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Behavior of stress-corrosion crack in a high-strength aluminum alloys structure

Bore Jegdić MSc (Eng)[1)]

Stress-corrosion cracking (SCC) tests are performed in the laboratory using the fracture mechanics approach (constant crack opening displacement COD methodology). Double-cantilever beam (DCB) specimens have been used for testing SCC high-strength aluminum alloy in distilled water and the 3.5% aqueous solution of NaCl at room temperature. These SCC data are applied for predicting the behavior of the crack in the structure (exposed to simultaneous effects of tensile stress and corrosive environment) as well as for calculating the lifetime of a structure. In the cases when existing SC crack relatively fast propagate in the given structure, possibility to reduce the applied stress to the value when the crack stops to grow (K_I is lower than K_{ISCC}) is discussed, as well as the possibility to apply the same alloy with other heat treatment or to choose other metallic material which provides higher SCC resistance (higher K_{ISCC} and lower SC crack propagation rate). A general block scheme of the design/performance model (adapted from Jackson and Wight) is given for the cases when SC has a dominant role during exploitation.

Key words: **stress-corrosion cracking (SCC), fracture mechanics testing, aluminum alloys, threshold stress intensity factor K_{ISCC}, SC crack propagation rate, nondestructive evaluation.**

Introduction

THIS paper concentrates on the possibilities to apply some of existing fracture mechanics (FM) procedures to the failure of components with cracks in corrosive environment. The experimental results obtained by the fracture mechanics analysis in inert environment, such as fracture toughness K_{IC}, threshold value for fatigue crack propagation ΔK_{th} and fatigue crack propagation rate da/dN etc. are widely applied in practice for design, material selection and failure analysis.

These procedures are explained in detail in the literature [1-5]. The existing design/performance model of Jackson and Wight [1] has been adapted for cases when stress corrosion cracking (SCC) plays a dominant role during exploitation and is applied to a high-strength aluminum alloy series 7000. More information about SCC characteristics of the tested and similar high-strength aluminum alloy can be found in the literature [6-10]. (see Fig.1).

The experimentally obtained data are applied for predicting the behavior of the crack in the structure (exposed to simultaneous effects of tensile stress and corrosive environment) as well as for calculating the lifetime of a structure. In the cases when existing SC crack relatively fast propagate in the given structure, possibility to reduce the applied stress to the value when the crack stops to propagate (K_I is lower than K_{ISCC}) will be discussed as well as the possibility to apply the same alloy with other heat treatment or to choose other material which provides higher SCC resistance (high K_{ISCC} and lower SC crack propagation rate). Other possibilities of decreasing the risk of SCC failures such as applying cathodic (or anodic) protection, inhibitors, and organic or inorganic coatings were not discussed in this paper.

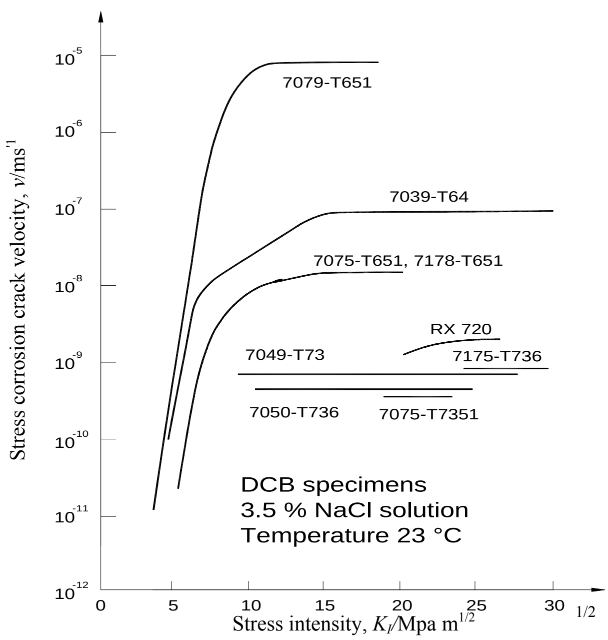

Figure 1. SCC characteristic of several high-strength aluminum alloys [2]

A general block scheme design/performance model (adapted from Jackson and Wight) is given for the cases when SC has a dominant role during exploitation.

Theoretical part

Stress-corrosion cracking (SCC) is a phenomenon in which time-dependent crack growth occurs when necessary elec-

1) Military Technical Institute (VTI), Katanićeva 15, 11000 Beograd

trochemical, mechanical and metallurgical conditions are fulfilled. When hydrogen is generated as a product of the corrosion reaction, crack growth can occur due to a local hydrogen embrittlerment process. Corrosion fatigue is a related process in which the load is cyclic rather than static as in stress-corrosion cracking. A common feature of these processes is sub-critical crack growth to a size at which catastrophic failure occurs. A second common feature of these processes is that these mechanisms are localised in the crack tip region. Such processes are the major cause of service failures.

No crack propagation is observed below the threshold stress intensity level K_{ISCC} (Figure 2). This level presumably corresponds to the stress level for synergetic alloys-environment interaction. At low stress intensity levels (but higher than K_{ISCC}), the crack propagation rate increases rapidly with the stress intensity factor K_I (stage I). At intermediate K_I levels, the crack propagation rate approaches some constant value that is independent of the mechanical driving force K_I. This rate at the plateau v_{pl} is characteristic of alloy-environment combinations and is the result of the rate limiting environmental processes (stage II). In the next stage, the rate of crack propagation exceeds the plateau velocity as the K_I approaches the critical stress intensity level for mechanical fracture in inert environment K_{IC} (stage III) [1,2].

The SC crack growth rate at the first stage of the kinetic diagram log v-K_I (Figure 2) can be written in the following form [11]

$$v_I = C_I \exp\,(m\,K_I) \qquad (1)$$

where: C_I and m are the constants not depending on K_I but on the tested material and corrosive environment and can be experimentally determined.

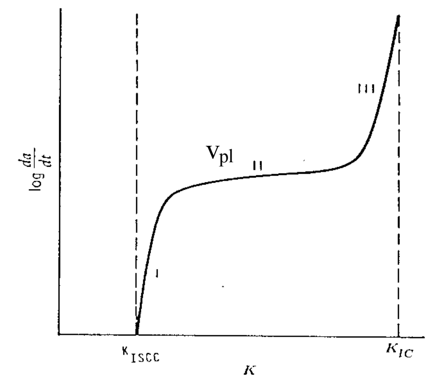

Figure 2. Schematic presentations of the SC crack growth rate dependence on the K_I value [2]

The SC crack growth rate at the plateau v_{pl} is controlled by the processes such as electrochemical (or chemical) reaction kinetics on the crack tip, or the hydrogen diffusion rate through metal from the crack tip to the point of the maximum three-axial stress state where the fracture actually occurs. Therefore, that rate can be expressed by the following equation [11]

$$v_{pl} = C_{II} \exp\left(-\frac{E_a}{R \cdot T}\right) \qquad (2)$$

where E_a is the activation energy of the previously mentioned (or other) processes which control the crack growth rate at the plateau, R is the universal gas constant (8.314 J mol^{-1} K^{-1}), T is the temperature in K, and C_{II} is the constant depending on the metal/environment relation and can be experimentally determined.

Similarly to the parallel processes where the slowest process controls the overall process rate, the same approach can be used here [11]

$$\frac{1}{v_T} = \frac{1}{v_I} + \frac{1}{v_{pl}} \qquad (3)$$

where v_I is the SC crack growth rate in the first stage, v_{pl} is the SC crack growth rate in the second stage (plateau of velocity), while the effect of the third SC crack growth rate stage is neglected (due to the high SC crack growth rate at that stage when K_I approaches K_{IC}).

The total SC crack growth rate v_T from the previous eq.(3) is

$$v_T = \left(\frac{da}{dt}\right)_T = \frac{v_I \cdot v_{pl}}{v_I + v_{pl}} \qquad (4)$$

If the values for the SC crack growth rate v_I and v_{pl} are incorporated into eq.(4), the total SC crack growth rate thus depends on K_I and temperature and can be calculated. It is assumed in advance that the constants (in eq.1 and 2) are previously experimentally determined.

The lifetime (time to failure) is then calculated in the following way. First, the initial crack length a_o in the structure must be determined by some nondestructive evaluation methods (NDE), and after that the final crack length, which can be critical when the failure occurs a_C or it can be tolerable a_T i.e., lower than the critical value. The critical crack length a_C can be calculated by the following equation [1,2]

$$a_c = \frac{1}{\pi} \cdot \left(\frac{K_{IC}}{R_{app} \cdot Y}\right)^2 \qquad (5)$$

where K_{IC} is the fracture toughness of the tested material, R_{app} is the applied stress and Y is the geometrical factor for the given structural configuration and crack geometry.

Assuming that, for the sake of simplification, the temperature stays constant during exploitation, then the SC crack growth rate at the plateau is also constant. By incorporating the v_{pl} value and the v_I value into eq. (4), the total lifetime expression is obtained

$$t_f = \int_{a_o}^{a_c} \frac{C_I \cdot \exp(m\,K_I) + v_{pl}}{C_I \cdot v_{pl} \cdot \exp(m\,K_I)} \cdot da \qquad (6)$$

Since the SCC usually occurs at a constant applied stress R_{app}, then the m K_I can be written as $D\sqrt{a}$, where D is constant and equals m $Y\,R_{app}\sqrt{\pi}$, supposing that the geometrical factor Y is constant. If the Y is not constant, which is generally the case, its change has to be taken into account. The same applies to environment, temperature and stress changes. The solution of the integral eq.(6) is as follows

$$t_f = \frac{a_c - a_o}{v_{pl}} - \frac{2}{C_I \cdot D^2 \cdot \ln^2 10} \cdot \left[\frac{D \cdot \ln 10 \cdot \sqrt{a_c} + 1}{10^{D\sqrt{a_c}}} - \frac{D \cdot \ln 10 \cdot \sqrt{a_o} + 1}{10^{D\sqrt{a_o}}}\right] \qquad (7)$$

The experimentally obtained data for the SCC of a high-strength aluminum alloy in distilled water and the NaCl solution will be applied for predicting the behavior of the previously detected crack and calculating the lifetime of a structure with this crack.

Experiment

The following table shows the basic composition of the tested aluminum alloy.

Table 1. Basic composition of the tested high-strength aluminum alloy (in mass. %)

Zn	Mg	Cu	Mn	Cr	Zr	Al
7.2	2.15	1.46	0.28	0.16	0.12	rest

The specimens are formed in the S-L orientation from the extruded high-strength aluminum alloy, and heat-treated according to *T*1 and *T*2 tempers.

*T*1 temper consists of annealing at 460 ºC for one hour, quenching in water of room temperature and one-step precipitation hardening at 120 ºC for 24 hours.

*T*2 temper consists of annealing at 460 ºC for one hour, quenching in water of 60 ºC and natural aging at room temperature for two days and two-step precipitation hardening at 120 ºC for 24 hours, and at 160 ºC for 14 hours.

The SCC testing was performed using a constant COD methodology. The basic FM requirement that the specimen thickness value is higher than a minimum value providing plain strain conditions at the crack tip was fulfilled.

In order to monitor the SC crack propagation, specimens of relatively great length are applied. The most convenient for these purposes are DCB specimens (double cantilever beam specimens), which have been used in this test. The dimensions of the DCB specimen are determined based on the calculated specimen thickness (B=25 mm), in accordance with the ISO standard 7539-6: 1989 and the ASTM standard G 168 - 2000.

The specimens were stressed by a bolt and exposed to the effects of SC environment at room temperature. Distilled water and the 3.5 % aqueous solution of NaCl were used as SC environment. During the first test period, the crack length was measured every day (using the low magnification microscope) and in the rest of the period, the measurements were carried out in longer time periods. The monitoring of the crack length value was performed until the moment of significantly low crack propagation growth. After the testing, the specimens were mechanically fractured (separated) and on the fracture surface the initial mechanical crack length (caused by pop-in) was measured as well as the total length of the mechanical and stress corrosion crack before the SC crack arrest.

On the basis of the values of mechanical (pop-in) crack lengths a_C and the corresponding COD values, the fracture toughness K_{IC} of the tested aluminum alloy was determined by inserting these values into the FM equation for DCB specimens (ASTM G 168 - 2000)

$$K_I = \frac{\sqrt{3} \cdot E \cdot V_{LL}}{4 \cdot \sqrt{H} \cdot \left(\frac{a}{H} + 0.673 \right)^2} \tag{8}$$

where H is the specimen half length, V_{LL} is the load line crack opening displacement, a is the crack length, and E is Young's Modulus (for this aluminum alloy it equals 72.5 GPa [6]).

The calculated stress intensity values of K_{IC} are the initial values of K_I for the further SCC testing. Almost an identical procedure of fracture toughness K_{IC} determination and further SCC testing on DCB specimens is suggested by Speidel [8]. In analogous way, the value of the stress intensity factor at the crack arrest K_{ISCC} was determined. The crack length data are incorporated into the diagram showing the dependence of the crack length and the testing time in corrosive environment and used later for the calculation of the crack propagation rate da/dt as well as for the corresponding K_I values (as shown in Fig.1).

Result and discussion

The experimental results for the aluminum alloy are presented in Table 2.

Table 2. Results obtained in testing the aluminum alloy in different environments

Heat treatment/environment		R_p (MPa)	K_{IC} (MPa m$^{1/2}$)	K_{ISCC} (MPa m$^{1/2}$)	v_{pl} (mm day^{-1})
*T*1	Air	560	29	-	-
	Distilled water	-	-	17	0.48
	3.5% NaCl	-	-	10	1.24
*T*2	Air	475	31	-	-
	3.5% NaCl	-	-	28	0.072

Let us suppose that there is a half-elliptic surface crack (a_0 = 2.4 10^{-3} m and 2c = 8 10^{-3} m) in the aluminum plain plate (temper T1) thickness which providing plain strain conditions. During exploitation the plate is exposed to simultaneous effects of chloride anions and tensile stress (R_{app} = 220 MPa). It is possible to use the laboratory obtained results of SCC in NaCl solution for predicting the behavior of the detected crack, i.e. if it starts to grow under the given conditions and for predicting its growth rate and lifetime. For the half-elliptic surface crack in the plate, the following expression for K_I can be applied [2]

$$K_I = 1.12 \cdot R \cdot \sqrt{\frac{\pi \cdot a}{Q}} \tag{9}$$

where Q is the factor of the crack shape (depending on the a/2c and R_{app}/R_p relation and equals 1.57).

According to eq.(9), a real value of K_I in the plate is 17.1 MNm$^{-3/2}$. Since K_I is greater than K_{ISCC}, the existing crack will start to grow. The lifetime is calculated using eq.(7) and equals $t_f \cong 5$ days. The procedure of the detected crack behavior is summarized in the following text:

Given data:

R_{app} = applied stress = 220 MPa
K_{IC} = fracture toughness = 29 MPa m$^{1/2}$
R_p = yield strength = 560 MPa
a_0 = depth of the half-elliptic crack detected by NDE = 2.4·10^{-3} m
2c = width of the detected half-elliptic crack = 8·10^{-3} m

Experiment:

K_{ISCC} = threshold stress intensity factor (for temper T1) in the 3.5% NaCl = 10 MPa m$^{1/2}$
v_{pl} = SC crack grow rate at the plateau = 1.44·10^{-8} m s^{-1} (=1.24 mm day^{-1})
C_I = experimental constant (in eq. 1) = 10^{-21} m s^{-1}
D = experimental constant (in eq. 7) = 360 m$^{-1/2}$

Procedures:

I) determination of the constant Q (in eq.9)

$$Q = 1.57 \text{ (for } a_0/2c = 0.3 \text{ and } R_{app}/R_p = 0.4)$$

II) calculation of the real stress intensity factor K_I in the plate (eq.9)

$$K_I = 1.12 \cdot R_{app} \cdot \sqrt{\frac{\pi \cdot a_o}{Q}} = 17.1 \text{ MPa m}^{1/2}$$

III) establishing the critical crack size (because $K_{ISCC} < K_I < K_{IC}$)

$$a_c = \frac{Q}{\pi} \cdot \left(\frac{K_{IC}}{1.12 \cdot R_{app}} \right)^2 = 6.9 \ 10^{-3} \text{ m}$$

IV) calculation of lifetime (eq.7)

$$t_f = \frac{a_c - a_o}{v_{pl}} - \frac{2}{C_I \cdot D^2 \cdot \ln^2 10} \cdot$$

$$\cdot \left[\frac{D \cdot \ln 10 \cdot \sqrt{a_c} + 1}{10^{D \cdot \sqrt{a_c}}} - \frac{D \cdot \ln 10 \cdot \sqrt{a_o} + 1}{10^{D \cdot \sqrt{a_o}}} \right] = 430000 \text{ s } (\cong 5 \text{ days})$$

If the environment does not contain chlorides or other SCC activators, then the results of testing the aluminum alloy in distilled water are of great importance for crack behavior predicting. Under the same conditions, SC crack growth also occurs but the time to failure is significantly longer ($t_f \cong 70$ days).

Since the calculated lifetime in both cases is very short, it is necessary to consider other possibilities to decrease effects of SC environment. One of the possibilities is to reduce the applied stress to the value when the crack stops to propagate (i.e. when K_I is lower than K_{ISCC}). The other possibility is to apply a heat treatment that provides higher SCC resistance, for example *T*2, which has proved its quality during many years of service. In the case of temper T2, detected crack cannot grow, because $K_I < K_{ISCC}$ (in 3.5 % NaCl as well as in distilled water). Another solution is to to choose other material with high resistance to SCC.

A general block scheme in APPENDIX gives the layout of all that has been mentioned above in the paper. It is an adaptation of the existing design/performance model of Jackson and Wight [1] for the cases when SC has a dominant role during exploitation.

Conclusions

The experimentally obtained data are applied for predicting the behavior of a half-elliptic crack detected by a non-destructive evaluation method in a structure exposed to simultaneous effects of tensile stress and corrosive environment as well as for the calculation of the structure lifetime. The possibility to reduce the applied stress to the value when the crack stops to propagate, i.e. when K_I is lower than K_{ISCC} is discussed, as well as the possibility to apply the same aluminum alloy with other heat treatment or to choose other material which provides higher SCC resistance. A general block scheme of the design/performance model (adapted from Jackson and Wight) is given for the cases when SCC has a dominant role during exploitation. Other possibilities of decreasing the risk of SCC failures such as applying cathodic (or anodic) protection, inhibitors, and organic or inorganic coatings were not discussed in this paper.

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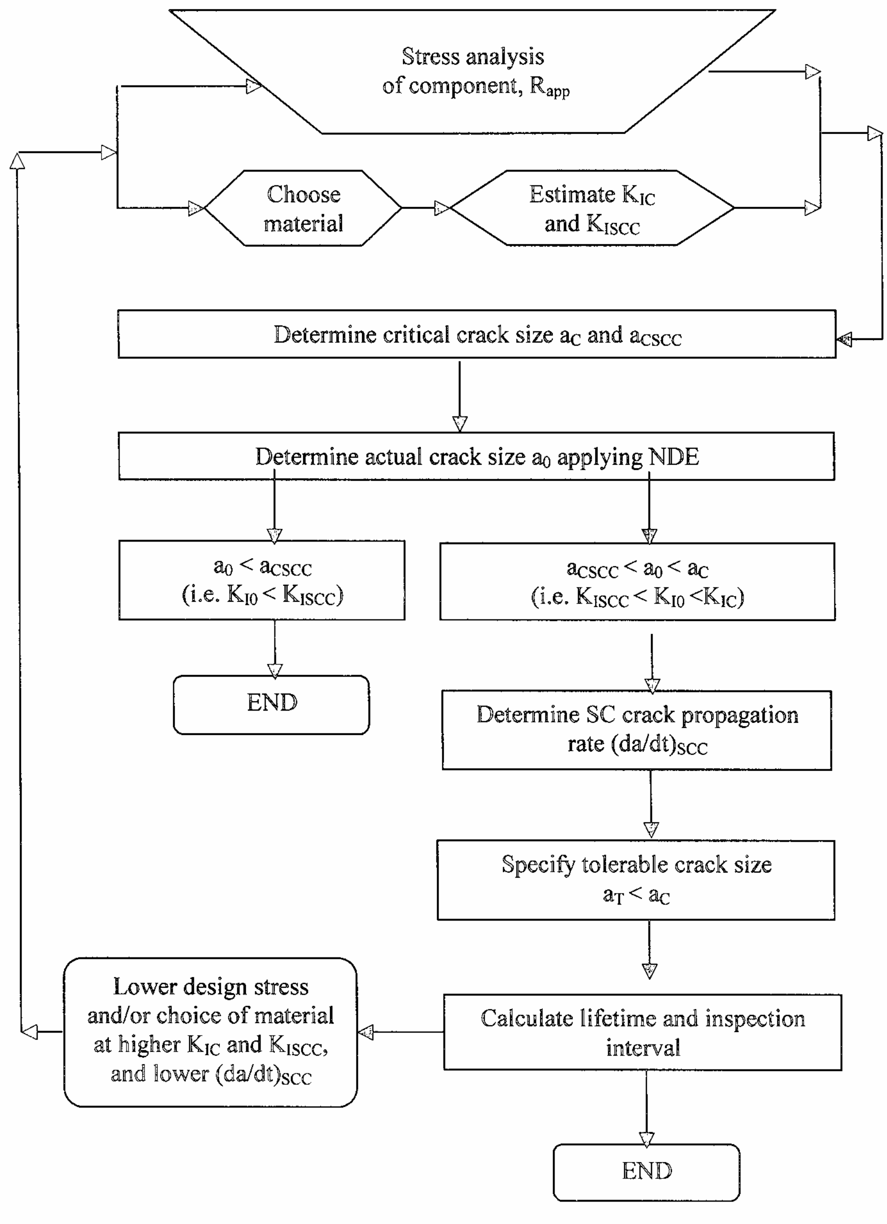
Appendix: General scheme of the adapted design /performance model for SCC



Ponašanje naponsko-korozione prsline u konstrukciji od aluminijumske legure visoke čvrstoće

Primenom mehanike loma (metoda konstantnog otvaranja prsline) izvršena su ispitivanja naponske korozije aluminijumske legure visoke čvrstoće. Ispitivanja su izvedena na DCB uzorcima u destilovanoj vodi i u 3,5% vodenom rastvoru NaCl sobne temperature. Dobijeni rezultati su primenjeni za predviđanje ponašanja prsline u konstrukciji (izloženoj istovremenom dejstvu zateznih naprezanja i korozione sredine), kao i proračun preostalog veka te konstrukcije. U slučajevima kada postojeća naponsko-koroziona prslina relativno brzo raste u datoj konstrukciji, razmatrana je mogućnost smanjenja primenjenog naprezanja do vrednosti kada prslina prestaje da raste (K_I niže od K_{ISCC}), mogućnost primene iste legure sa drugačijom termičkom obradom, kao i izvor druge legure koja ima veću otpornost prema naponskoj koroziji (veću vrednost za K_{ISCC} i nižu vrednost brzine rasta naponsko korozione prsline). Na kraju rada data je opšta blok šema dizajn/performans modela (prilagođena na osnovu radova Jacksona i Wighta) za slučajeve kada je naponska korozija preovlađujuća tokom eksploatacije.

Ključne reči: **naponska korozija (SCC), ispitivanje mehanikom loma, aluminijumske legure, kritični faktor intenziteta napona (K_ISCC), brzina propagacije naponsko-korozione prsline, nerazarajuća metoda.**

Comportement de la fissure de corrosion sous tension dans la structure d'un alliage d'aluminium à haute resistance

La mécanique des ruptures (la méthode COD-crack opening displacement) est appliquée dans l'analyse de la corrosion sous tension d'un alliage d'aluminium à haute résistance. Les essais ont été effectués sur les échantillons DCB dans l'eau distillée et dans la solution aqueuse de 3,5% NaCl à la température ambiante. Les résultats obtenus sont appliqués pour la prévision du comportement de la fissure dans une structure exposée aux effets simultanés de tension et ambiance corrosive aussi bien que pour le calcul du restant de sa durée de vie. Un schéma général de la conception/performance (adapté sur la base des oeuvres de Jackson et Wight) est également donné pour les cas où la corrosion sous tension a un rôle dominant pendant l'exploitation.

Mots-clés: **création de fissure de corrosion sous tension (SCC), essai par la mécanique des ruptures, alliages d'aluminium, facteur critique d'intensité de tension (K_{ISCC}), vitesse de propagation de la fissure de corrosion sour tension, évaluation non destructive.**