

A REVIEW ON STRESS CORROSION CRACKING MECHANISMS AND MODELS IN NUCLEAR POWER PLANTS

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Abstract

Stress corrosion cracking in the existing nuclear power plants consumes to the structures like a cancer does to human body. To estimate the exact value of the cracks and life of the structure, quantitative mechanisms and models play important role. In view of the stress corrosion cracking of materials in Light water environment, many scholars have proposed different mechanisms and models to explain the stress corrosion cracking phenomenon quantitatively and theoretically. Some of these models are quantitative formulas, while others are qualitatively explained. Not a single mechanism or model has been developed to explain or predict the effect of all the possible influencing factors on stress corrosion cracking growth rate in light water reactor environment. This research introduces all the possible mechanisms and corresponding models used to estimate the stress corrosion cracking growth rate at elevated temperature. The reasons for the failure of the mechanisms have been mentioned and a recommended new model of estimating the stress corrosion cracking growth rate may be further studied.

1. INTRODUCTION**Mechanisms****Slip-oxidation mechanism**

This mechanism is mainly based on several different variables that affect the Stress corrosion crack growth rate of carbon steel, stainless steel, and nickel-based alloys at high temperatures. This mechanism targets the model presented by Ford and Andresen[1–3]. The stress corrosion cracking (SCC) growth rate of the crack is related to the oxidation reaction of the crack tip with the increase of matrix strain. The rupture of the protective film of the crack tip occurs at that time when the exposed part of the crack tip begins to oxidize, which determines the growth rate of the crack. Faraday's law can be used to link to the charge generated by the dissolution and passivation reaction of the bare metal at the crack tip during the SCC growth rate. This connection is based on the idea that when the crack tip slips, it will cause structural damage to the passivation film, and the metal will be oxidized to a certain extent to return to its original state. The variables affecting the crack tip system can be basically divided into mechanical and chemical/Electrochemical factors. Mechanical factors (including stress, strain state, creep rate, yield stress, crack growth rate, and grain boundary structure of the crack tip) control the strain rate of the crack tip, and thus control the periodic oxide film rupture at the crack tip. Chemical factors (material composition and water chemistry of the crack tip, both are also affected by corrosion potential, impurities, and flow rate) control the passivation reaction of the crack

tip.

One of the main goals of the slip-oxidation mechanism is to predict the growth rate of cracks. The prediction of corrosion behavior is mainly based on the crack growth rate, which in turn is a function of the strain rate of the crack tip and parameter, n . According to the slip dissolution/membrane rupture model, the expression of the crack growth rate is as follows:

$$\bar{V}_t = \frac{M}{z\rho F} \frac{Q_f}{\varepsilon_f} d\varepsilon_{ct}/dt \quad (1)$$

where M = the atomic mass of the dissolved metal

ρ = metal density

F = Faraday's constant

z = number of electrons lost by oxidation

Q_f = oxidation charge density

ε_f = strain required for oxide film rupture

$d\varepsilon_{ct}/dt$ = the strain rate at the crack tip.

When the crack tip in the metal is completely exposed to the oxidation of the passivation film again, the oxidation current has an attenuation, the corresponding attenuation process can be expressed by the following power relationship:

$$i_t = i_0 \left(\frac{t}{t_0} \right)^{-n} \quad (2)$$

So, the equations (1) can be transformed into the following form.

$$\bar{V}_{max} = \frac{M}{z\rho F} i_0 \quad (3)$$

All influencing factors related to the passivation process in the slip-oxidation model are associated with the parameter n , which is an empirical value determined by the slope of the current decay curve during passivation. It is related to corrosion potential, solution conductivity and properties of the material. The crack rate prediction formula based on slip oxidation mechanism performs well in the practical situation, and the prediction results are in good agreement with the experimental data[4]. However, the oxidation mechanism does not give a clear picture of control steps for crack propagation neither, the rate of control step in derivation of the crack propagation formula for this mechanism is estimated correctly. After considering various influencing factors, Andresen and its collaborators believe[5] that the kinetic processes of passivation (such as the formation and growth of a passivation film on the fresh and bare surface of the crack tip metal) are the main factors that control the crack growth. In this way, in a specific environment, when the crack tip chemistry is highly aggressive, the crack rate is also faster, because the rate of rupture and reoxidation of the oxide film is faster in this environment. Different scholars have different views on the rate of control steps in slip-oxidation mechanism.

Taylor et al.[6] proposed that the rate of control step for stress corrosion in Inconel 600 at 288°C pure water is due to water diffusion. Congleton and Parkins[7] believe that the cracking mechanism is electrochemically controlled, and that the nature of the oxide film is the most important aspect. Ruther et al.[8] believe that the rate of step for stress corrosion cracking of AISI 304 stainless steel is a cathodic reaction that depends upon the reduction or oxidation of oxygen ions being at central location of atoms and varying multiple oxidation states. At the same time, the slip-oxidation mechanism has also received a lot of criticism. MacDonald[9] believed that the model violates Faraday's fundamental law and the law of conservation of charge. Rebak and Szklarska-Smialowska[10] noted that the slip-oxidation mechanism does not explain in detail variations in temperature, pH, and the influence of carbides at grain boundaries. Turnbull and Psaila Dombrowski think that for some of the experimental results on which the oxidation mechanism is based are inherently problematic. For example, the compact tensile specimens of Teflon used in the experiment led to the ignorance of the reactions that occur on the inner wall of the crack and their influence on conductivity

and the distribution of the potential field inside the crack, as well as the current intensity[11].

In general, the slip-oxidation mechanism is based on several well-established concepts which are typical examples of combining existing theoretical foundations, crack chemistry and relevant variables (oxide failure and re-passivation) in any BWR environments through empirical characteristics.

Surface Migration Mechanism (SMM)

Different embrittlement phenomena usually have similar characteristics, but no environmental induced cracking theory can explain this phenomenon. Based on this phenomenon, a universal mechanism was proposed. This is also the first mechanism that can predict the environmental sensitivity of materials before cracks occur. According to this mechanism, the atoms at the tip of the crack move from the high-stress region to the low-stress zone inside the crack through surface diffusion, so that the crack generates a distance between atoms. Crack multiplication occurs when the stressed lattice at the tip of the crack hits the hole. The rate of control step of this process is the rate at which the adsorbed atoms move along the crack surface and the environment changes the size of the self-diffusion effect on the crack surface of the metal or alloy. Based on SMM mechanism the calculation formula for the crack growth rate is as follow[12]:

$$\frac{da}{dt} = \frac{D_s}{L} \left[\exp \left(\frac{\sigma a^3}{kT} \right) - 1 \right] \quad (4)$$

where $D_s(\text{m}^2/\text{s})$ = the surface diffusion coefficient

$L(\text{m})$ = the diffusion path length

$a(\text{m})$ = the atomic diameter

$\sigma(\text{N}/\text{m}^2)$ = the maximum stress at the crack tip

$T(\text{K})$ = temperature

$k(\text{J}/\text{K})$ = Boltzmann constant

For prefabricated sharp elliptical crack specimens, the stress expression for the crack tip is as follows:

$$\sigma = \frac{K_I}{\sqrt{\pi d}} \left(0.34 \frac{d}{a} + 1 \right) \quad (5)$$

where d = half the crack length and a is the atomic spacing

According to the SMM mechanism, the crack rate does not always increase with the increase of K_I , but when the K_I reaches a certain level, the crack rate change curve appears a plateau, because the dislocation released by the crack tip will lead to the passivation of the crack tip. In this case, the stress no longer increases, and the material begins to yield.

In some cases, the predictive mechanism based on SMM performed well, but Sieradzki et al.[13] noted that the model overestimated the stress corrosion cracking crack rate of blunt face-centered cubic metals by large difference of magnitude. Galvele argues that Sieradzki's calculation process does not consider the role of the environment. Gutman [14] believed that under stress, the creep is based on self-diffusion of mass transport. The SMM mechanism is not credible because on the basis of SMM, the calculated crack propagation rate is not equal to the diffusion creep deformation rate tested simultaneously with the same stress and the same material. Trunbull [11] was of the view that correctness of the surface mass transmission assumption is questionable. He also pointed out that although the model considers the role of local chemistry in determining the characteristics of surface membranes, however the model lacks the relationship between environment and membranes.

Internal oxidation mechanism

On the basis of the diffusion of oxygen into the metal gold grid, the explanations were proposed by Scott and Calvar[15] for Alloy 600 stress corrosion cracking in nuclear power plants. The mechanism depends on the brittle fracture along the crystal. The embrittlement of materials under this mechanism is caused by the oxygen atomic layer at the grain boundary or by the internal oxide formed at the grain boundary (Cr_2O_3) and bubbles (CO/CO_2) caused. The internal oxidation model is more suitable when the corrosion potential is

close to the oxidation potential of the solvent metal. In this case, the trace alloying element with a negative potential will oxidize inside the material, leaving the body element of the alloy in its original state. This situation is normal in case of atmospheric corrosion of nickel-based alloys. When nickel-based alloys are in an atmospheric environment with low partial pressure of oxygen, that time they can meet the requirements of trace amounts of alloying elements with negative potential (Fe,Cr) , while the potential is positive for solvent metals. At the same time, oxidizing particles such as Cr must also be below a certain concentration to prevent only this particle from forming a protective outer film. According to the bubbles generation process near the grain boundary, this mechanism also gives the calculation formula of crack growth rate:

$$\frac{da}{dt} = \left[\frac{81kTD_0}{512\gamma^3 a^2} \right] \left[\frac{\delta N_s}{6\pi z} \right]^{0.5} \sigma_p K_I \quad (6)$$

where k =Boltzmann constant

T = the absolute temperature

D_0 =grain boundary diffusion coefficient of oxygen

γ = surface energy

a =atomic spacing

δ = grain boundary thickness

N_s = the surface solubility of oxygen

z =number of regions where gas atoms jump

σ = the yield strength

K_I = stress strength factor,

By putting the corresponding parameters of Alloy 600 in Equation (6) at 330°C (light water reactor environment), the relationship between crack growth rate (CGR) and stress intensity factor is as follows:

$$CGR = 2.6719 \times 10^{-11} K_I \quad (7)$$

The unit of CGR is m/s and the unit of K_I is $\text{MPa.m}^{1/2}$.

Staehle and Fang [16]pointed out that the experimentally observed diffusion rate of oxygen in nickel-based alloys was much lower than the diffusion rate required to explain the low-potential of Inconel 600/Alloy 600 stress corrosion growth rate. At the same time, the internal oxidation model is not suitable for boiling water reactors (BWR) environments, where corrosion potentials are much higher than pressurized water reactors (PWRs).

Hydrogen-induced cracking mechanism

One of the most common mechanisms for visualization of stress corrosion cracking is the hydrogen-induced cracking mechanism for nickel-based alloys and stainless steel[17]. Under the action of corrosion and polarization, atomic hydrogen is dissolved in the alloys which leads to the initiation of cracks, that has also been confirmed by relevant experiments[18]. However, the current experimental results still do not confirm that hydrogen plays a leading role in the process of environmental cracking. The hydrogen inside the crack comes mainly from the cathodic reaction of the crack tip at a lower corrosion potential. J.M.Olive[19] observed solution of MgCl_2 at 117°C using a telephoto microscope, under open potential 316L and found that hydrogen gas produced by stainless steel during the growth of corrosion fatigue cracks. The resulting gaseous hydrogen will also diffuse into the alloy as atomic hydrogen.

The current hydrogen-induced cracking mechanism is only in the stage of qualitative description and cannot quantitatively explain the influence of hydrogen. An explanation was proposed by Shen and Shewmon[20] based on high-density bubbles nucleating at grain boundaries of alloy 600 mechanism for corrosion cracking along crystal stress. The formation of bubbles was the result of the combined effect of pressure and external

stress caused by methane formed by the interaction of hydrogen and carbon generated by corrosion at grain boundaries. Shen and Shewmon believed that the anodic dissolution only has an indirect effect on the control of hydrogen content inside the injected alloy and the crack growth rate was determined by the diffusion of grain boundaries. Some experimental results also confirmed that when the activity of carbon and hydrogen in the alloy becomes high, the corresponding crack sensitivity becomes high too. However, other experimental results show that the material does not develop cracks under the action of high-pressure drying hydrogen, which is contrary to the basic principles of this mechanism. The bubbles at the tip of the crack and methane hypothesized by the authors have never been experimentally confirmed.

Redox mechanism at the crack tip

In a variety of different stress corrosion cracking mechanisms in high-temperature water environments, the oxidation reaction promoted at the crack tip is a mechanism to be considered. Although the basic reaction process of the oxidation reduction promoted by the crack tip is not described frequently in different mechanisms due to its limited use. Other mechanisms have also been failed with different reasons under specified conditions. In this mechanism, the failure can be the rupture of the oxide film at the crack tip, or the process by which the oxide film of the crack tip loses its corrosion resistance due to physical, chemical action or the original electrochemical state of the interface and the strength of the applied stress/strain, depending on the metal/oxide/solution. The applied stress can affect the rate of the interface reaction at the crack tip in a variety of ways such as through physical or physicochemical action or both. The physical action refers to the destruction of the oxide film at the tip of the crack under the action of stress strain in such a way that the base metal is exposed to the local environment and this damage can be the rupture of the oxide film or the oxide film becomes porous or more easily penetrated by the reaction solvent. Physicochemical action means that the stress-strain accelerates the basic reaction rate (such as electron transport step, mass transport step) without changing the rate to determine the type of step. Physical and chemical effects can also play a role at the same time.

By combining the oxidation kinetics of the crack tip and the mechanics through the strain rate of the crack tip, Shoji[21-23] presented a mechanism, FRI, for predicting the rate of crack development. In Ford-Andresen mechanism,[24,25]the strain rate in this model comes from the distribution of the strain field at the crack tip. The crack growth rate formula is as follows:

$$\frac{da}{dt} = \left[\frac{M}{z\rho F} \cdot \frac{i_0 t_0^m}{(1-m)} \right] \cdot \frac{1}{(\varepsilon_f)^m} \cdot \left(\frac{d\varepsilon}{dt} \right)^m \quad (8)$$

where $d\varepsilon/dt$ is the strain rate at the crack tip r_0 in the following expression:

$$\frac{d\varepsilon}{dt} = \beta \frac{\sigma_y}{E} \frac{n}{n-1} \left(\frac{2}{K} \frac{dK}{dt} + \frac{1}{r_0} \frac{da}{dt} \right) \left\{ \ln \left(\frac{\lambda}{r_0} \left(\frac{K}{\sigma_y} \right)^2 \right) \right\}^{\frac{1}{n-1}} \quad (9)$$

where β and λ = dimensionless constants

n = Ramberg-Osgood strain strengthening factor

K = stress intensity factor

z = valence change of the oxidation process

F =Faraday's constant

ε_f = breaking strain of the oxide film.

m , i_0 and t_0 = characteristic parameters of the oxidation current decay curve

σ_y =the yield strength

E = Young's modulus

Equation 9 is the represents the formula to calculate the strain rate comes from Gao and Hwang[26] with the assumption that strain distribution at the crack tip under planar strain conditions explicitly includes tensile characteristics. In this calculation, the problem of mechanical fracture singularity is avoided by introducing

the eigen value distance r_0 , which is also a function of several factors.

Coupling Environmental Fracture mechanisms (CEFM)

The environment-coupled cracking mechanism, proposed by Macdonald and Urquidi-Macdonald[27] presents an idea similar that of the slip-oxidation mechanism but it is slightly different from slip-oxidation mechanism. This mechanism emphasizes that the internal environment of the crack and the external environment are coupled together, and at the same time, the law of conservation of charge is strictly followed in the establishment of the mechanism. In other words, the sum of the redox currents inside and outside the crack at the crack tip is zero. The environmental coupled cracking model was originally proposed for pre-embedded cracks. This mechanism was developed to check the sensitivity of stress corrosion cracking for 304 stainless steel in the light water reactor environment but after nearly two decades of development and improvement, the scope of application of this mechanism has gradually become wider, and the mechanism extends from high temperature and high pressure pure water environment to room temperature solution[28]. The material extends from stainless steel to carbon steel [29]Aluminum alloy[28], nickel-based alloys[30]. The corrosion type extends from stress corrosion cracking to pitting and crevice corrosion, and the predicted form also extends from the initial crack rate extension to the crack shape evolution[31].

This mechanism has also caused some controversy, such as slippage-formation of the oxidation mechanism as Andresen and Ford[32] think that CEFM generates different impurity anion pairs which cannot be distinguished with the same conductivity, hence, stress corrosion cracking growth rate is different than the actual values. Andresen and Ford at the same time think CEFM is not safe mechanism as it relies only on potential gradients for particle transport inside cracks as CEFM is the mechanism that depends only on physics, so far, an Electrochemical mechanism. However, there is an example for calculating the stress corrosion cracking growth rate of 304SS with high accuracy (0.5 orders of magnitude) under the BWRs conditions systematically by this mechanism where the calibration of the mechanism only needs one data point to predict accurately the influence of all environmental variables and the mechanism becomes relatively more worthy of recognition based on basic research evidence.

Calculation model of stress corrosion cracking crack propagation rate of nuclear power structural materials

Considering stress corrosion cracking a serious cause of failure in the materials of LWRs nuclear power plant environment and the various safety and economic problems caused by it, it is necessary to establish a model to predict the growth rate of stress corrosion cracking. The establishment of this model will provide theoretical guidance for the maintenance of nuclear power plants because unnecessary frequent shutdown maintenance will increase economic costs and untimely maintenance will cause serious leakage problems. To end or reduce this, researchers around the world are working hard to build a model that can accurately predict the growth rate of stress corrosion cracking in nuclear power plants. However, based on the fact that stress corrosion cracking is an extremely complex phenomenon, more than 20 influencing factors are known[33] in stress corrosion cracking which also makes the establishment of this model extremely difficult. At present, the world's common models are roughly divided into two categories, one is a deterministic prediction model based on various stress corrosion cracking mechanisms, and the other is an empirical prediction model based on many experimental data and field data.

Deterministic models

Slip oxidation model

The slip oxidation model or the slip-dissolution/film rupture model, which is based on the stress proposed by the slip oxidation mechanism. This model was proposed by Ford and Andresen, and at first this model was only for quantitative prediction of stress corrosion cracking of stainless steel and low alloy steel in different water environments below 115°C, but when the prediction data of this model was extrapolated from low temperature (115°C) to high temperature (288°C), it also matched the experimental observations. The

quantitative prediction of crack growth rate by slip oxidation model is based on the Faraday relationship between the oxidation current density of the crack surface and the amount of metal atoms oxidized from the metallic state to the oxidation state. Therefore, for a specific material and its crack tip environment, the crack growth rate is mainly determined by the frequency of changing relationship of oxidation current density with time and the film rupture in the crack tip strain state. The frequency of membrane rupture is mainly determined by the strain and strain rate of the membrane. By introducing Faraday's law, the environmental promotion stress corrosion cracking crack growth rate is related to the oxidation current density during membrane rupture:

$$\bar{V}_t = \frac{M}{z\rho F} \frac{Q_f}{\varepsilon_f} \dot{\varepsilon}_{ct} \quad (10)$$

where M and ρ = the atomic weight and density of the crack tip metal

F = Faraday's constant

z = the number of electrons migrating during the oxidation of metal atoms.

Since the oxidation current density relationship with time is mainly determined by the material and environmental composition, the Equations (10) can be expressed using the power relationship as follows:

$$\bar{V}_t = A(\dot{\varepsilon}_{ct})^n \quad (11)$$

where A and n = constants related to the crack tip material and environmental composition, which are related to a specific crack tip material, ambient oxidation reaction rate, or current density dependent.

When the crack tip metal is exposed, there is a peak current corresponding to the I_0 , and the time of this process is t_0 , so when the oxide is formed, or a deposition reaction occurs, the oxidation current will be power-decayed.

$$i_t = i_0 \left[\frac{t}{t_0} \right]^{-n} \quad (12)$$

When the crack tip metal is exposed (e.g. $\varepsilon_f/\dot{\varepsilon}_{ct} < t_0$), this corresponds to the maximum crack propagation rate.

$$\bar{V}_{max} = \frac{M}{z\rho F} i_0 \quad (13)$$

However, in the LWR environment, the material is generally in a constant load or constant displacement state. In this case, the period of membrane rupture $\varepsilon_f/\dot{\varepsilon}_{ct}$ will be much greater than t_0 . At this point, the crack tip metal will no longer be in exposed state, integrate Equation (11) and by substituting the resulting accumulated electricity Q_f into Equation (10), the following expression can be obtained to calculate the crack growth rate:

$$\bar{V}_t = \frac{M}{z\rho F} \frac{i_0 t_0^n}{(1-n)\varepsilon_f^n} \dot{\varepsilon}_{ct}^n \quad (14)$$

In the case of constant load or constant displacement $\dot{\varepsilon}_{ct}$, is the correlation with creep processes of propagating cracks. In monotonic changes or under the systemic strain condition of cyclic change, $\dot{\varepsilon}_{ct}$ is related to the applied strain rate. Therefore, the slip-oxidation model is not only suitable for stress corrosion, but also for strain-induced cracks or corrosion fatigue [34].

With a deeper study and understanding of the basic reaction of the crack tip system, the parameters in Equations (14) have been determined for stainless steel, and the expression of the crack growth rate can be simplified to the following form:

$$da/dt = 7.8 \times 10^{-3} \cdot n^{3.6} \cdot (d\varepsilon/dt)_{ct}^n \quad (15)$$

where da/dt is measured in cm/s and n has a value of range 0.33-1.0, and its determinants are discussed below. The unit of strain rate at the crack tip is /s. As mentioned above, n is a passivation rate parameter controlled by the crack tip environment (e.g., pH, potential, cationic activity) and the material (e.g., percentage of chromium consumed at grain boundaries). To quantify n, think of it as a function of testable

system variables, such as the conductivity of water (κ), the corrosion potential (ϕ_c) determined by the content of dissolved oxygen and hydrogen peroxide, and the electrochemical potential reactivation (EPR parameters) associated with chromium at grain boundaries. The expression for n is as follows:

$$n = \left\{ \frac{e^{f(\kappa)}}{e^{f(\kappa)} + e^{g(\phi_c)}} \right\}^{h(EPR)} \quad (16)$$

The strain rate $d\varepsilon/dt$ at the crack tip is related to the stress (or strength). Under constant load conditions, the relationship between the strain rate of the crack tip and the stress intensity factor is as follows:

$$(d\varepsilon/dt)_{ct} = 8.8 \times 10^{-14} \cdot K^4 \quad (17)$$

where the unit of strain rate is /s and the stress intensity factor K has unit equal to $\text{MPa} \cdot \text{m}^{1/2}$.

FRI model

FRI Model stands for Fracture Research Institute Model, which was developed in Tokyuu University in Japan by Professor Tetsuo Shoji and his collaborators[23,35]. FRI model considers both electrochemical influences and mechanical fractures. In the latest version of model, Ford extended it to changes in stress in the material. The influence of strain characteristics and crack propagation rate on the crack tip was considered[35,36]. FRI General expressions of the model, is represented below, see Equation (18).

$$\dot{a} = \frac{Mi_0}{z\rho F(1-m)} \left(\left(\frac{t_0}{\varepsilon_f} \right) \left[\frac{\beta \sigma_{0.2} n}{E(n-1)} \right] \left(2 \frac{\dot{K}}{K} + \frac{\dot{a}}{r_0} \right) \left\{ \ln \left[\left(\frac{\lambda}{r_0} \right) \left(\frac{K}{\sigma_{0.2}} \right)^2 \right] \right\}^{\frac{1}{n-1}} \right)^m \quad (18)$$

where $\dot{a}$ = crack growth rate CGR (mm/s)

M = relative atomic mass (g/mol) and

i_0 = oxidation current density of the activated surface (A/mm^2)

z = electron transfer number

ρ = mass density (g/mm^3)

F = Faraday's constant ($96500\text{C}/\text{mol}$)

t_0 = current decay starts time (s)

ε_f = breaking strain of the oxide film (mm/mm)

β, λ = dimensionless constant

$\sigma_{0.2}$ = yield strength (MPa)

E = Young's modulus (MPa)

n = strain hardening factor

K = stress intensity factor ($\text{MPa} \cdot \text{m}^{1/2}$)

r_0 = characteristic distance (mm) in the core region, region in which the crack propagates.

CEFM model

Like the slip-oxidation model, the CEFM model calculates the crack propagation rate based on the periodic rupture of the passivation film at the crack tip. The formula for calculating cracks is given by Faraday's law

$$\frac{dL}{dt} = \frac{MI_0}{2\rho_m zFW\delta} \quad (19)$$

There ρ_m = density of the metal (g/cm^3)

F = Faraday's constant

L = crack length (cm)

I_0 = the average current density of the crack tip

M = average atomic mass calculated according to the composition of each element of the alloy

z = the average number of electrons gained and lost in the dissolution oxidation reaction of the alloy at the crack tip calculated according to the composition of each element of the alloy.

Empirical models**PM Scott model**

For the continued safe operation of nuclear power plants, Westinghouse USA, since 1992, have been developing a reliable forecast for a model to calculate the crack growth rate of alloy 600 in nuclear power plants. However, at that time there was not much crack growth rate data that could be used for the tip protruding device, and there were only a few articles related to crack growth rate of alloy 600 materials. One of the best described models for the rate of crack propagation is Peter model. According to the relevant experimental data, Peter Scott [37] used the fitted equation below to predict alloy 600 crack propagation rate.

$$\frac{da}{dt} = C \cdot (K - 9)^{1.16} \quad (20)$$

where K is measured in MPa.m^{1/2}, and this equation also states that the threshold of the stress intensity factor used is K_{ISCC}=9 MPa.m^{1/2}. Here C is the correction coefficient, which corresponds to different temperatures, and the value is different.

MRP-55 model

Material Reliability Program MRP-55 model [38,39] is associated with Electric Power Research institute (EPRI) which is based on the experimental data. The stress corrosion cracking propagation rate of alloy 600 is mainly measured by applying the curve caused by the main circuit of manufactured thick-walled components. The piping of the steam generator is a thin-walled part, so it is not within the prediction range of this curve. The relevant test data mainly came from Westinghouse in the United States and Sweden. Test materials include 22 Different grades of control rod drives (CRD), thick-walled pipes, rolled bars, forged bars and 4 Different grades of plates. The relevant tests can accurately investigate the effects of applied load and temperature on crack propagation rate. It is generally believed that the crack growth rate of material such as alloy 600 in the PWR environment can be calculated by modeling the stress intensity factor. The influence of different temperatures on the crack growth rate can be explained by introducing the Arrhenius formula, and the corresponding expression is as follows:

$$a' = \exp \left[-\frac{Q_g}{R} \left(\frac{1}{T} - \frac{1}{T_{ref}} \right) \right] \alpha (K - K_{th})^\beta \quad (21)$$

where a' (m/s) = crack growth rate at temperature T

Q_g = crack growth rate temperature activation energy which is about 130kJ/mol

R = constant with a size of 8.314×10⁻³kJ/mol.K

T(K) = absolute temperature corresponding to crack propagation

T_{ref}(K) = reference temperature corresponding to normalized data

α = amplitude of crack propagation rate at 325 °C, $\alpha=2.67 \times 10^{-12}$, the corresponding units of a' are m/s, and the unit of K is MPa.m^{1/2}

K (MPa.m^{1/2}) = crack tip stress intensity factor

K_{th} (MPa.m^{1/2}) is the stress intensity factor threshold

β = exponent, and its value is 1.16.

The MRP prediction curve represents the average of the upper half of the discrete distribution of different crack growth rate data for different grades of materials, so the MRP curve can be used to describe the crack growth rate of sensitive materials that are faster than the average crack initiation rate. Because cracks detected in operating nuclear power plants are generally located on components made of these sensitive materials.

Conclusion and Recommendations

So far, the models for predicting the growth rate of stress corrosion cracking in nuclear power structural materials have been based on mechanical or electrochemical theories. However, a common feature of these models is that they cannot fully predict the influence of every factor of stress corrosion cracking phenomenon

on it because of the complexity of stress corrosion cracking.

Considering the complexity of the stress corrosion cracking mechanism into the models used for calculating the stress corrosion cracking and rendering these models difficult to predict crack growth rate, artificial neural networks provide a solution that can make accurate predictions by doing analysis from existing data. Another advantage of artificial neural networks is that their predictions can go beyond the scope of experimental data, and their predictions can allow people to study a complex problem more deeply.

For a modeling analysis with multiple input and output systems, the artificial neural network models can be used. The input of the system is given to the neural network model, and the output of the system is taken as the target output of the artificial neural network, and when the neural network undergoes a certain cyclic learning period, it will establish the non-algebraic model corresponding to the system. Stress corrosion cracking is a very complex process by materials, environment, and stress. through screening to find out various influencing factors as input variables, and at the same time, there is a need to study objects (such as stress corrosion cracking crack growth rate) as output variables, by exercising and prediction of the artificial neural networks, will be able to provide a new way for the study of stress corrosion cracking.

Conflicts of Interests

The authors have no conflicts of interests.

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