Environmental Effects on the Crack Growth Properties of Alloy 600

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1. INTRODUCTION

The steam generator tubing system is one of the most critical system in pressurized water reactors. It is well-documented that Inconell alloys used for SG tubing, such as Alloy600, are susceptible to intergranular stress corrosion cracking (SCC) in NaOH solution at 533 ~ 703 K [1]. In general, the U bend test method is used for evaluating the SCC properties of Alloy600 in high pressure and high temperature environments. The test environment for the U bend method is usually selected severe than the actual plant environment. However, at this time the effects of this severe test environment on SCC properties is hard to assess. So, a crack growth test method at high stress ratio, aimed at evaluating SCC properties by fracture mechanics parameter ΔK, was proposed[2].
This paper will describe the effects of NaOH concentration on the crack growth properties of Alloy600 as identified by this crack growth test.

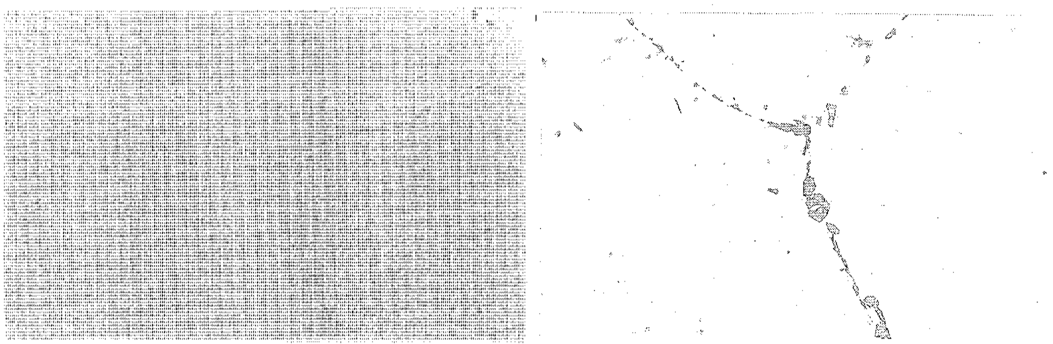
2 EXPERIMENTAL PROCEDURE

2.1 Material

Table 1 shows the two methods for preparing the samples of Alloy600. The mill annealed sample (MA) was heat-treated once; the thermal treatment sample (TT) was heat-treated twice after cold working. The purpose of the thermal treatment was to improve the anti stress corrosion cracking properties. Figure 1 shows replica observation at grain boundaries. The chemical composition and mechanical properties of Alloy600 are shown in Table 2 and Table 3, respectively.

Table 1 Material preparation

	MA	TT
Forging	1223 ~ 1453 K	1223 ~ 1453 K
1st H.T.	1298 K 1hour W.Q.	1318 K 3/4hour W.Q.
Cold work	30%	30%
2nd H.T.	1373 K 1hour A.C.	1198 K 1hour W.Q.
3rd H.T.	--------------------	973 K 30hour A.C.



MA Alloy600 — 10μm   TT Alloy600 — 10μm

Fig. 1 Carbide precipitation in Alloy600

Table 2 Chemical composition (wt%)

C	Si	Mn	P	S	Ni	Cr	Ti	Sol.Al	N	O
0.025	0.30	0.32	0.007	0.001	74.85	15.32	0.18	0.13	0.0045	0.002

Table 3 Mechanical properties

Temperature	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Reduction in area (%)
R.T.	160	563	57.5	75.0
598 K	116	511	50.3	66.9

2.2 Test condition

Compact-Type (CT) specimens were used for the crack growth tests as designated in ASTM E647, where W is 50mm and B is 25mm. A machined groove with a 3mm radius and a 1mm depth was introduced at both surfaces, to control the crack growth path. The CT specimen was machined in T-L direction.
The crack growth test was carried out by an electric-hydraulic closed loop fatigue test system with a $\pm 3.92 \times 10^4$ N and 2×10^{-2} m^3 autoclave. The test environment is described in Table 4.

Table 4 Test environment

Temperature	598 K
Pressure	12.3MPa
Potential	E_{corr} + 100mV
Stress ratio R	0.85
Frequency f	0.5Hz

3 TEST RESULTS

3.1 Effect of NaOH concentration on crack growth properties

Figure 2 shows the effects of NaOH concentrations between 0.04% and 40% on the crack growth rate in MA Alloy600, with All Volatile Treatment (AVT) environment.
Increased NaOH concentration accelerated crack growth rate and the da/dt ~ Kmax curve in the accelerated region became convex. Where the NaOH concentration was lower than 0.4%, the fracture surface was a transgranular type. In 4% NaOH solution, every fracture surface, except for one sample, was an intergranular type.
These intergranular fractures are identified in Fig. 2 by the mark *. However, in the case of NaOH solutions of more than 10%, the ratio of samples exhibiting intergranular type decreased, and the intergranular fractures were limited to the mid Kmax region.
Figure 3 shows the effect of NaOH concentrations between 0.4% and 10%, on crack growth properties of TT Alloy600. The curve of TT Alloy600 is straight, even in a 4% NaOH solution.
Some examples of fracture surfaces for both MA Alloy600 and TT Alloy600 are shown in Fig. 4. Each fracture surface consisted of either all intergranular or all transgranular fractures.

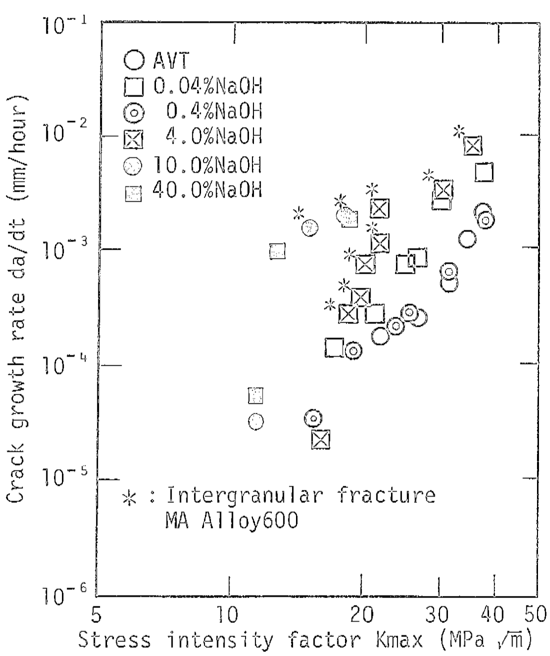


Fig. 2 Effect of NaOH concentration on crack growth properties in MA Alloy600

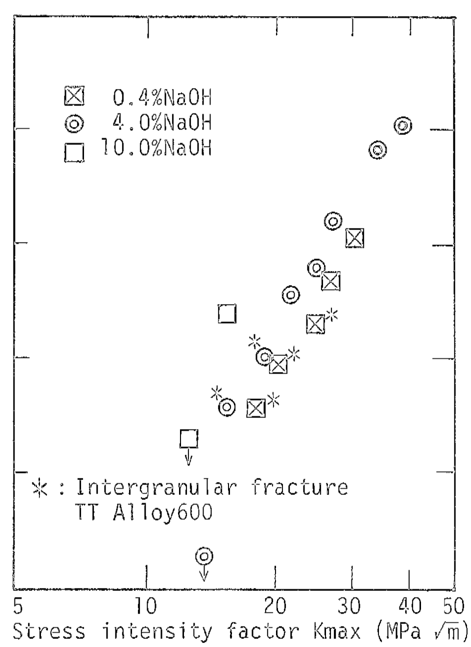


Fig. 3 Effect of NaOH concentration on crack growth properties in TT Alloy600

MA Alloy600 Kmax 98.2MPa√m TT Alloy600 Kmax 88.0MPa√m

Fig. 4 Fracture surfaces of Alloy600 in 4% NaOH solution

3.2 Effect of heat treatment on crack growth properties

Figure 5 shows a comparison of crack growth properties in MA Alloy600 and TT Alloy600 in a 4% NaOH solution. At the mid Kmax region, between 20 and 30 MPa $\sqrt{m}$, the difference in the crack growth rate of the two samples is significant. In the mid Kmax region, every fracture surface consists of intergranular fractures.

Figure 6 indicates crack growth properties in a 10% NaOH solution. Although it is a little difficult to compare results in this environment because of very limited data, the difference in crack growth rate between MA Alloy600 and TT Alloy600 is remarkable.

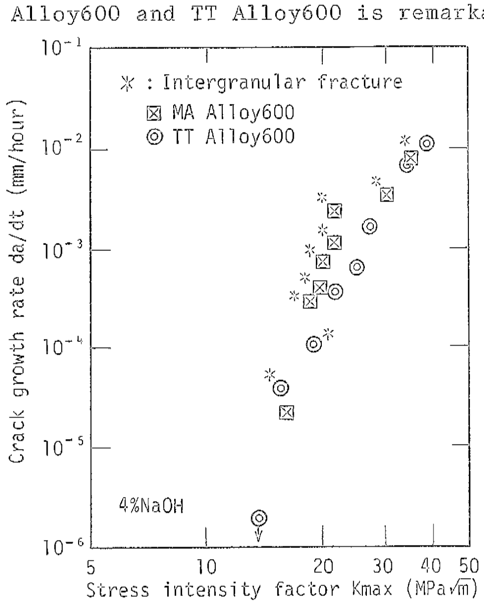


Fig. 5 Effect of heat treatment on crack growth properties in 4% NaOH solution

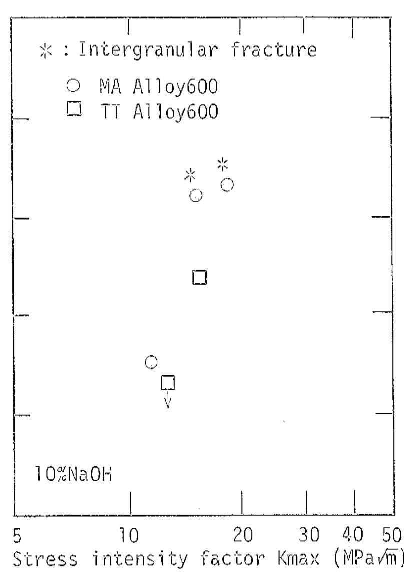


Fig. 6 Effect of heat treatment on crack growth properties in 10% NaOH solution.

4 DISCUSSION

In order to examine in detail the crack growth mechanism, Wei's model[3] was applied to the result. Wei's model is as follows;

$$(da/dN)_e = (da/dN)_r + (da/dN)_{cf} + (da/dN)_{scc}$$

where

$(da/dN)_r$ = the rate of fatigue crack growth in an inert (reference) environment

$(da/dN)_{cf}$ = the growth rate which represents a cycle-dependent contribution requiring interaction of fatigue and environmental attack

$(da/dN)_{scc}$ = the rate by sustained-load crack growth

In this paper, the following equation is derived analogically:

$$(da/dt) = (da/dt)_r + (da/dt)_{cf} + (da/dt)_{scc}$$

Where indices have the same meaning as in Wei's model. The crack growth rate in an inert environment $(da/dt)_r$ should be measured in a vacuum at room temperature. However, in this paper, $(da/dt)_r$ is substituted for crack growth rate in air at room temperature. The rate can be approximated by the following equation:

$$(da/dt)_r = 2.336 \times 10^{-11} \times (Kmax)^{5.052}$$

[mm/hour] [MPa $\sqrt{m}$]

$[(da/dt) - (da/dt)_r]$ or $[(da/dt)_{cf} + (da/dt)_{scc}]$, which is referred to as crack growth acceleration factor in this paper, is useful for representing the effect of NaOH concentration on crack growth rate, as shown in Fig. 7. Figure 8 is schematic diagram which represents the relationship between the crack growth acceleration factor and the stress intensity factor. It can be considered that the inclination of lines is closely related to the growth rate $(da/dt)_{cf}$ and the deviation from the lines is related to the rate $(da/dt)_{scc}$.

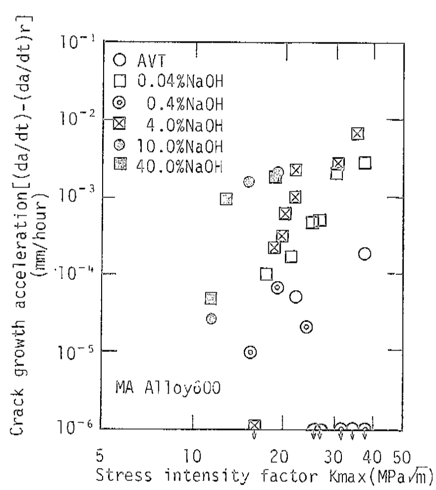


Fig. 7 Effect of NaOH concentration on crack growth acceleration in MA Alloy600

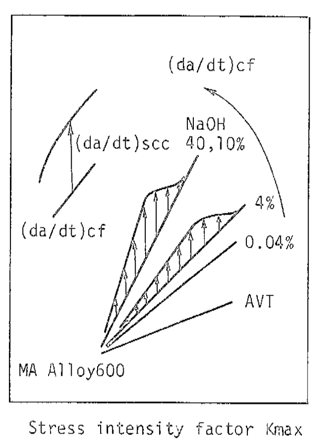


Fig. 8 Schematic illustration of crack growth acceleration in MA Alloy600

5 CONCLUSION

Crack growth tests of Alloy600 in high temperature high pressure NaOH solution were conducted. The following conclusions were derived from observation of crack growth rate and the fracture surface.

(1) The crack growth curve of MA Alloy600 in full-logarithmic graph was straight for a solution of less than 0.4% NaOH and became convex for a solution of more than 4% NaOH. Intergranular fractures were observed at the Kmax region corresponding to the convex curve. On the other hand, the curve of TT Alloy600 was always straight at NaOH concentration between 0.4 to 10%.

(2) The crack growth rate of MA Alloy600 was greater than that of TT Alloy 600 in the mid Kmax region at 4% NaOH solution, and in every Kmax region at 10% NaOH solution.

(3) Crack growth rate (da/dt) was divided into the following terms: $(da/dt)_r$, $(da/dt)_{cf}$ and $(da/dt)_{scc}$ derived analogically from Wei's model. The crack growth acceleration factor defined as $[(da/dt)-(da/dt)_r]$ or $[(da/dt)_{cf} + (da/dt)_{scc}]$ was effective for explaining both the interaction of fatigue and environmental attack, and for explaining sustained-load crack growth, where $(da/dt)_r$ was substituted for crack growth rate in air at room temperature.

REFERENCE

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