Effect of corrosion pits on fatigue life and crack initiation

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Abstract Corrosion fatigue is identified as one of the main failure mechanism for structures working in corrosive environment. The existing study on pit corrosion showed that cracks do not necessarily initiate from the bottom of the pit. Where the crack initiate from pit depends on the pit shape (aspect ratio), loading and the corrosive environment. In this study, firstly, the corrosion pit development in size and shape and its effect on fatigue life were reviewed. Fatigue tests were conducted on pre-pitted and smooth samples to further investigate the pit effect. Then various aspect ratios of pits were modeled to calculate the SCF in a round bar under tension and bending loadings.In addition, the SCF of a wide range of aspect ratios of pits were calculated, by which it is expected to offer the engineering practice and researchers convenience to find SCF value.

Keywords Corrosion pits 1; Aspect ratio 2; Stress concentration factor 3; Fatigue life 4

1. Introduction

Pitting corrosion is considered to be one of the principal degradation mechanisms for many metallic materials subjected to corrosive environment. The fatigue life was shortened due to formation of corrosion pits on surface of the material causing the initial damage and then cracks initiated from these pits. Pit development and its effect on corrosion fatigue crack growth have been extensively studied, but there is little consensus with regard to the exact relationship between the pit size and the time due to the interaction of environment and loading and the dependence on microstructural state and stress level.

The main purpose of the present paper is to provide a review of the pit formation and its effect on fatigue lives, attempting to develop a generalized understanding of how the pits develop. Then fatigue tests were conducted on pre-pitted and smooth samples to further investigate the pit effect. Finally, various aspect ratios of pits were modeled to calculate the SCF in a round bar under tension and bending loadings.

2. Corrosion pit development

2.1 Pit size development

Corrosion pit size varies as exposure time in solution increases and depends on electrochemical and mechanical conditions. Many researchers have conducted extensive studies on pit development and various relationships between and pit size and time were proposed. Sriraman et al [1] developed a model that considers the coexistence of corrosive environment and fatigue loading conditions and took into account the influence of cyclic stresses in the pitting corrosion process. Boag et al [2] observed stable pit formation on AA2024-T3 in a NaCl environment, and indicated that local clustering played an important role in pit initiation. Ryuichiro Ebara [3] emphasizes initiation and growth of corrosion pits in the corrosion fatigue crack initiation process. The pit size distribution data in [4] suggests that the depth of the pits in alloys such as 7075-T6 increases by the interconnection of the pits that have nucleated at constituent particles at various depths through the thickness of the exposed alloy. Rybalka's study [5, 6] on pitting development on Stainless Steel 403 Steel and 20Kh13 showed that the size of pit is affected by the PH and temperature of the solution and the electrode rotation. Additionally, the depth of growing pits as a function of time can be described by the equation h = 2.25+3.39$t^{1/2}$. While the depth h of growing pits on 20Kh13 steel in 0.01 M NaCl solution at ΔE= 30 mV increases with the time as h~$t^{1/2}$, and an average pit diameter d obeys the relationship d= d_0(1–$e^{-0.07t}$). P. Ernst [7, 8] proposed that the pit width increases almost linearly with time, and the pit growth in depth follows a parabolic law with time ($\propto\sqrt{t}$) and is independent of the potential, whereas lateral pit growth is linear with time and dependent upon potential. Harlow and Wei [9] assumed that the pit maintained hemispherical geometry and grew at a volumetric rate determined by Faraday's law, and the aspect ratio is a continuous function of time. The relationship between the depth (a) and the diameter (2c) of pits was studied by Kondo [10] and showed that the pit growth occurred at the same aspect ratio a/c≈0.7. The corrosion pit growth law can be formulated as $2c\propto t^{1/3}$. Cavanaugh [11] used optical profilometry and Weibull functions to characterize pit depth and diameter distributions and found pit growth kinetics varied by environment, but most followed approximately $t^{1/3}$ kinetics. Sriraman [12] proposed the depth a_p is considered proportional to the cube root of t through the relationship of a_p=B$t^{1/3}$. Buxton [13] described the pit growth law following a typical power law curve (x=Bt^{β}) with a relatively large exponent value of 0.596. Turnbull [14] also assumed that the depth can be described by x=αt^{β}, and examples of the results [15] for three environmental exposure conditions in terms of the variation of aspect ratio with pit depth are illustrated.

As illustrated above that various relationship was developed for pit depth and width. But the literature mostly suggests that the pit width follows a linear relationship with time shown in Fig. 1 (left) and the pit depth is linearly proportional to the square root of time in Fig. 1 (right).

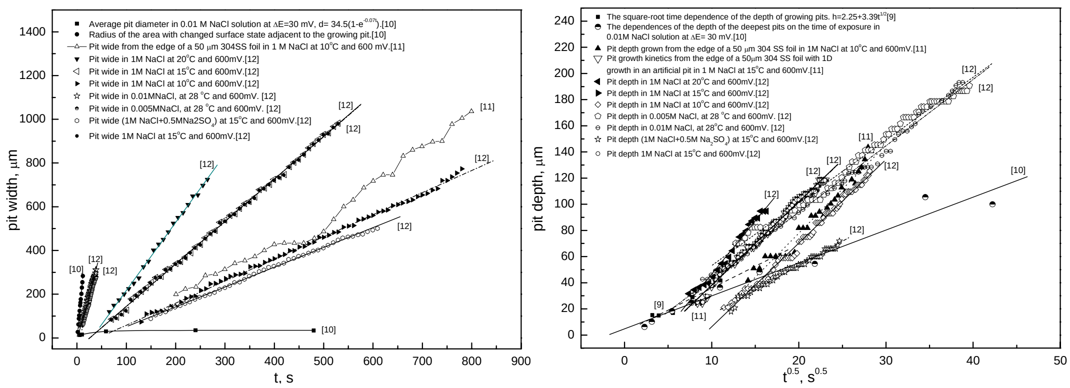


Fig. 1. Corrosion pit width vs t and depth vs $t^{0.5}$.

2.2 Pit shape development

Pidaparti et al [16] noted that the pit/defect profile changing its shape (both depth and width) from slightly conical to more hemispherical shape with increasing corrosion time and stress distribution and levels vary non-linearly around a single pit/defect. Melchers [17] proposed that the sequence consists of the development of anodic areas, development of small pits and shallow broad pits, the apparent coalescence of small pits into larger localized corrosion and eventually the appearance of stepped or benched, perhaps irregular shaped broad or macro-pits. Ernst [7, 8] carried out a semi-quantitative model to explain lacy pit cover formation and pit growth, representing the shape of a pit and pits within pits grown from the edge of a 50 μm 304 SS foil in 1 M NaCl at 15℃ and 600 mV. An SEM microfractograph of a typical nucleating corrosion pit on the fracture surface of a specimen that had been precorroded for 384 h was given by Dolley [18]. And elliptical pits developed from the artificial pit were given in [19].

3. Effect of the corrosion pit on fatigue lives (crack initiation)

3.1 Effect of the corrosion pit on crack initiation and propagation.

Corrosion pits acted as pre-existing flaws in the material to nucleate fatigue cracks. Burstein [20] and Li Lei [21] indicated that the evolution of corrosion pit followed three stages: nucleation, metastable growth and stable growth. The pit size observed on the fracture surface is considered to give the critical pit size that depends on the cyclic stress amplitude at which the transition occurred [10]. A comprehensive seven-stage model is developed in [22, 23] for pitting corrosion fatigue damage process, including pitting nucleation, pit growth, transition from pit growth to short crack, short crack growth, transition from short crack to long crack, long crack growth, and fracture. Bastidas-Arteaga [24] assessed the total corrosion-fatigue life as the sum of three critical stages: corrosion initiation and pit nucleation; pit-to-crack transition, and crack growth. Turnbull [14, 15] noted that fundamental steps in the overall process of crack development include pit initiation, pit growth, the transition from a pit to a crack, short crack growth and long crack growth, and suggested that cracks do not necessarily initiate from the bottom of the pits, for the reason that there were many cracks with a depth smaller than that of the corresponding pit. While Ebara [25] found that the crack initiated at the bottom of corrosion pit where stress concentration is large and is presumably electrochemically active, and indicated that corrosion fatigue cracks essentially nucleated and grew from one or two large pits at the circular hole surface near the area of maximal stresses [26]. It is indicated that the largest pits did not nucleate cracks, which is due to the result of a combination of the ‘bluntness’ of the larger pits, and they were not located at the root of the notch, where the stress concentration is highest [27]. As regards to the SUS 630 specimen, the fracture surface showed that the fatigue crack propagation displayed high non-linear in route [28].
The initiation and growth of corrosion pit, crack initiation from corrosion pit and the crack propagation appearance can be vividly identified in [25]. Based on the modeling results of Bastidas-Arteaga [24], G. S. Chen [26] and Medved [27], two criteria are proposed to describe the transition from pit growth to fatigue crack growth: (1) the stress intensity factor of the equivalent surface crack has to reach the threshold stress intensity factor, ΔK_{th}, for fatigue crack growth, assuming that a corrosion pit may be modeled by an equivalent semi-elliptical surface crack; (2) the time-based corrosion fatigue crack growth rate also exceeds the pit growth rate.
The results of Sriraman and Pidaparti [1, 12] indicated crack initiation from pit sites can be extremely fast at high stress levels and can occur even from relatively small pits. And Kondo [10] pointed that at higher stress levels, transition occurred at fairly small pit sizes. On the other hand, at lower stress levels, transition occurred at larger pits. Medved [27] arrived at the conclusion that pits were deeper than wide with aspect ratios up to 4, many of which nucleated fatigue cracks were not

singular pits, but rather comprised of multiple needlelike pits. The observed synergistic effects of environmental, material and loading parameters on the environmental acceleration of fatigue crack growth in low-alloy RPV steels are discussed in [29]. Sivaprasad [30] noted the mechanism of corrosion fatigue crack growth for the two HSLA steels changes with attendant change in the Paris slope, and temperature, water flow speed, ionic concentration, material quality, and load condition play a crucial role in the behavior of fatigue crack propagation of SUS 630 [28]. Bjerkén [31] examined the manners in which the cracks grow and coalesce on the surface and showed that the cracks avoid each other initially and coalesce crack tip to crack side.

3.2 Stress intensity factor/ stress concentration factor around corrosion pits

Ramsamooj [32] suggested the parameters needed to predict corrosion fatigue might be the crack velocity caused by stress-corrosion, the applied mechanical stress, frequency, and the threshold stress intensity factor. Cerit and Genel [33] investigated the stress distribution at the semi-elliptical corrosion pits and pointed out that the aspect ratio is the main parameter affecting the stress concentration factor (SCF). The initiation and propagation of the non-propagating crack at the bottom of the artificial corrosion pit, were explained with the stress concentration factor of the pits and the stress intensity factor (SIF) range of the crack tip in [34]. Sankaran et al [4] concluded that the effects of pitting corrosion on fatigue lives can be related to the effects of equivalent stress concentration factors that are routinely used in structural design. Eduardo R. de los Rios [35] proposed an equation to evaluate the stress concentration as a function of distance from the pit center. Carpinteri et al [36-38] calculated the SIF of elliptical-arc surface cracks and the maximum stress-intensity factor is obtained at the deepest point on the crack front. W. Guo [39] showed that the SIF is strongly dependent on SCF, and the influence of notch geometry is negligibly weak for a given stress concentration coefficients. Toribio's [40] review on SIF for surface cracks in round bars under tension loading indicated that SIF increases with the crack depth and decreases with the crack aspect ratio and changes continuously from the crack center to the crack surface.

3.3 Effect of the corrosion pit on fatigue life

The influence of the pitting was on initiation and very early growth stages of fatigue. Further reductions in fatigue lives were associated with increases in pit size. And corrosion fatigue lives were reduced by 40-50% from those of pristine samples [27]. Y. Kondo [10] proposed a residual life prediction method for fatigue crack initiation for the case where crack initiation is controlled by pitting. P. Shi [22] studied on the damage tolerance approach for probabilistic pitting corrosion fatigue life prediction and found that pit nucleation time and the material constant for short crack growth are the two most important random variables affecting corrosion fatigue life. Emilio Bastidas-Arteaga [24] developed a model to predict the corrosion fatigue lifetime. The results showed that the coupled effect of corrosion-fatigue on structures strongly affects its performance, leading to large reduction in the expected lifetime.

Together with the rotating bending fatigue tests with various loads on shaft specimens in various extent of pitting corrosion conditions and the fatigue fracture surface analyses, the fatigue lifetime of SUS 630 shaft under various extent of pitting corrosion condition is found to be in a range of only 2.5-27% of that of the uncorroded condition [28]. Sriraman [12] presents a simple integrated deterministic model for life prediction in a high-strength aluminum alloy subject to pitting corrosion under cyclic stresses. The overall corrosion-fatigue life is the sum of crack initiation and propagation. At higher stress levels, there is not enough time for pits to develop and hence failure is not associated with stress concentration at the base of a pit, whereas life prediction at low stress amplitude is possible using only pit growth times [13]. Dolley [18] interpreted the reduction in fatigue life depending upon the pre-corrosion time and in turn the initial pit size. Rokhlin [19] established an empirical relation to predict fatigue life $N = N_{th}(d/h)^{-3/4}$. Yongming Liu [41] predicted the probabilistic fatigue life by using an equivalent initial flaw size (EIFS) distribution, which is independent of applied load level and only uses fatigue limit and fatigue crack threshold stress intensity factor. A method for estimation of the cumulative distribution function (CDF) for the lifetime is demonstrated to predict the lifetime, reliability, and durability beyond the range of typical data by integrating the CDFs of the individual RVs into a mechanistically based model [42].

4. Corrosion fatigue testing

To further illustrate the effect of corrosion pit on fatigue life, the test on pre-pitted in air and in corrosion solution of 3.5% NaCl were conducted. Fig.2 shows the *S-N* data for air and corrosion fatigue tests. It can be seen that the air fatigue P1200 samples have the longest fatigue lifetimes. The stress concentration factor of the pre-pitted samples, with a pit aspect ratio of 0.11, is around 1.5 [33]. This geometry of defect significantly reduces the fatigue life by over 60%. At 298 MPa, the air fatigue life of the pre-pitted sample is only 16% of that of the P1200 samples, while the corrosion fatigue lives are further reduced. The corrosion fatigue strength reduced from 279 MPa (in air) to 126 MPa (in 3.5 % NaCl) at 10^7 cycles. A previous study by Masaki et al [34] showed that the fatigue strength of pitted specimens for 316NG at 10^8 cycles is approximately half that of unpitted specimens, where the SCF of the pre-pit was assumed to be approximately 2, almost equivalent to the fatigue strength reduction factor. However, the present study shows that the fatigue strength reduction factor is much greater than the stress concentration factor.
The corrosion pits have smaller stress concentration factor than the pre-pit due to their smaller depth [33], implying that pre-pitted samples having longer fatigue lives than initially-smooth samples that develop pits within a corrosive solution. Furthermore, the smooth samples in 3.5%NaCl have shorter fatigue lives than the pre-pitted samples in air, indicating that electrochemical effects, i.e., localized corrosion, has a greater effect on fatigue life than mechanical effects, especially as stress levels fall below the in-air fatigue limit.

5. Modeling of corrosion pit development

As literatures stated above that the corrosion pits can be simplified as semi-elliptical pits. Cracks originates from pits where the SCF is the biggest. To calculate the SCF around pits, a 3-D model is developed on a round bar under uniaxial tension and bending loading by using FEM. The 3-D model has various pit diameter (*2c*) and depth (*a*) ranging from 80 to 1000 μm. A total of 82878 finite elements and 118406 nodes are employed.

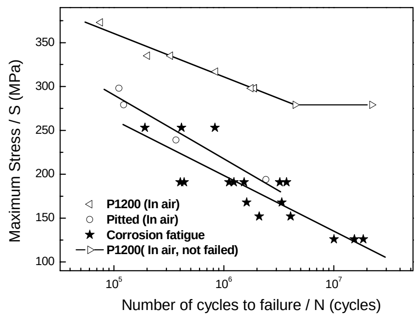
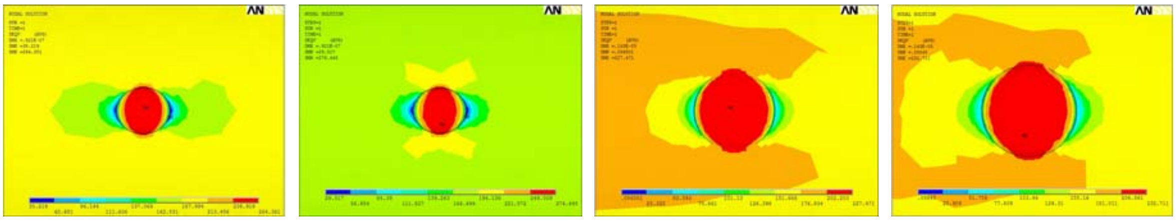


Fig. 2. S-N data for air and artificial seawater environments.

Figs. 3 show the maximum stress within the pit. The maximum stress is not always at the bottom of corrosion pit and it moves to the mouth with the aspect ratio *a/2c* increasing. The maximum stress occurs at the bottom when *a/2c* is less than 1/7 under tension loading and *a/2c* less than 1/10 under bending loading.



(a) *a/2c* =1/7 (b) *a/2c* =1/6 (c) *a/2c* =1/10 (d) *a/2c* =1/9

Fig. 3.The maximum stress distribution at various aspect ratios under tension (a), (b) and bending (c), (d).

Cracks initiate from the point where the stress concentration is highest. Then the corrosion pit transfers to crack when the stress intensity factor for the equivalent surface crack growth for the pit reaches the threshold stress intensity factor for the fatigue crack growth, and the corrosion fatigue crack growth rate exceeds the pit growth rate.

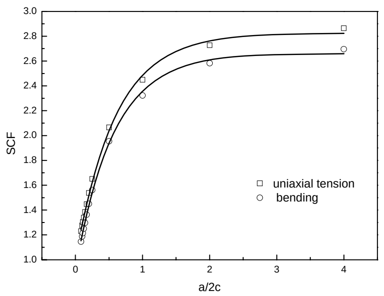
The SCF is largely influenced by the aspect ratio (*a/2c*) and the type of loading mode, as shown in Fig.4. The SCF increases greatly with increasing aspect ratio when *a/2c* is less than 1, and slow down when *a/2c* is between 1-2. It remains unchanged as *a/2c* is greater than 2. The tension loading produces bigger SCF than the bending. Also compared is the depth effect and width effect, illustrated in Fig. 5. The pit depth has much bigger effect than the pit width.

6. Conclusion

The corrosion pit size and shape development and its effect on crack initiation and fatigue life were reviewed. It suggested the following:

1) Various relationships were developed for corrosion pit depth and pit width. But the literatures mostly suggest that the pit width follows a linear relationship with time and the pit depth is linearly proportional to the square root of time.

2) The higher the stress amplitude the more corrosion pits formed. Compared to artificially-induced pits, real corrosion pits have a smaller stress concentration factor, but lead to shorter fatigue lifetimes.



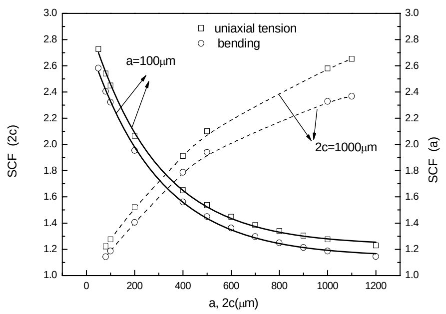


Fig. 4 SCF variation with *a/2c* Figure. Fig.5 SCF variation with *2c* and *a*

3) Cracks do not necessarily originate from the bottom of the pit. Rather, it starts from the point which has the biggest SCF. The aspect ratio affects the SCF greatly when *a/2c* is less than 1 but almost has no effect when *a/2c* is greater than 2. The pit depth has much bigger effect on SCF than the pit width does.

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References

[1] Sriraman M R, Pidaparti R M, Crack initiation life of materials under combined pitting corrosion and cyclic loading. J. Mater. Eng. Performance, 19 (2010) 7-12.

[2] Boag A, Taylor R J, Muster T H, Goodman N, McCulloch D, Ryan C, Rout B, Jamieson D, Hughes A E, Stable pit formation on AA2024-T3 in a NaCl environment. Corro. Sci., 52 (2010) 90-103.

[3] Ebara R, Corrosion fatigue crack initiation in 12% chromium stainless steel. Mater. Sci. Eng. A, 468–470 (2007) 109-113.

[4] Sankaran K K, Perez R, Jata K V, Effects of pitting corrosion on the fatigue behavior of aluminum alloy 7075-T6: modeling and experimental studies. Mater. Sci. Eng.: A, 297 (2001) 223-229.

[5] Rybalka K V, Shaldaev V S, Beketaeva L A, Malofeeva A N, Development of pitting corrosion of stainless steel 403 in sodium chloride solutions. Russian J. Electrochem., 46 (2010) 196-204.

[6] Rybalka K V, Beketaeva L A, Shaldaev V S, Kasparova L V, Davydov A D, Development of pitting corrosion on 20Kh13 steel. Russian J. Electrochem., 45 (2009) 1217-1225.

[7] Ernst P, Newman R C, Pit growth studies in stainless steel foils. I. Introduction and pit growth kinetics. Corro. Sci., 44 (2002) 927-941.

[8] Ernst P, Newman R C, Pit growth studies in stainless steel foils. II. Effect of temperature, chloride concentration and sulphate addition. Corro. Sci., 44 (2002) 943-954.

[9] Harlow D G, Wei R P, A probability model for the growth of corrosion pits in aluminum alloys induced by constituent particles. Eng. Fract. Mechan., 59 (1998) 305-325.

[10] Kondo Y, Prediction of fatigue crack initiation life based on pit growth. Int. J. Fat., 11 (1989) 280.

[11] Cavanaugh M K, Buchheit R G, Birbilis N, Modeling the environmental dependence of pit growth using neural network approaches. Corro. Sci., 52 (2010) 3070-3077.
[12] Sriraman M R, Pidaparti R M, Life Prediction of Aircraft Aluminum Alloys Subjected to Pitting Corrosion Damage Under Cyclic Stresses. J. AIRCRAFT, 46 (2009) 1253-1259.
[13] Buxton D C, Cottis R A, Scarf P A, McIntyre P, Life prediction in corrosion fatigue, in: Proc. Int. Conf. Corrosion-Deformation Interaction, Fontainebleau, France, 1992, pp. 901-913.
[14] Turnbull A, McCartney L N, Zhou S, A model to predict the evolution of pitting corrosion and the pit-to-crack transition incorporating statistically distributed input parameters. Corro. Sci., 48 (2006) 2084-2105.
[15] Turnbull A, Zhou S, Pit to crack transition in stress corrosion cracking of a steam turbine disc steel. Corro. Sci., 46 (2004) 1239-1264.
[16] Pidaparti R M, Patel R K, Investigation of a single pit/defect evolution during the corrosion process. Corro. Sci., 52 (2010) 3150-3153.
[17] Jeffrey R, Melchers R E, The changing topography of corroding mild steel surfaces in seawater. Corro. Sci., 49 (2007) 2270-2288.
[18] Dolley E J, Lee B, Wei R P, The effect of pitting corrosion on fatigue life. Fat. Fract. Eng. Mater. Struct., 23 (2000) 555-560.
[19] Rokhlin S I, Kim J Y, Nagy H, Zoofan B, Effect of pitting corrosion on fatigue crack initiation and fatigue life. Eng. Fract. Mechan., 62 (1999) 425-444.
[20] Burstein G T, Pistorius P C, Mattin S P, The nucleation and growth of corrosion pits on stainless steel. Corro. Sci., 35 (1993) 57-62.
[21] Li L, Li X, Dong C, Huang Y, Computational simulation of metastable pitting of stainless steel. Electrochimica Acta, 54 (2009) 6389-6395.
[22] Shi P, Mahadevan S, Damage tolerance approach for probabilistic pitting corrosion fatigue life prediction. Eng. Fract. Mechan., 68 (2001) 1493-1507.
[23] Shi P, Mahadevan S, Corrosion fatigue and multiple site damage reliability analysis. Int. J. Fat., 25 (2003) 457-469.
[24] Bastidas-Arteaga E, Bressolette P, Chateauneuf A, Sánchez-Silva M, Probabilistic lifetime assessment of RC structures under coupled corrosion – fatigue deterioration processes. Struct. Safety, 31 (2009) 84-96.
[25] Ebara R, Corrosion fatigue crack initiation behavior of stainless steels. Procedia Eng., 2 (2010) 1297-1306.
[26] Chen G S, Wan K C, Gao M, Wei R P, Flournoy T H, Transition from pitting to fatigue crack growth-modeling of corrosion fatigue crack nucleation in a 2024-T3 aluminum alloy. Mater. Sci. Eng.: A, 219 (1996) 126-132.
[27] Medved J J, Breton M, Irving P E, Corrosion pit size distributions and fatigue lives—a study of the EIFS technique for fatigue design in the presence of corrosion. Int. J. Fat., 26 (2004) 71-80.
[28] Ma F Y, Wang W H, Fatigue crack propagation estimation of SUS 630 shaft based on fracture surface analysis under pitting corrosion condition. Mater. Sci. Eng.: A, 430 (2006) 1-8.
[29] Seifert H P, Ritter S, Corrosion fatigue crack growth behaviour of low-alloy reactor pressure vessel steels under boiling water reactor conditions. Corro. Sci., 50 (2008) 1884-1899.
[30] Sivaprasad S, Tarafder S, Ranganath V R, Tarafder M, Ray K K, Corrosion fatigue crack growth behaviour of naval steels. Corro. Sci., 48 (2006) 1996-2013.

[31] Hejman U, Bjerk E N C, Environmentally assisted initiation and growth of multiple surface cracks. Int. J. Solids and Structures, 47 (2010) 1838-1846.
[32] Ramsamooj D V, Shugar T A, Modeling of corrosion fatigue in metals in an aggressive environment. Int. J. Fat., 23, Supplement 1 (2001) 301-309.
[33] Cerit M, Genel K, Eksi S, Numerical investigation on stress concentration of corrosion pit. Eng. Failure Analysis, 16 (2009) 2467-2472.
[34] Masaki K, Ochi Y, Matsumura T, Small crack property of austenitic stainless steel with artificial corrosion pit in long life regime of fatigue. Int. J. Fat., 28 (2006) 1603-1610.
[35] de Los Rios E R, Mechanisms and Modelling of Cracking under Corrosion and Fretting Fatigue Conditions. Shot Peening, 241-254.
[36] Carpinteri A, Elliptical-arc surface cracks in round bars. Fat. Fract. Eng. Mater. Structu., 15 (1992) 1141-1153.
[37] Carpinteri A, Vantadori S, Surface cracks in round bars under cyclic tension or bending. Key Eng. Mater., 378-379 (2008) 341-354.
[38] Carpinteri A, Brighenti R, Vantadori S, Surface cracks in notched round bars under cyclic tension and bending. Int. J. Fat., 28 (2006) 251-260.
[39] Guo W, Shen H, Li H, Stress intensity factors for elliptical surface cracks in round bars with different stress concentration coefficient. Int. J. Fat., 25 (2003) 733-741.
[40] Toribio J, Alvarez N, Gonzalez B, Matos J C, A critical review of stress intensity factor solutions for surface cracks in round bars subjected to tension loading. Eng. Failure Analysis, 16 (2009) 794-809.
[41] Liu Y, Mahadevan S, Probabilistic fatigue life prediction using an equivalent initial flaw size distribution. Int. J. Fat., 31 (2009) 476-487.
[42] Harlow D G, Wei R P, Probability approach for prediction of corrosion and corrosion fatigue life. AIAA j., 32 (1994).