [2] for similar welded joints fatigued in air. The value of a_f' was evaluated from the intersection of the adjacent segments of the corrosion fatigue crack growth rate characteristics (Fig.3), i.e. by the following equation :

$$a_f' = \left(\frac{20}{\pi^{1/2}\gamma \cdot (t_w)^{\delta} \Delta S} \right)^{1/(0.5-\delta)} \tag{8}$$

CORROSION FATIGUE CRACK PROPAGATION LIFE

Integration of the assumed crack growth rate characteristics (Fig.3) leads to the following formula :

$$N_p = \frac{(a_f')^{\alpha_a} - (a_i)^{\alpha_a}}{C_a \alpha_a (\pi^{1/2}\gamma \cdot (t_w)^{\delta} \Delta S)^{m_a}} + \\ + \frac{(a_f)^{\alpha} - (a_f')^{\alpha}}{\beta_{cat} C \alpha (\pi^{1/2}\gamma \cdot (t_w)^{\delta} \Delta S)^{m}} \tag{9}$$

where :

$$\alpha_a = 1 - m_a\,(0.5 - \delta)$$
$$\alpha = 1 - m\,(0.5 - \delta)$$
$$C_a = 5 \cdot 10^{-9}\ \Delta K^{m_a}$$
$$m_a = \frac{\log\left(\frac{\beta_{cat} C 20^m}{5 \cdot 10^{-9}} \right)}{\log\left(\frac{20}{\Delta K_0} \right)}$$

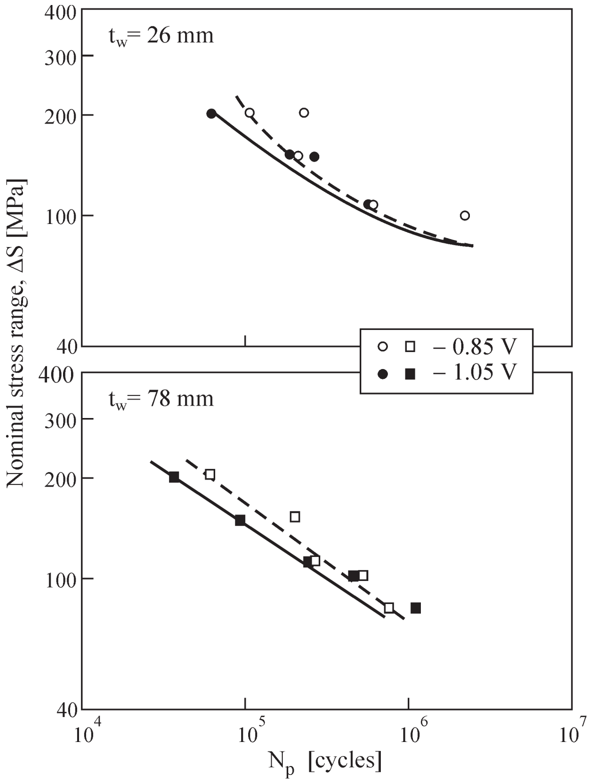

Fig. 4. *Comparison of the corrosion fatigue crack propagation curves,* "S-Np" *, acc. to equation (9) with the tests results published in [8] (here shown as the points)*

In Fig.4 corrosion fatigue lives of the welded joints shown in Fig.1, predicted by the above given formula, are compared to the lives of the same joints, determined empirically by Vosikovsky *at al*. [8] for two values of the applied cathodic potential. In order to evaluate the crack propagation life N_p obtained by Vosikovsky the crack initiation life N_i was subtracted from the total life, both read off from the appropriate figures in [8]. Values of N_p , especially those for t_w = 26 mm, demonstrate rather large scatter ; it can be partly due to the reading-off errors. The predicted "S-N_p" curves give a conservative assessment as they approximately correspond to the lower bounds of the test results, although for thicker joints such prediction is only slightly conservative.

SUMMARY

- A procedure for conservative prediction of the corrosion fatigue crack propagation life N_p of cathodically protected welded steel joints was presented. The procedure has limited applicability – it can be applied to joints manufactured of higher strength steels (of class E315 and E355, denoted by IACS as AH32, DH32, EH32, AH36, DH36, and EH36) fatigued at any applied potential lower than - 0.8 V (Ag/ /AgCl$_2$) under sea wave loading of frequencies within the range of 0.05 ÷ 0.2 Hz and stress ratios R ≈ 0 ÷ 0.2.
- The predictions for joints of steels of lower strength classes at any higher loading frequency and R values are expected to be more conservative, whereas for steels of higher classes (E390 or higher) at a lower frequency and R values it should be expected that the procedure can overestimate the crack propagation life of the joints.
- Residual welding stresses were not considered.
- The final expression for N_p concerns fillet welded joints in bending, however, the procedure can be applied to every welded joint geometry for which it is possible to calculate the stress intensity and the stress concentration factors.

NOMENCLATURE

a – crack length
a_f – final crack length, [m/cycle = m/c]
a_i – initial crack length, [m/c]
A – coefficient of the applied cathodic potential effect
c – cycle
C – material constant in the Paris equation, [m · (MPa $\sqrt{m}$)^m]
C_a – material constant in the Paris equation for region I under cathodic protection, [m · (MPa $\sqrt{m}$)^m]
$\left(\frac{da}{dN}\right)_{air}$ – fatigue crack growth rate in air, [m/c]
$\left(\frac{da}{dN}\right)_{\Phi}$ – corrosion fatigue crack growth rate under cathodic potential Φ, [m/c]
E_{free} – free corrosion potential, [V](Ag/AgCl$_2$)
ΔK – range of stress intensity factor , [MPa $\sqrt{m}$]
ΔK_f – final stress intensity factor, [MPa $\sqrt{m}$]
K_t – stress concentration factor, [-]
m – exponent in the Paris equation in air, [-]
m_a – exponent in the Paris equation for region I under cathodic protection, [-]
N – fatigue life, [cycles]
N_p – crack propagation life, [cycles]
P – loading force, [kN]
r – weld toe radius, [m]
R – stress ratio (= S_{min}/S_{max}), [-]
S – nominal stress, [MPa]
ΔS – nominal stress range, [MPa]
t_p , t_w – thickness of joined plates, [m]
Y – correction factor in the formula for stress intensity factor, [-]
α, α_a – functions appearing in eq.(9), [-]

β_{cat} – coefficient of cathodic potential effect on crack growth rate, [-]
γ – constant in eq. (3) [-]
δ – exponent in eq.(3) [-]
σ_y – yield point stress, [MPa]
Φ – cathodic potential, [V] (Ag/AgCl$_2$)
θ – weld toe angle, [radian]
IACS – International Association of Classification Societies

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CONTACT WITH THE AUTHOR

Marek Jakubowski, D.Sc., Eng.
Faculty of Ocean Engineering
and Ship Technology,
Gdańsk University of Technology
Narutowicza 11/12
80-952 Gdańsk, POLAND
e-mail : marjak@pg.gda.pl

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