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Crack shape changes with fatigue crack growth of carbon steels in high temperature water

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ABSTRACT

Fatigue surface crack propagation behavior has been investigated by using Japanese carbon steel STS410. Small size flat plate specimens with surface crack were subjected to cyclic bending, bending-tensile and tensile loads in air at room temperature and in simulated BWR environment. So far, the effect of loading condition on crack shape change and the effect of sulfur content on crack growth rate have been investigated.

INTRODUCTION

The light water reactor (LWR) plants in Japan have accumulated over 25 years of operational experience, and all of them (49 units in number and 42,376MWe in capacity) are now (as of February, 1997) successfully operating, maintaining the highest level of capacity factor over 70% in the world. Nevertheless, twelve nuclear power plants (NPPs) have been operated long over 20 years, thus susceptible to steady plant aging.

In order to cope with such NPP aging, Japan is conducting national projects to maintain and enhance the safety of NPP equipment and piping, by concentrating on (1) more enhanced maintenance control techniques and (2) the building-up and maintenance of aging related data and corrective measures techniques.

Such being the case, as part of backup activities for this policy, the 10 year national project named as "Structural Assessment of Flawed Equipment (SAF)" started in 1991. This project has been conducted under the contract with Ministry of International Trade and Industry(MITI) by Japan Power Engineering and Inspection Corporation(JAPEIC). It consists of large scale model verification tests (including a full-scale piping model test, and 1/2.5 scale RPV model test) and small flat plate test conducting a fatigue crack growth test under actual environment.

Aim of the SAF project is to introduce a concept which allows small flaw to Japanese maintenance rule. To establish the allowable crack concept, the three items of the modeling of detected flaw, evaluation of fatigue flaw growth and evaluation of final fracture has been investigated in this SAF project. The concept is planed to include the data of surface crack behavior obtained in this project.

This report describes the results of small flat plate test so far obtained.

EXPERIMENTAL PROCEDURE

Outline of Small Flat Plate Test

The small flat plate test in the SAF project has been performed in order to establish detected flaw evaluation criteria in Japan. Procedure of flaw evaluation is essentially same with ASME Code Sec. XI. But it seems that the ASME base data are lack of surface crack behavior data, especially, in environment. In this test, crack shape changes during crack extension and coalescence of multiple surface flaws were examined by using flat plate specimen with single/multiple surface crack.

Test Conditions

To evaluate the effect of loading pattern to the crack shape change with the fatigue crack growth and coalescence behavior of multiple cracks, three types of loading patterns were prepared as tension, tension + bending and bending. The test specimens are flat plate with 25~30mm in thickness and 100mm in width. Each specimen has a initial surface crack given by electric discharge machining (EDM). Two types of initial crack shapes (relatively shallow and deep flaws) were employed.

The flat plate tests have been conducted in air and simulated BWR environment. Each test condition is as follows;

Test in air
Environment Temperature ; Room temperature
Atmosphere ; Air
Test condition Applied load ; Lower than yield strength
Loading wave ; Triangle
Stress ratio ; 0.1
Frequency ; 1 Hz

Test in simulated BWR environment
Water chemistry Temperature ; 288℃
Pressure ; 8 MPa
Dissolved oxygen ; 0.2 ppm
Conductivity ; $<0.1\mu$S/cm
Test condition Applied stress ; Lower than yield strength
Loading wave ; Saw teeth
(slow loading speed, high unloading speed)
Stress ratio ; 0.1
Rise time ; 25 s

The depth and length of surface crack were in-situ measured by unique potential drop method(PDM).The detail of this method are given elsewhere [1].

Test Material

Two heats of carbon steel for high pressure service piping, JIS STS410 were used as the test materials. Chemical compositions of materials are listed on Table 1. HCS and LCS mean high sulfur material(0.021wt% S) and low sulfur material(0.007wt%S) , respectively. Mechanical properties of the test materials are listed on Table 2.

Table 1 Chemical Composition of the Test Material

(Unit : wt.%)

	C	Si	Mn	P	S
Carbon Steel, HCS	0.21	0.27	1.29	0.011	0.021
Carbon Steel, LCS	0.20	0.30	1.18	0.020	0.007
JIS Specification	<0.30	0.10 ~0.35	0.30 ~1.40	<0.035	<0.035

Table 2 Mechanical Properties of the Test Materials at Room Temperature and 288°C

	Yield Strength σ_y (MPa)		Tensile Strength σ_B (MPa)		Elongation (%)	
	RT	288°C	RT	288°C	RT	288°C
Carbon Steel, HCS	407	234	560	528	30	29
Carbon Steel, LCS	317	207	512	488	36 .	32

TEST RESULTS

CT Test

In order to evaluate the surface crack growth for the flat plate test specimen, fatigue crack growth tests were performed using CT specimen in air and in simulated BWR environment. The notch direction of CT specimen coincided with the direction of circumferential flaw in pipe. The crack growth rates of HCS and LCS materials expressed by Eq.(1) are almost correspond to the reference curve of ferritic steel proposed by ASME Code Sec. XI in air.

$$da/dN = 4.468 \times 10^{-9} \Delta K^{3.02} \quad \text{(in Air)} \qquad (1)$$

unit : da/dN [mm/cycle], ΔK [MPa$\sqrt{}$m]

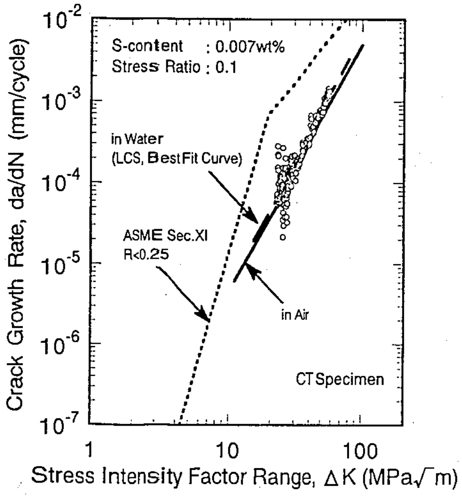

Fig. 1 Crack Growth Property of LCS in Simulated BWR Environment Obtained in CT Specimen

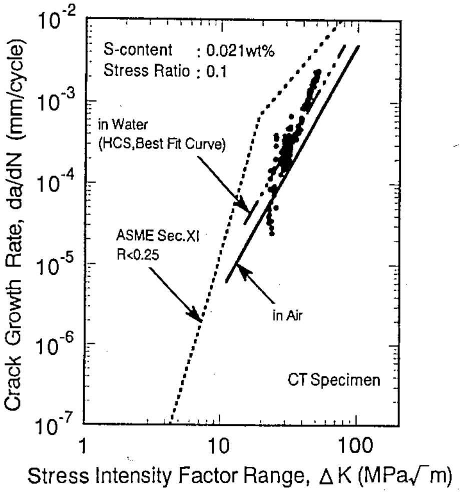

Fig. 2 Crack Growth Property of HCS in Simulated BWR Environment Obtained in CT Specimen

The crack growth rates for LCS and HCS materials in simulated BWR environment are shown in Figs. 1 and 2. The crack growth rates in air is also shown as the solid line. Relationship between crack growth rates, da/dN [㎜/cycle] and stress intensity factor range, ΔK [$\mathrm{MPa}\sqrt{\mathrm{m}}$] are expressed by Eqs.(2) and (3).

$$da/dN = 4.815 \times 10^{-9}\, \Delta K^{3.07} \quad \text{(LCS)} \qquad (2)$$
$$da/dN = 8.954 \times 10^{-9}\, \Delta K^{3.02} \quad \text{(HCS)} \qquad (3)$$

Single surface crack behavior in Small Flat Plate Test

The relationship between surface crack aspect ratio, a/c and normalized crack depth, a/t in air is shown in Fig. 3, where a is crack depth, c is a half crack length and t is thickness. In spite of initial crack configurations, the crack shape changes occur as that the aspect ratios approach to certain values with loading patterns. The value of aspect ratios, a/c approach about 0.8 for tension, about 0.6 for tension + bending and about 0.4 for bending at crack penetration. It is considered that the crack shape change behavior with propagating can expected by the accurate stress intensity factors.

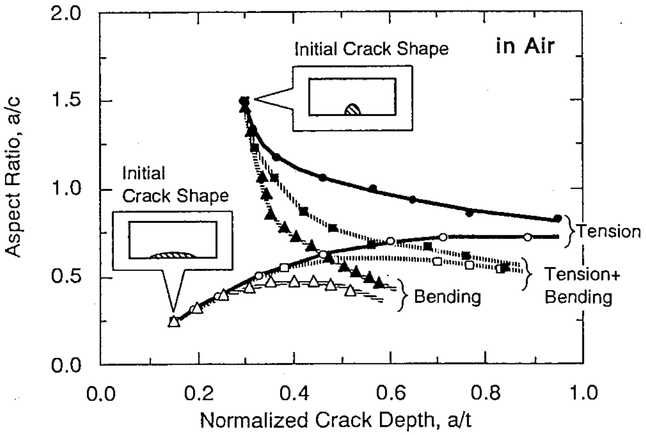

Fig. 3 Crack Shape Change with a Fatigue Surface Crack Growth in Air

The results of crack growth test using the bending specimen with a shallow crack are shown in Figs. 4 and 5. The results of crack growth calculation are also shown in these figures. The stress intensity factors at the deepest and surface points of the surface crack were calculated using Newman-Raju's formula [2] .Eqs.(2) and (3) are used as the crack growth rates in the simulated BWR environment for LCS and HCS materials, respectively. The crack growth rates are also employed the reference curve proposed by ASME Code Sec. XI for ferritic steel. The calculation using best fit curves as Eqs. (2) and (3) gives well estimation of surface crack growth behavior. However, the calculation using ASME reference curves is found to give very conservative estimation in the simulated BWR environment for LCS and HCS materials.

The crack growth rates at the deepest and surface points of the surface crack in simulated BWR environment are shown in Figs. 6 and 7, respectively. The crack growth curve in air and ASME reference curve in high temperature water are also shown in these figures as solid line and dotted line, respectively. In Fig. 6, the effect of sulfur content to the crack growth rate at deepest point is found to be negligible small. In Fig. 7, the crack growth rate at the surface

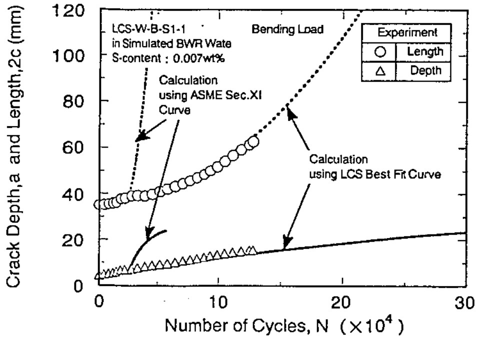

Fig. 4 Relationship between Surface Crack Depth/Length and Number of Cycles for LCS in Simulated BWR Environment

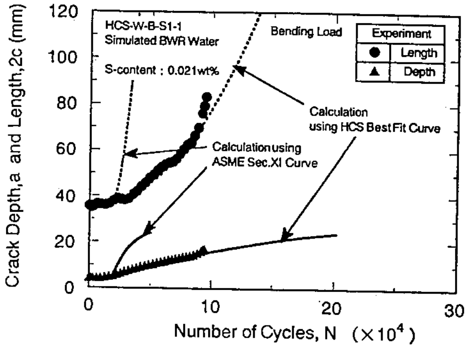

Fig. 5 Relationship between Surface Crack Depth/Length and Number of Cycles for HCS in Simulated BWR Environment

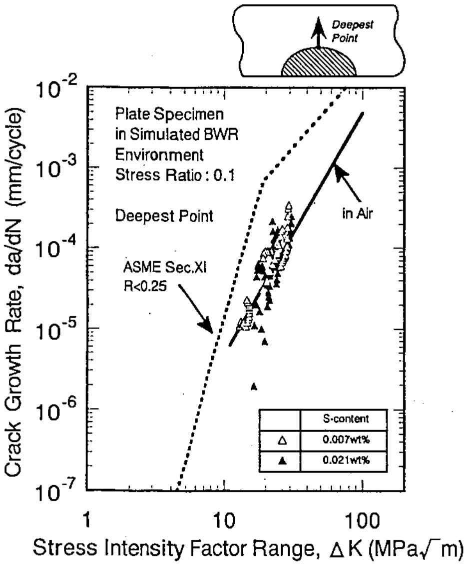

Fig. 6 Surface Crack Growth Property in Simulated BWR Environment at the Deepest Point

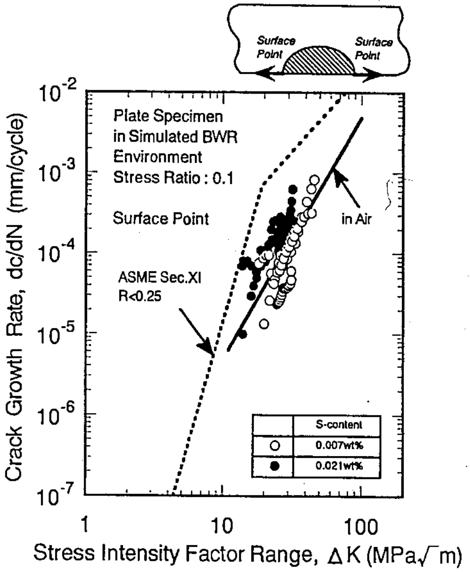

Fig. 7 Surface Crack Growth Property in Simulated BWR Environment at the Surface Point

point is recognized the effect of sulfur content. The higher sulfur content carbon steel, HCS (0.021wt%S) seems to have higher crack growth rate than the lower sulfur content one, LCS (0.007wt%S) in simulated BWR environment. It is found that no data of crack growth rate exceeds the reference curve proposed by ASME Code Sec.XI through these small flat plate test.

Multiple Surface Crack Coalescence Behavior in Small Flat Plate Test

Coalescence behavior of multiple surface cracks was examined by using flat plate specimen with aligned two separate surface crack in air at room temperature. The test results and calcurational analysis showed that the interaction between two cracks was not recognized until neighboring crack's edges approach together within a distance of about 0.2 crack length.

Coalescence behavior of multiple surface cracks in simulated BWR environment will be tested using PDM in the future. Based on the results of these tests, the margin of ASME Code Sec. XI is expected to be cleared.

CONCLUSION

Part of our activities toward the establishment of the unique flaw behavior evaluation criteria in Japan was introduced centering on the SAF (Structural Assessment of Flawed Equipment) project which is now being managed by JAPEIC. The project is now in the middle of the intended schedule, the results of the small flat plate tests begin to be obtained, and the model verification tests are expected to start soon after.

The fatigue crack growth tests, using small flat plate specimens made of Japanese carbon steel STS410 ,have been conducted. From the small flat plate test, crack shape change depends on loading patterns and higher sulfur content makes a crack growth rate in simulated BWR environment higher. Newman-Raju's formula gives good estimation for crack shape change.

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REFERENCES

1. Kanno, S., M. Hayashi, K. Miyazaki & J. Sanoh 1995. Monitering of Fatigue Crack Shape Change in Elevated Temperature Water by DC Potential Drop Method. *Proc.13th ICNDE*: 267-270. Kyoto.

2. Raju, I.S. & J.C. Newman 1979. Stress-Intensity Factors for a Wide Range of Semi-elliptical Surface Cracks in Finite-Thickness Plate, *Eng. Fract. Mech.*11: 817-829.