STUDY FOR EXTENSION AND IMPROVEMENT ON MODELING OF PRIMARY WATER STRESS CORROSION CRACKING AT CONTROL ROD DRIVE MECHANISM NOZZLES OF PRESSURIZED WATER REACTORS[1]

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Abstract

Study for to extend and to improve the existing modeling for Alloy 600 for to propose a local approach to assess the primary water stress corrosion cracking in nickel-based components. It is includes a modeling methodology for new data for Alloy 182 and Alloy 600 initiation and crack growth according with a method based on Electric Power Research Institute-MRP-115 (2004), and United States National Regulatory Comission-NUREG/CR-6964 (2008). The experimental data will be obtained from CDTN-Brazilian Nuclear Technology Development Center, in SSRT equipments. The model concept assumed is to construct Pourbaix diagrams which indicate a thermodynamic condition for the occurrence of corrosion submodes in Nickel Alloys at high temperature primary water. Over these diagrams, it is superimposed different models including a semi-empiric-probabilistic one, to quantify the primary water stress corrosion cracking initiation time, and also a crack growth rate model in function of stress intensity factor of testing materials. These models shall be validated with experimental data. This study aims to extend some obtained models to weld metals like the Alloy 182, to develop crack growth rate tests, and to improve the originals for Alloy 600, according with a revised methodology. This one comprises laboratory testing procedures, data collecting, data screening, modeling procedures, data assembling from some laboratories in the world, plotting of results, compared analysis, and discussion of these results.

Key words: Nickel alloys; Pressurized water reactor; Slow strain rate testing; Stress corrosion.

ESTUDO PARA EXTENSÂO E APERFEIÇOAMENTO DA MODELAGEM DA FRATURA POR CORROSÃO SOB TENSÃO EM MECANISMO DE ACIONAMENTO DE BARRAS DE CONTROLE DE REATORES DE ÁGUA PRESSURIZADA

Resumo

Estudo para a extensão e aperfeiçoamento da modelagem existente para a liga 600 e proposta de uma abordagem local para avaliação da fratura por corrosão sob tensão em água pura em componentes de ligas de níquel. É proposta uma metodologia de modelagem de novos dados para a iniciação e crescimento de trincas nas ligas 182 e 600 de acordo com um método baseado no Programa de Confiabilidade dos Materiais do EPRI-MRP-115 (2004) e de Norma Reguladora da USNRC-NUREG/CR-6964 (2008). Os dados experimentais serão obtidos do Centro de Desenvolvimento da Tecnologia Nuclear, através de equipamentos de Ensaios de Taxa de Deformação Lenta. O conceito do modelo é a construção de diagramas de Pourbaix que indicam as condições termodinâmicas de ocorrência de submodos de corrosão nas ligas de níquel em água do circuito primário de reatores de água pressurizada. Sobre esses, são sobrepostos diversos modelos incluindo um semi-empírico-probabilístico, para quantificar o tempo de iniciação das trincas e também um modelo de propagação de trincas em função dos fatores de intensidade de tensão dos materiais ensaiados. Eles devem ser validados com os dados experimentais. Este estudo visa estender alguns modelos aos metais de solda como a liga 182, desenvolver modelos para propagação de trincas e melhorar os existentes para a liga 600, de acordo com uma metodologia aperfeiçoada. Essa inclui procedimentos de ensaios de laboratório, coleta e filtragem de dados, procedimentos de modelagem, comparações com conjuntos de dados de alguns laboratórios no mundo, visualização gráfica dos resultados, análise comparada e discussão dos resultados.

Palavras-chave: Corrosão sob tensão; Ensaio de taxa de deformação lenta; Ligas de níquel; Reator de água pressurizada

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1 INTRODUCTION

One of the main failure mechanisms that cause risks to pressurized water reactors (PWR) is the primary water stress corrosion cracking (PWSCC) occurring in alloys like the Alloy 600 (75Ni-15Cr-9Fe), or Alloy 182 (67Ni-15Cr-8Fe). It can be located, besides another places, at the control rod drive mechanism (CRDM) nozzles. It is caused by the joint effect of tensile stress, temperature, susceptible metallurgical microstructure and environmental conditions of the primary water. These cracks can cause problems that reduce nuclear safety by blocking the displacement of the control rods, and may cause leakage of primary water that requires repair or replacement of the reactor pressure vessel head.

In an earlier work, concerning a Doctoring Thesis, it was performed a study of the existing models and proposed a new approach to assess the PWSCC in nickel-based Alloy 600 CRDM nozzles. The proposed model is obtained from the superposition of electrochemical and fracture mechanics models, and validated using experimental and literature data. The experimental data were obtained from CDTN-Brazilian Nuclear Technology Development Center, in a SSRT equipment.(1,2)

This study aims to extend some obtained models to weld metals like the Alloy 182, and to improve the originals for Alloy 600, according with a revised methodology. It is includes a modeling proposal for new data for Alloy 182 and Alloy 600 initiation and crack growth according with a method based on Electric Power Research Institute -MRP-115,(3) and United States National Regulatory Comission-NUREG/CR-6964.(4) The new experimental data also will be obtained from CDTN.

In this paper is presented an improved methodology for modeling of Alloy 182, and Alloy 600 data.

2 MATERIALS AND METHODS

Most of the western PWR have CRDM penetration in the pressure vessel head made of stainless steel and Alloy 600. Its nominal composition is in Table 1. The yield strength of this material varies between 213 and 517 MPa. Normally this material is mill annealed at 885^{0}C, final anneal for 4 to 6 hours followed by air cooling. Nevertheless this treatment could to be subject to vary depending of vendors. This material works with some variation at 315^{0}C and 15.5 MPa in pure water. PWSCC appears in the lower part of each nozzle which is fabricated in Alloy 600 and welded to the internal vessel head surface with dissimilar material Alloy 182 (Table 1). There are typically 40 to 90 penetrations per vessel that may include some spare penetrations which are not fitted with CRDM or through core instrumentation of PWR.(1)

Table 1. Main chemical composition (weight %) of nickel alloys(2,3)

Alloy	Ni %	Cr %	Fe %	Mn %	Nb %	Ti %
182	67.0	15.0	8.0	7.0	1.8	0.5
600	75.0	15.6	8.8	0.2	0.2	0.2

One of the results of the earlier work, based on CDTN data, has generated modeling as showed in Figure 1, and Eq. (1): it is a semi-empirical one, with only a deterministic part, and superimposed at point P_{ssrt}.(1,2)

$$t_i = 1.45.\ 10^{-13}.\ \sigma^{-4}.\ \exp\ (32882.35/T) \qquad (1)$$

with t_i = initiation time in days; σ= stress in MPa and T=absolute temperature in K; the not experimental parameters of modeling were taken off Gorman et al.[5]

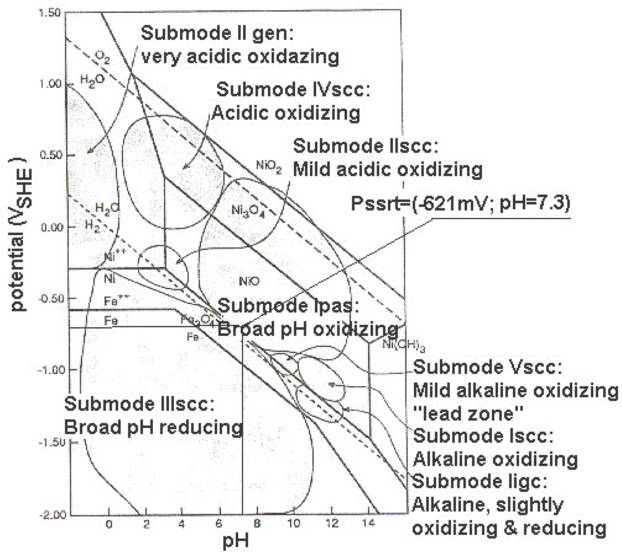

Figure 1. (a) Bi-dimensional diagram base, the Pourbaix pH x potential V_{SHE}; point marked P_{ssrt} was obtained through CDTN tests: V=-621mV; pH=7.3. Based diagram marked with corrosion submodes is from Staehle.[6] From Aly et al. [2]

Other modelings were obtained in the complete earlier work,[1,2] through the application of models like the Simplified Damage Model, the Damage Model of Boursier, and also a semi – quantitative one giving the evaluation to PWSCC.

This study is for to extend the existing modeling for Alloy 600 and to propose a local approach to assess the primary water stress corrosion cracking in nickel-based components. It is includes a modeling proposal for new data for Alloy 182 and Alloy 600 initiation and crack growth.

For this study, the same method will be used, but it needs data concerning Alloy 182, more data concerning Alloy 600, and also a reviewed methodology.

3 PROPOSED METHODOLOGY AND DISCUSSION

The first methodology stage is to improve tests accuracy through rigorously classify them in about 50 -100 “microprocesses” of stress corrosion according Staehle:[7] in Figure 2 is showed the main necessary parameters to be find, before the tests initiation. A proper formulary can be used to help this identification.

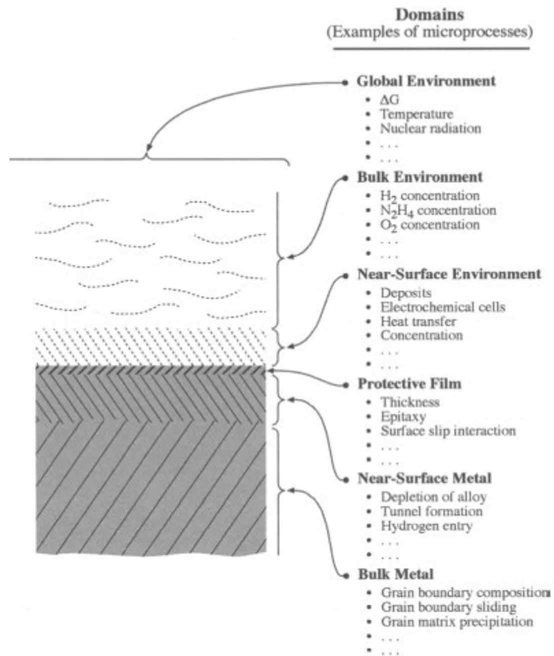

Figure 2. Scheme of six domains for quantifying microprocesses relating to the continuity from a global environment through the bulk metal: examples of these are indicated.(7)

The second methodology stage is to screen the tests data, according with a criteria suggested in MRP-115.(3) In Table 2 is showed some factors to screening data.

Table 2. Key factors for consideration in tests and data reporting(3)

1	Material within specifications including composition/condition/heat treatment
2	Mechanical strength properties
3	ASTM specimen size criteria and degree of plastic constraint
4	Pre-cracking technique (including straightness criteria, plastic zone size, crack morphology)
5	Special requirements for testing welds (e.g. pre-crack location, residual stresses/strains)
6	Environment (chemistry, temperature, electrochemical potential (ECP), flow rate at specimen, neutron/gamma flux)
7	Loop configuration (e.g., once-through, refreshed, static autoclave)
8	Water chemistry confirmation by analysis (e.g., Cl, SO4, O2, Cr, total organic carbon (TOC), conductivity)
9	Active constant or cyclic loading versus constant displacement loading (e.g., using wedge)
10	On-line measurement of crack length versus time during test (including precision)
11	Actual crack length confirmed by destructive examination (assessment method/mapping)
12	Appropriateness of crack characteristics (fraction SCC along crack front, uniformity, adequate SCC increment, transgranular portions within IGSCC fracture surface, etc.)
13	Possible effects of changes in loading or chemistry conditions during a test (including heat up and cool down)
14	Calculation and reporting of K or ΔK values
15	Reporting of raw a vs. t data and derivation of da/dt values
16	Reproducibility of data under nominally identical test conditions

The third methodology stage is to establish a clear distinction between time to initiation and time to failure, an important stage seldom treated in literature. Pathania et al [8] present a method to distinct them according a linear Eq. (2).

$$t_0=t_f-(a_f-a_0)/(a/t) \quad (2)$$

with: t_0 = initiation time, t_f = failure time a_f = crack lenght at failure time, a_0 = crack lenght at initiation time, a/t= average rate of estimating crack growth considering standard deviation $+2S_e$.

The initiation time t_0 is considering for a_0=20μm, that according with authors is the minimum crack lenght to distinguish between intergranular attack and SCC. Another authors consider a_0=10μm. In Figure 3 is showed a schematic procedure to estimate time to initiation.

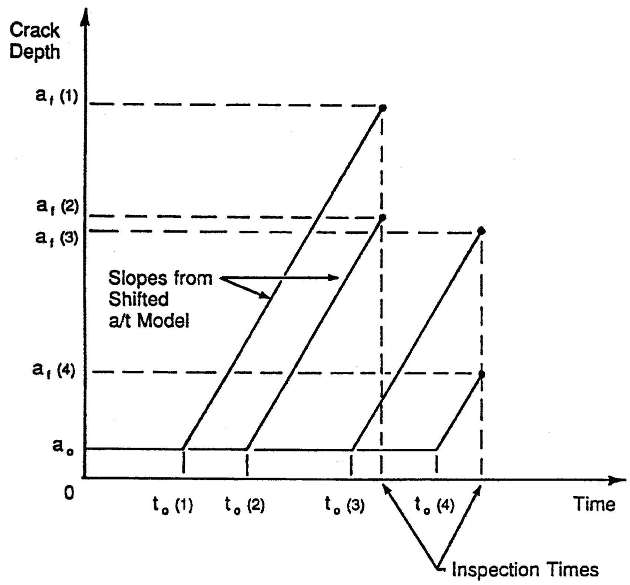

Figure 3. Schematic procedure to estimate time to initiation.[8]

The fourth methodology stage is to establish a fixed procedure to tests, not only concerning SSRT, but looking at details like using the same type of specimen uniformly manufacturated (specially important in the case of Alloy 182 welded specimens because the scattering data tendency due to factors like weld dendrites structures with different directions, welding procedures inequalities, and so on), to test enough specimen number, to allow statistic regression (e.g. according Weibull distribution, minimum recommended number in each test in the same conditions is 7). Another point is to research enough literature data in case of scarce data as for time to initiation of Alloy 182. A very good example for this methodology stage is given in the paper of Scott et al.:[9] a total of about thirty capsules was manufactured of dissimilarly welded tubes of Alloy 600 and Alloy 182. Then, they had been pressurized till 300 MPa, for generation of hoop stresses along welds, and exposed to the simulated PWR primary environment at 330°C, 350°C, or 360°C. The results are indicated in Figure 4.

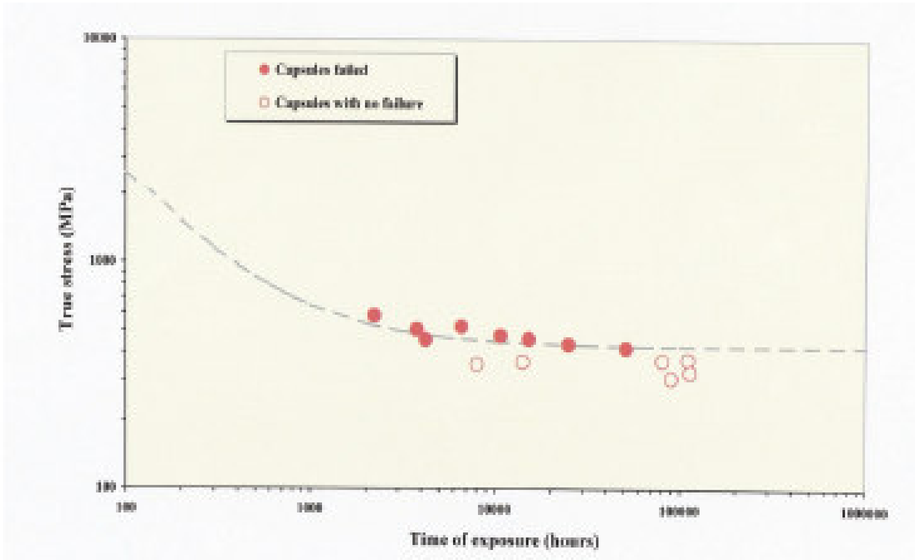

Figure 4. Time to initiation cracking of test capsules with an Alloy 182 weld as a function of the applied stress.[9]

The fifth methodology stage is to establish a procedure to tests for evaluation of crack growth rates, both for Alloy 600, and Alloy 182. The basic guideline for this stage is available on the work by Alexandreanu et al.:[4] it presents very completely the test facilities, test procedure, analysis of crack growth rate data, microstructural characterization of specimens, determination of values and discussion of activation energy for SCC crack growth, cycling effects and fatigue superimposed with SCC, and practical results like Davis Besse and V.C.Summer Nuclear Power Plants specimen analysis.

It follows, as example, some interesting points of this work, a true guideline for crack growth rate tests:

- For Alloy 600, SCC crack growth rate (m/s) is done by White, Hickling, and Mathews equation (Eq. 3).

$$\dot{a}_{A600} = \alpha \exp\left[-\frac{Q}{R}\left(\frac{1}{T}-\frac{1}{T_{ref}}\right)\right](K-K_{th})^{\beta} \qquad (3)$$

with: Q = activation energy for crack growth =130 kJ/mole, R = universal gas constant = 8.314 x 10^{-3} kJ/mole K, T = absolute operating temperature (K), T_{ref} = absolute reference temperature used to normalize crack growth rate data = 598K, α= crack growth amplitude (2.67 x 10^{-12} at 325°C), K = crack tip stress intensity factor ($MPa.m^{1/2}$), K_{th} = crack tip stress intensity factor threshold (9 $MPa.m^{1/2}$) and β = exponent 1.16.

- For Nickel Alloys welds, like Alloy 182, Eq. (3) has been modified to Eq. (4). It shall be noted that for these alloys, there is not crack tip stress intensity factor threshold.

$$\dot{a}_{Ni-weld} = \alpha \exp\left[-\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right] K^{\beta} \quad (4)$$

with Q, R, T, and T_{ref} the same as Eq. 3; α= crack growth amplitude (1.5×10^{-12} at 325°C), and β = exponent 1.6.

- In Figure 5 is showed a typical micrograph of a nickel weld alloy specimen, obtained for a practical case analysis.

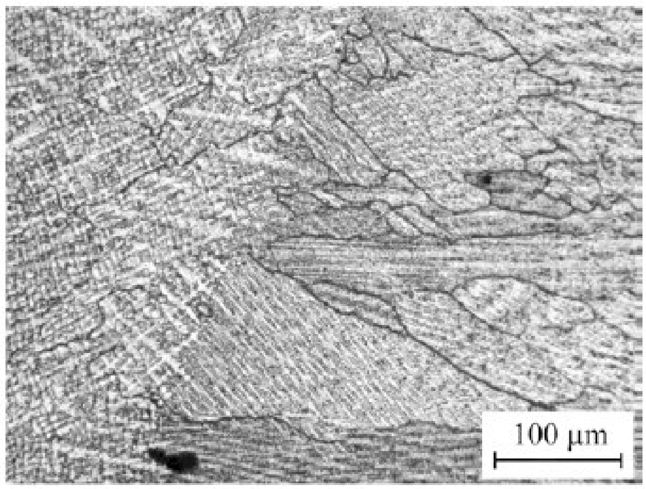

Figure 5. Micrograph of Alloy 182 from Davis Besse - J groove weld; note the typical weld dendrites.(4)

- In Figure 6 is showed typical results obtained at Argonne National Laboratory for cracking growth rate data for Alloy 600 from CRDM nozzle #3 from Davis-Besse in PWR primary water at 316°C, constant load test, and for Alloy 182 weld material compaired with available data for Alloys 182 and 82 in PWR primary water.

All these data and results may be used for to compare with our own results to be obtained at CDTN.

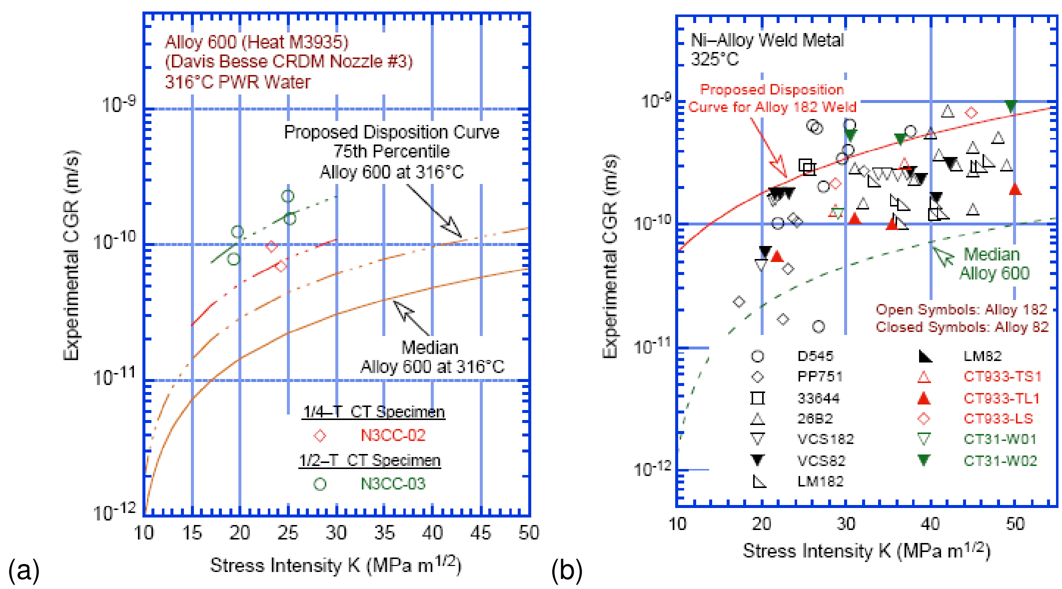

Figure 6. Examples of results obtained at Argonne National Laboratory: (a) CGR data for Alloy 600 from CRDM nozzle #3 from Davis-Besse in PWR primary water at 316℃, constant load test; (b) CGR data for Alloy 182 weld material compaired with available data for Alloys 182 and 82 in PWR primary water. Literature data according references 59-68.[4]

4 CONCLUSIONS

According with the points explained in this paper, and based on our previous experience, it can be possible to outline an own improved and extended methodology for modeling of primary water stress corrosion cracking at control rod drive mechanism nozzles of pressurized water reactors, adjusted to our actual laboratories, and work facilities.

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