CONSTRAINT EFFECT ON ENVIRONMENTALLY ASSISTED CRACKING OF THE AUSTENITE STEEL 08Kh18N10T IN THE CONCENTRATED SOLUTIONS AT 270°C

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ABSTRACT

Effect of constraint is studied for austenitic steel of steam generator (SG) tubes in concentrated solutions at 270°C. The solutions simulate environments in crevices between tubes and support plates during long term operation of SG. Experimental results of accelerated environmentally assisted cracking (EAC) tests demonstrate that constraint significantly affects the crack growth rate and the threshold intensity factor K_{IEAC}. Results of the testing showed that higher crack propagation velocity can be reached in case of the different stress - strain conditions in specimens than in SG tubes.

INTRODUCTION

Probability of a crack occurrence in tubing of a horizontal type steam generator for WWER 440 MW nuclear power plants is very low but several cracks can be found during regular inspections. It was recognised that the most of the cracks was initiated on the secondary side in crevices between tube supports and tubes.

Many efforts were devoted to determine characteristics of empirical expressions for lifetime calculations. Experimental and numerical works were carried out to elucidate all tube damage processes in different concentrated solutions that could be likely attained in the crevices during the SG service.

The steam generator operates with water as cooling liquid. Tubes made from the steel 08Kh18N10T (equivalent to AISI 321) are of 16 mm in diameter and 1.5 mm of the wall thickness, typically a thin wall construction. It means that a shallow crack after initiation will propagate in lost of constraint conditions. To evaluate characteristics of the EAC process - the threshold K_{IEAC} value and the crack growth velocity it could be known if they are affected by the lost of constraint conditions.

According the slip dissolution model [1, 2] the threshold value for EAC crack propagation could be a function of a constraint λ and yield stress σ_y, r is a distance from growing crack,

$$K_{IEAC} = \sigma_y \sqrt{\frac{r}{\lambda}} \quad . \qquad (1)$$

Here in the model, the constraint λ is dimensionless constant in relation for a plastic zone size

$$R_p = \lambda \cdot \left(\frac{K}{\sigma_y} \right)^2 . \qquad (2)$$

Another definition of a constraint, a factor of stress multiaxiality β, is normally used:

$$\beta = \frac{T\sqrt{\pi a}}{K_I} , \qquad (3)$$

where T is T stress, a is a crack length, K_I is a stress intensity factor.

Theoretical crack growth rate based on the slip dissolution model depends on the plastic strain rate at the crack tip and due to on the constraint λ:

$$\frac{da}{dt} = C_1 \left(\frac{d\varepsilon_{CT}}{dt} \right)^m = C_2 \left(2 \frac{\frac{dK}{dt}}{K} + \frac{\frac{da}{dt}}{r} \right) \left(\ln \left(\frac{R_p}{r} \right) \right)^{1/(n-1)} \qquad (4)$$

The crack growth rate could be higher for the higher λ in case of the same loading conditions ((dK/dt)/K).

For the experimental works specimens with low and high constraints were used. The EAC damage process of SG tubes was considered to consist of the crack initiation on the outer tube surface, in a crevice between tube and the support plate, and the crack grow through the tube wall. The characteristics of the EAC crack propagation process were measured and they are discussed in the paper.

EXPERIMENTAL

The test specimens were manufactured from two pieces of the steel 08Kh18N10T. The A piece was test in as-received state. The B piece was prestrained and heat treated (pre-strain 0.66, furnace 850°C / 20 minutes / water) to obtain the material of the typical fine grain size as in the SG tube. The mechanical properties of the A, B and SG tube materials are compared in the Table 1.

TABLE 1

MECHANICAL PROPERTIES OF THE TEST MATERIAL AND THE SG TUBE

Material	Grain size [μm]	T [°C]	σ_y [MPa]	σ_{ult} [MPa]	Elongation [%]
SG tube	11.7	20	360	680	41
		300	280	540	42
Test material A	40	25	216	510	35
		300	177	412	26
Test material B	8.9	25	387	688	50
		280	330	513	33

Test specimens of SENT type were chosen for EAC experiments because the both the stress intensity K and the T stress of the SG tube and SENT were found in good agreement. In contrary to that CT specimen do not show the similar correlation, see Table 2.

The SENT specimen dimensions are shown in Fig.1. The SENT specimens were of 11 mm in thickness, the CT of 12.5 mm. In frame of the program three different specimens were used: shallow pre-cracked SENT (a/W = 0.25), deep pre-cracked SENT (a/W = 0.5) and deep pre-cracked CT.

EAC tests were carried out in three alkaline concentrated water environments which simulate local crevice environments under heat exchange tube support plates in hot legs of SG tubing. Local water parameters were calculated by MULTEQ Code. Chemical compositions of blowdown water during power plant unit shut downs and the maximum value of the local temperature increase were used as input data for the calculations [3]. The compositions and pH values of the concentrated environment is preferentially controlled by higher content and relationships of Na, Cl, SO_4 and SiO_2. The test environment parameters are given in Tab. 3.

TABLE 2

STRESS CHARACTERISTICS USED FOR THE TEST SPECIMEN SELECTION
(t IS TUBE WALL THICKNESS, W IS SPECIMEN WIDTH)

Specimen	a/W or a/t	a [mm]	K [$MPam^{1/2}$]	T [MPa]	β
SG tube	0.333	0.5	2.0	- 22.0	-0.44
SENT	0.064	0.7	2.0	- 22.4	-0.53
SENT	0.5	5.5	2.0	- 2.4	-0.16
CT	0.5	12.5	2.0	+ 5.4	+0.54

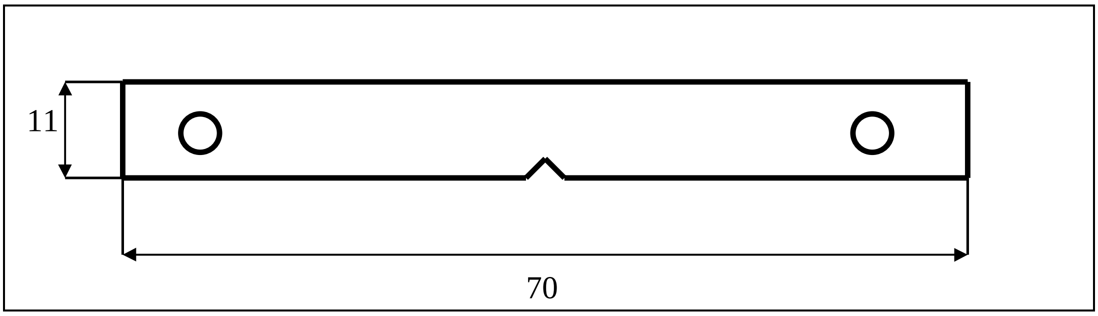

Figure 1: SENT specimen.

For the EAC testing the titanium autoclave of 0.3 l in volume without circulation loop was employed. The tests were done using the rising displacement test method (RDT) [4]. The method is based on the J - R curve measurement using slow displacement rates. Here, the test rates were used ranging from 43 to 0.6 μm/hour on specimen. For the crack length monitoring the reversed dc potential drop method was used.

TABLE 3

CONCENTRATED TEST ENVIRONMENTS, TEST TEMPERATURE 270°C

Constituents	Test environment		
[mg/kg]	Env II	Env III	Env IV
Cl	779	13 856	25 560
Na	3550	63 218	86 960
SO_4	730	12 990	103 490
SiO_2	2260	45 898	13 310
Ca	4970	34 640	-
Al	234	4 330	-
pH_T	9.7	10.4	9.8

RESULTS

EAC test started at K = 0 and than the K value was slowly increased during the test. Measuring the crack length by the dc potential drop method an initiation point could be indicated in all the tests. An example of a test data is shown in Fig. 2.

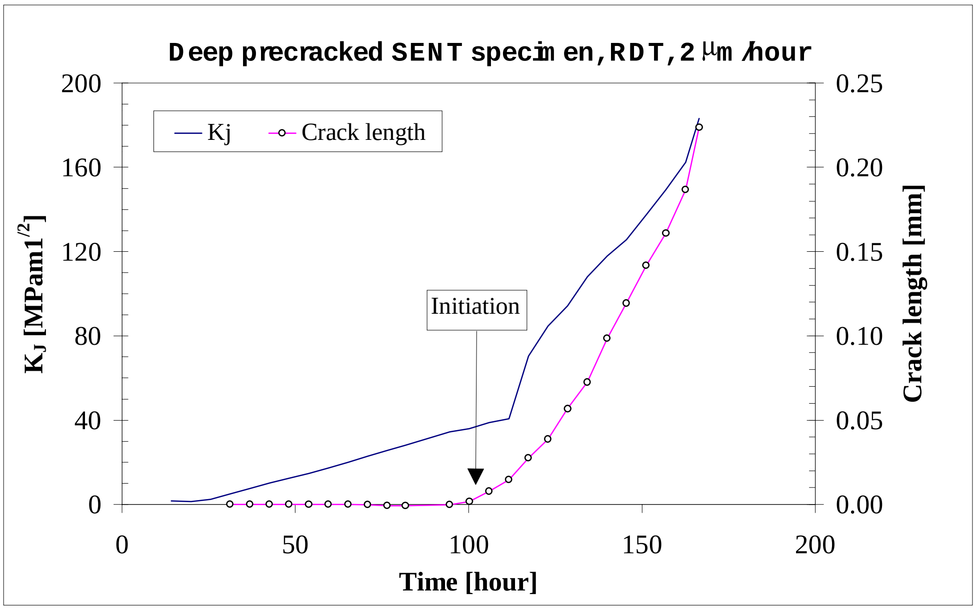

Figure 2: The initiation K_{Ji} value determination in RDT experiment with deep precracked SENT specimen of material B in Env IV

The constraint effect was studied on three different specimen sizes. It was analysed the effect on the K initiation value, K_{Ji}, and the average crack growth rate. The constraint λ and plastic zone size R_p were calculated by FEM method for SENT specimen of shallow and deep crack. Results are shown at Tab.4. R_p max means a maximum dimension of the plastic zone in an inclined direction from the crack direction.

TABLE 4

RESULTS OF FEM CALCULATIONS OF PLASTIC ZONE SIZE

Specimen	a/W	K[$MPam^{1/2}$]	R_p max[mm]	λ
shallow cracked SENT	0.2	17.0	0.710	0.232
		29.7	4.900	0.568
deep cracked SENT	0.5	18.6	0.530	0.157
		35	2.350	0.197

Experimental results are described at Fig. 3 - 5. The initiation values K_{Ji} were measured lower for the shallow cracked SENT specimens than for the deep cracked one and CT.

Using FEM crack tip strain rates were evaluated at points of EAC crack initiation. The relationship of K_{Ji} and the crack tip strain rate can be seen from Fig. 4. It could be pointed out the shift of the two points of shallow cracked SENT towards lower strain rates values.

The average EAC crack growth rates are plot on the initiation K_{Ji} value in Fig.5. Only the crack growth rate values from RDT test relatively low influenced by the test displacement rate are displayed. From the Fig. 5 one can found that the crack growth rate was measured higher in case of the deep cracked specimens, SENT and CT.

EAC fracture surface appearance of the both short and deep cracked specimens was found very similar as it is shown in Fig. 6, 7. There were observed cleavage like facets with many steps and secondary cracks. For the shallow cracked specimens the features looked more brittle in agreement with the low values of the K initiation.

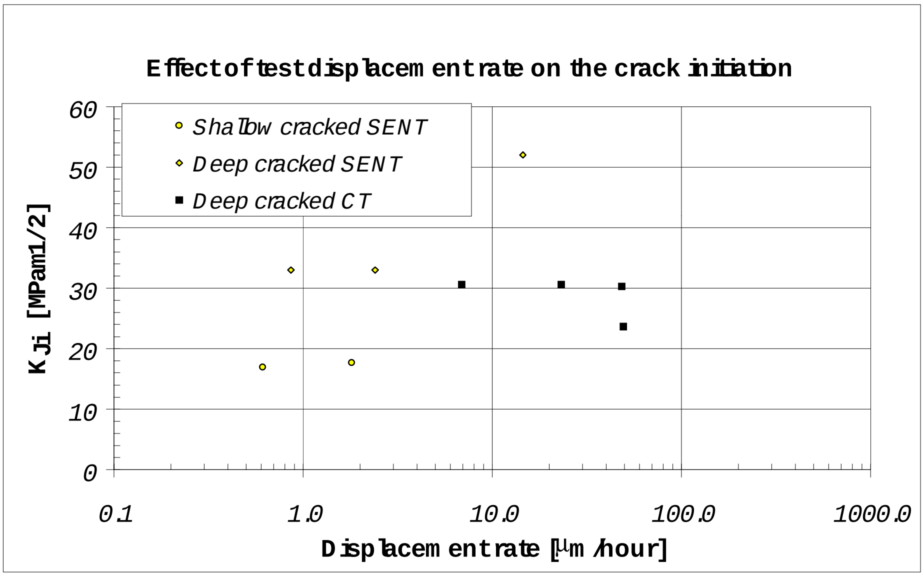

Figure 3: Results of RDT tests in concentrated alkaline environments.

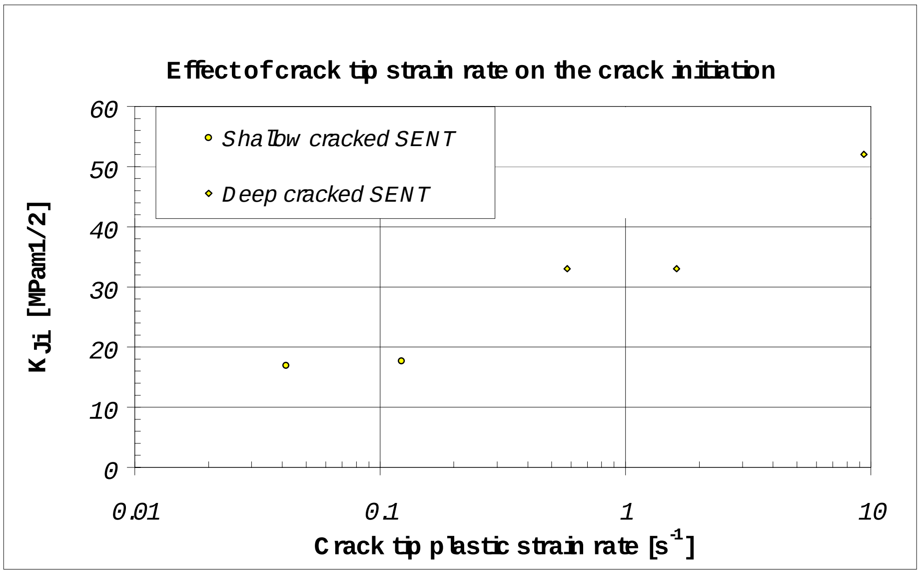

Figure 4: Plot of the initiation K_{Ji} values versus calculated plastic strain rates.

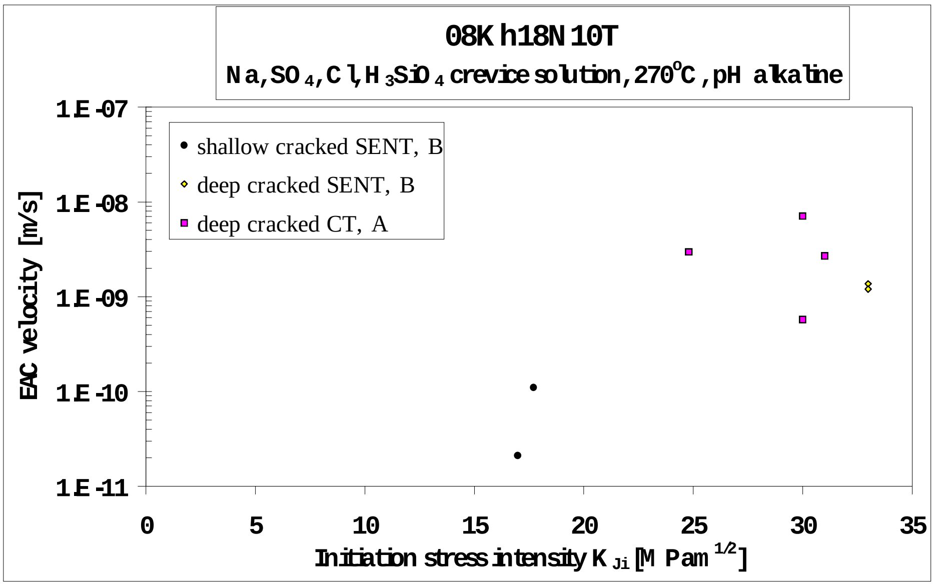

Figure 5: Results of EAC crack growth rates measurements in concentrated alkaline environments.

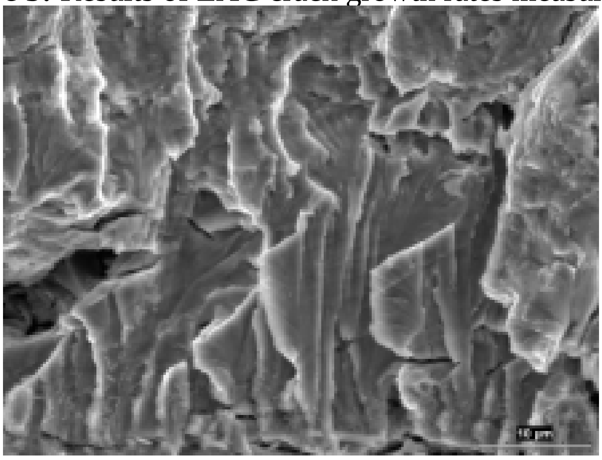

Figure 6: EAC growth after initiation in shallow cracked SENT in the alkaline environment.

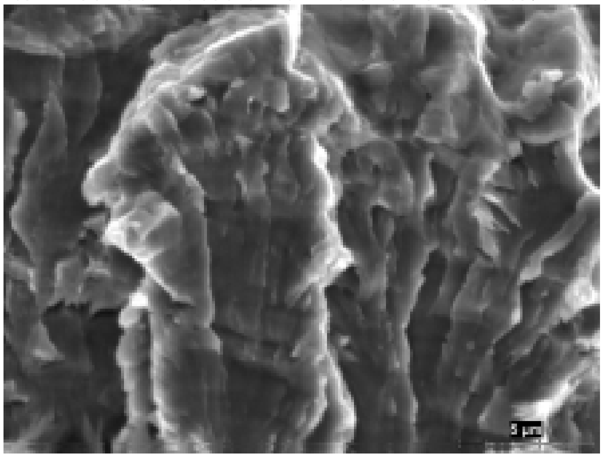

Figure 7: EAC growth in deep cracked SENT in the alkaline environment.

DISCUSSION

From the obtained test results it is clearly seen that the constraint value of specimen could affect the EAC crack growth process in the concentrated environment. The constraint effect have been predicted [1] and measured [5] on a corrosion system: austenite steel A304 and high temperature demineralised water (BWR). It was found that [5] „when stress multiaxiality ratio β takes negative number, EAC initiation retards but once starts, its propagation rate increases“. In contrary, our experimental data showed completely different picture that EAC process starts at lower K threshold values when β is more negative and that the crack propagation rate has higher value for less negative β. These discrepancies could reflect another role of an environmental factor in our corrosion system than in the clean BWR water. In the BWR water[5] , the low conductivity environment, there was found that less crack tip opening angle (CTOA), as it is in case of a deep crack, affects the crack tip chemistry. In case of the high conductivity environment as the test solutions there is no significant diference between crack tip environment of shallow and deep crack.

The results of the crack growth rate measurements of the shallow SENT specimens have to be used carefully. The number of specimens is low to make a general conclusion. During the experiments only very small crack increment were found for the shallow SENT specimens. As it was recognised earlier in case of small crack increment during RDT test and K values very close to threshold value an average velocity result can be underestimated[6] . It means that the result has to be validated by testing of another specimens and longer crack increments have to be reached during the tests to prove the calculation of the crack velocity. Besides, in all the RDT tests of the deep cracked specimens the EAC crack increment reached more than 120 μm in average over the specimen thickness. The measurements of the crack growth rates are without doubts.

In our opinion the value of the crack growth rate depends strongly on an accumulated strain energy in specimen before EAC initiation. It could be the reason why the crack growth rates are higher if the EAC iniciates at higher K values.

CONCLUSIONS

- The EAC initiates at lower K values at alkaline concentrated crevice environment in lost of constraint conditions.
- The EAC crack growth velocities are likely higher in case of deep cracked SENT specimens comparing to shallow cracked ones.

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