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PRELIMINARY STRESS CORROSION CRACKING MODELING STUDY OF A DISSIMILAR MATERIAL WELD OF ALLOY (INCONEL) 182 WITH STAINLESS STEEL 316

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ABSTRACT

Dissimilar welds (DW) are normally used in many components junctions in structural project of PWR (Pressurized Water Reactors) in Nuclear Plants. One had been departed of a DW of a nozzle located at a Reactor Pressure Vessel (RPV) of a PWR reactor, that joins the structural vessel material with an A316 stainless steel safe end. This weld is basically done with Alloy 182 with a weld buttering of Alloy 82. It had been prepared some axial cylindrical specimens retired from the Alloy 182/A316 weld end to be tested in the slow strain rate test machine located at CDTN laboratory. Based in these stress corrosion susceptibility results, it was done a preliminary semi-empirical modeling application to study the failure initiation time evolution of these specimens. The used model is composed by a deterministic part, and a probabilistic part according to the Weibull distribution. It had been constructed a specific Microsoft Excel worksheet to do the model application of input data. The obtained results had been discussed according with literature and also the model application limits.

1. INTRODUCTION

Dissimilar welds are normally used in many components junctions in structural project of PWR in Nuclear Plants. One had been departed of a DW of a nozzle located at a RPV of a PWR reactor, that joins the structural vessel material with an A316 stainless steel safe end. This weld is basically manufactured with Alloy 182 with a weld buttering of Alloy 82. It had been prepared some axial cylindrical specimens retired from the Alloy 182/A316 weld end to be tested in the slow strain rate test machine located at CDTN laboratory (Figure 1).

In this paper is done a preliminary modeling and analysis of primary data obtained at CDTN-Brazilian Nuclear Development of Nuclear Technology, related to testing of Inconel 182 for evaluation of primary water stress corrosion cracking (PWSCC) in DW of Spanish Lemoniz reactor (which never entered operation). The objective of these tests is to evaluate the

PWSCC in different positions of the dissimilar welding existing in the cold leg of the reactor (Figure 1), at two temperatures, 303 º C and 325 º C [1].

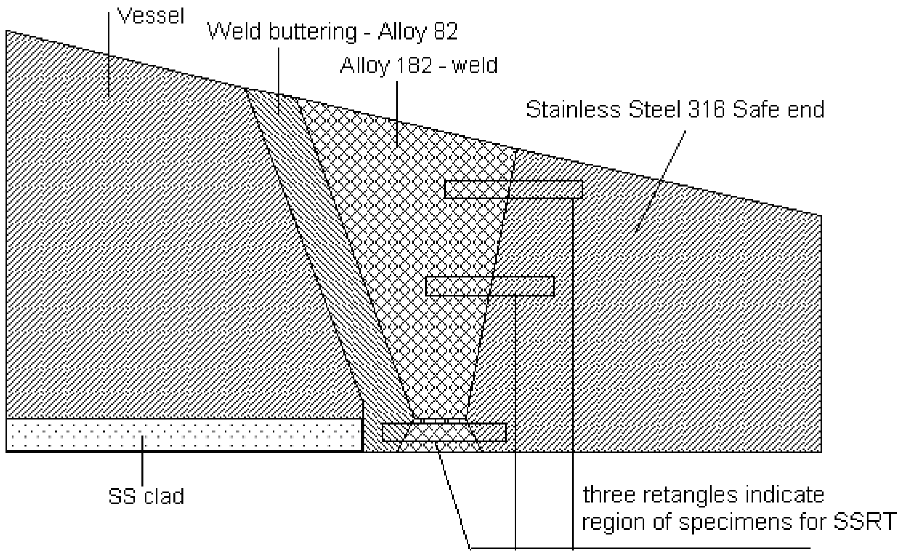

Figure 1. Sketch of Dissimilar Weld of reactor #1 from Lemoniz [1].

The CDTN tests of Inconel/Alloy 182 were taken at different temperature conditions. Two tests at T=303 ^{o}C were completed [1].

Based in these data, it was done a preliminary modeling, showed in the next Section.

2. MODELING THE EXPERIMENTAL DATA

For the modeling, it has been departed from three tests realized at T equal to 303 ^{o}C.

It was used the semi-empiric model according to Eq. (1), adapted from reference [2].

$$t_i = A \times \sigma^n \times \exp\left(\frac{Q}{RT}\right) \qquad (1)$$

with t_i =initiation time (days), σ =stress (MPa), T=absolute environment temperature (K); Q= activation energy (kcal/mol); R= universal gas constant =0,001987 kcal/mol; A=parameter to be adjusted according other dependences such as material treatment, environment composition including hydrogen content.

1) First, it has been necessary to research the most probable value to Alloy 182 activation energy which has been found as Q_{A182}= 31 kcal/mol at T=325 ^{o}C [3];

2) It has been necessary to evaluate the stress exponent "n", through data correlating stress with initiation time: the unique article localized where is there a direct correlation between these two parameters was the reference wrote by Scott et al. [4]: the test procedure in this article is different from the used in CDTN, but the estimative is reasonable for a preliminary modeling. It was used the Figure 4 from [4], here reproduced as Figure 2.

Based in it, the exponent "*n*" was equal to -7, which is according to other literature references such as [5];

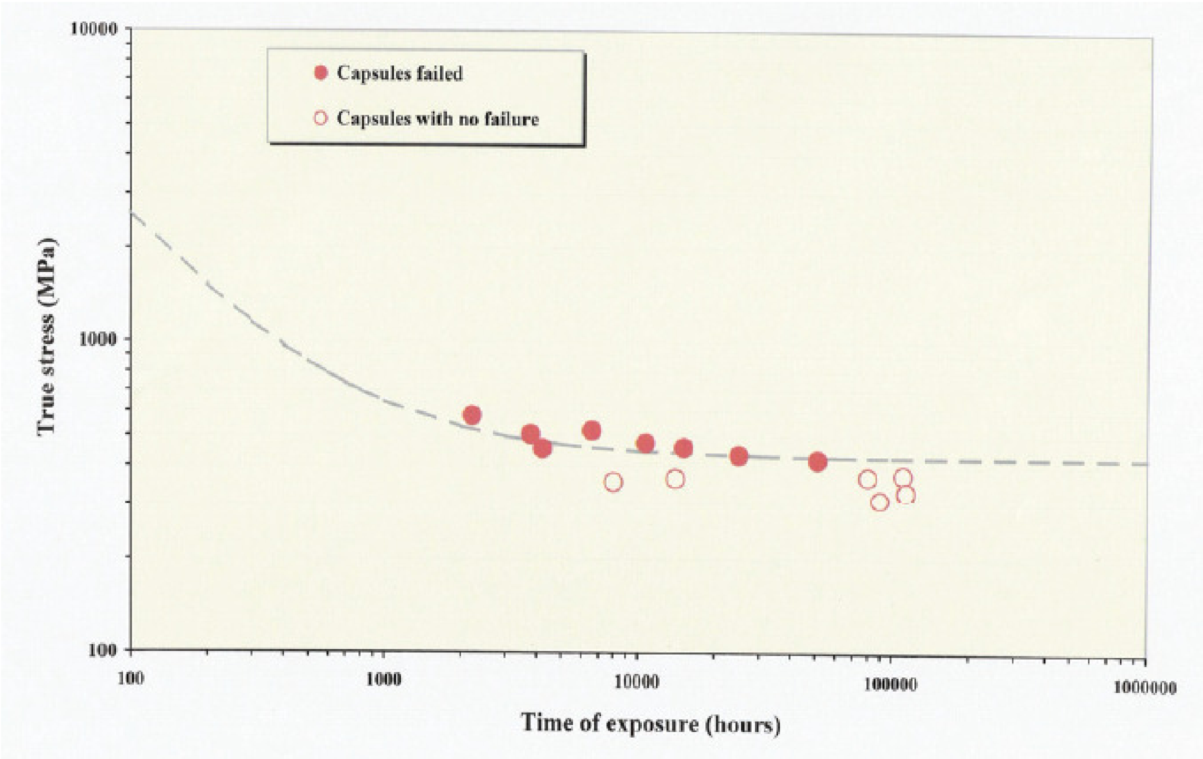

Figure 2. Initiation time/time to cracking of test specimens (capsules) with an Alloy 182 weld in function of the applied/tensile stress [4].

3) The initiation time considered in Equation (1) was the average time of three CDTN experiments (more details in [1]). Thus, t_i = (15. 1+14. 3+13. 5)/3 = 14. 3 days;

4) The considered stress "σ" was about 450 MPa, extracted from stress vs. strain graphics provided for two CDTN tests (see other details and attached files provided by CDTN in [1]);

5) Thus, the resulting semi-empiric modeling for the Alloy 182 CDTN tests is represented by Eq. (2).

$$t_i^{A182} = 92176093.62 \times \sigma^{-7} \times \exp\left(\frac{15601.41}{T}\right) \quad (2)$$

where: t_i^{A182}=PWSCC initiation time for Alloy 182 (days), σ = stress (MPa), T= absolute environment temperature (K).

6) This modeling was applied to other CDTN tests at other temperatures, and the results are in Table 1.

The larger deviations were in the CDTN tests 22, 24 and 29. In the test 29 if was admitted σ=450 MPa, the resulting modeling value grows to 5.4 days, near the experimental result.

Table 1. Deterministic modeling deviation related to CDTN experimental data [1].

CDTN Test Number	Test Temperature (°C)	σ average (MPa)- admitted values(*)	Experimental Results (days)	Modeling Results (days)	Deviation (%)
19,20,21	303	450	14. 3 (average for three experiments)	14. 30	0.0
25,26	315	450	8.23 (average for two experiments)	9.15	10.0
28	325	450	4.7	5.28	12.3
29	323	500	5.4	2.76	48.9
22	324	450	9.2	5.51	40.1
24	323.5	450	10.5	5.64	46.3

Note (*): Admitted from the Stress vs. Strain results to the CDTN tests 19, 20 e 29.

7) The deviations between modeling and experimental are not uncommon in the SCC case: as the SCC process is multiple variable dependent, data scattering is frequent. Thus, is not easy to apply deterministic models, which should do after a very hard data filtering: this should consider only data rigorously collected at same condition, and that is not easy. A practical solution is to consider a probabilistic regression together with a semi-empiric numeric modeling. For this case is normally used the Weibull distribution as showed in Eq. (3) [2].

$$F = 1 - \exp\left[-0.0101\left(\frac{t}{t_{1\%}}\right)^{b}\right] \qquad (3)$$

where: F= accumulated fraction of population of components under consideration all susceptible to the same failure mode that experience PWSCC; t= time; b=Weibull slope, a fitted parameter determined by the analysis of failure data; $t_{1\%}$= time which corresponds to the time of failure when 63.2% of the components had experienced PWSCC.

Then it was done a probabilistic regression of CDTN data, through an Excel worksheet file (attached file "Ensaios Liga 182- CDTN_Modelagem Preliminar.xls" at reference [1]).

8) One of the graphics resulted is showed in the Fig. 3. It was considered a regression of experimental data at temperature of 303°C: the number of tests was only three, despite the least number of recommended tests is seven [2]. Thus, it was not detected data scattering in this case, which is common in the Alloy 182 SCC tests. The adjusted line showed that in this case it is practically a deterministic regression.

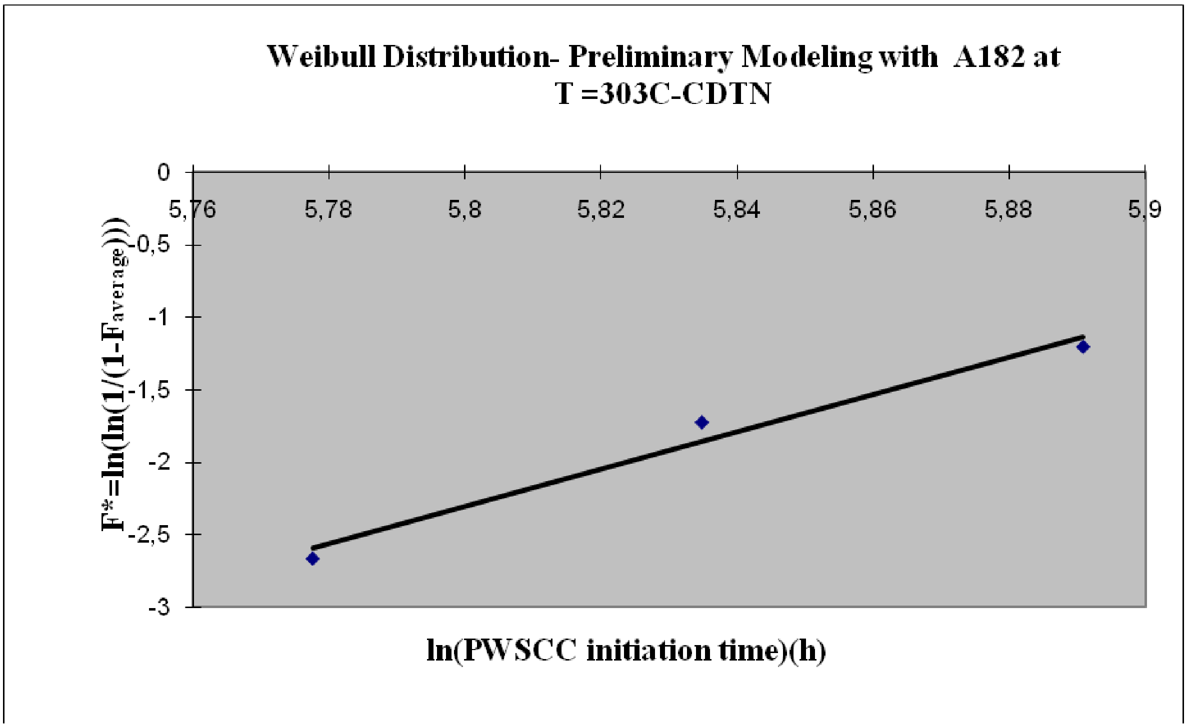

Figure 3. Excel graphic of the transformed F* in function of the initiation time, adjusted by mean of the Weibull distribution (Note: Numbers in scales are in Brazilian notation) [1].

A modeling exercise also was done considering an average temperature for all Alloy 182 SCC tests, of 314.9°C: as expected it showed data scattering, since the temperature is a very sensitive parameter which never should be considered constant [1].

9) It was done a Reliability Calculation Worksheet, appliable to CDTN data modeling, using the described model sem-empiric-probabilistic [6]. This worksheet allows immediate information about PWSCC failure/initiation time realiability in considered tests.It was constructed based on a similar worksheet proposed by Dorner [7].

It is based in the Weibull reliability equation (4) [7].

$$R(t) = \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \tag{4}$$

with: *R(t)*=reliability as test time function, α=life characteristic of the adjusted Weibull distribution, β= Weibull shape parameter, x=failure initiation time.

The data used to build the worksheet were as following:

a) Alfa and Beta – parameters according to the Table 2 [6].

Table 2. Alfa and Beta – parameters according to the Weibull distribution for data tests with Alloy 182 at 303°C [6].

Alfa (Life Characteristic)	394.8527766
Beta (Shape Parameter)	12.92999549

b) The probability values to failure occurence and reliability obtained in this worksheet are according to the Table 3.

Table 3. Occurrence Probability to PWSCC initiation and reliability parameters according to the Weibull distribution for data tests with Alloy 182 at 303°C [6].

Test Time (h)	Occurrence Probability	Reliability
100.0	1.94131E-08	0.999999981
200.0	0.000151488	0.999848512
300.0	0.028252883	0.971747117
400.0	0.693427928	0.306572072
500.0	0.999999999	6.3804E-10
600.0	1	0
700.0	1	0
800.0	1	0
900.0	1	0
1000.0	1	0

Note that, in the CDTN test conditions, from 600 hours of time testing, the probability to failure occurrence by PWSCC is equal to 1 (maximum PWSCC susceptibility), and the reliability is equal to 0 (minimum PWSCC resistance).

3. DISCUSSION

1) The preliminary modeling was performed with the semi-empirical-probabilistic model. The test data may be better adjusted in the deterministic mode using an activation energy at an average value at 325°C, the exponent value of n equal to -7, that was estimated based on an article of a particular test different from CDTN test, and the values of true stress were all considered with a mean value of 450 MPa, except for CDTN test number 29. The deterministic modeling showed small deviations for two thirds of the data and large deviation for one third of the data.

2) For a modeling including the probabilistic approach (based in a Weibull distribution), further testing would be desirable, e.g. to 303°C, to this adjustment is better consolidated and to check their level of reproducibility: one suggests that they be made at least 4 more PWSCC tests in the alloy 182 at 303°C.

3) For three tests of Alloy 182 at 303°C, there was not scattering, on the contrary, there was a reasonable deterministic setting (parameter β very high, well above 4 [8]), whereas the

PWSCC tests, regardless of the materials tested, already have tendency to give non-reproducible results, due to scattering. Usually in PWSCC tests of Fe-Ni-Cr alloys, the parameter β is between 1 and 4, according to Staehle [8] (a broad and deep work that is almost a technical recommendation ("guideline") for the application the semi-empirical-probabilistic model).

4) In the tests provided by CDTN it is not clear how it was obtained the crack initiation time: from an inspection that detects crack of 10μm or 20μm? It may be advisable to obtain a standardization of the time of initiation by a linear interpolation suggested by Figure 4. [9].

It should be used Eq. (5).

$$t_0 = t_f - \frac{a_f - a_0}{\frac{a}{t}} \tag{5}$$

with: t_0 = initiation time, t_f = failure time, a_f = crack length in the considered failure time , a_0 = crack length at initiation time, a/t= estimated average crack propagation rate considering standard deviation equal to $+2S_e$.[9]

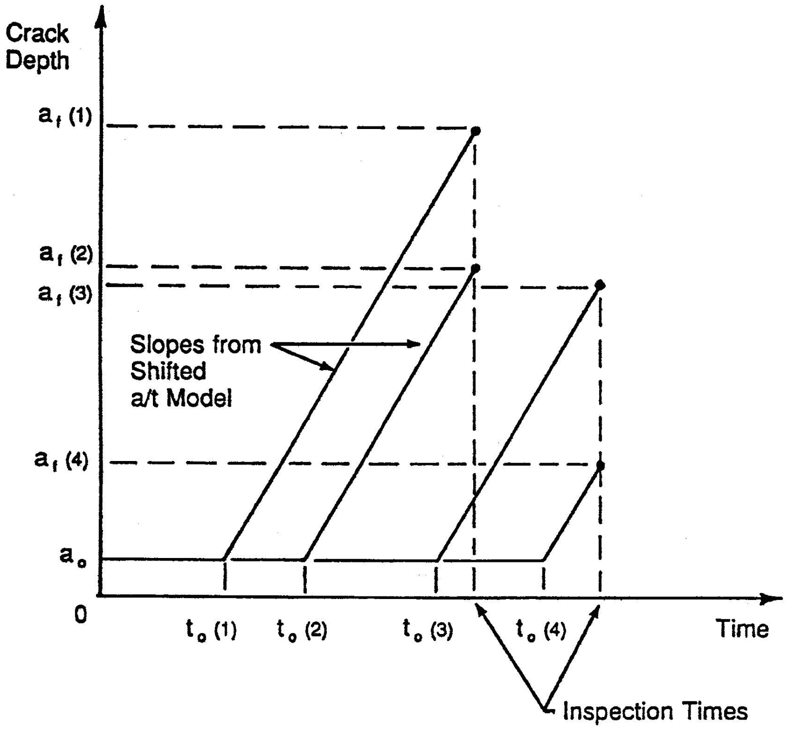

Figure 4. Schematic procedure to estimate time to initiation. From Pathania et al. [9].

5) Finally it should be provided a test standardization as showed in the Table 4 [10], to minimize scattering, and to allow better accuracy in the results.

Table 4. Key factors for consideration in tests and data reporting. From MRP-115[10].

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

3. CONCLUSIONS

It was presented a modeling study following a methodology to adjust and to analyze data provided by CDTN from PWSCC tests of Alloy 182 extracted from reactor material weld with stainless steel 316 of Lemoniz, Spain. The analysis was based on the deterministic and probabilistic approach using the very general semi-empiric-probabilistic model, which may be applied for majority of the initiation cases. It generates an Excel Worksheet, which could applied to the most of cases. In the Discussion section were given some suggestions for improvement of this modeling methodology.

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