Crack growth study on carbon steel in simulated BWR environments

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1 INTRODUCTION

For further advancement of BWR structural integrity, life time estimation and prediction of final failure mode for BWR components are indispensable. These analyses require quantitative characterization of subcritical flaw growth during plant operations.

This study focuses on crack propagation for BWR piping systems of carbon steels. Fatigue crack growth data were generated in simulated BWR water environments using compact tension specimens. Metallurgical, environmental and stress factor effects on the crack growth behavior were investigated.

A surface crack study relative to this was described elsewhere (Hasegawa 1987).

2 EXPERIMENTAL

The 1T CT specimens with side grooves were machined from 20B Sch. 100 pipe of JIS G 3455 STS42 carbon steel and from 26B Sch. 80 pipe of STS49 carbon steel with the crack extension directions being parallel to the circumference of these pipes. The chemical composition of these steel pipes are shown in Table 1. A few CT specimens made of weld metal were fabricated from a butt weld joint of STS42 Sch. 100 pipes.

Prior to the experiments, CT specimens were pre-cracked in air at room temperature by fatigue at a stress intensity factor not beyond an initial value for the experiments.

Corrosion fatigue crack growth test as basic data was accomplished under 2×10^{-2} Hz triangular waveform with stress ratio 0.5 in 288°C pure water containing 8 ppm dissolved oxygen. Then, the test conditions were changed independently in the basic crack growth test condition in order to examine their effects on the crack growth rates, from 2×10^{-2} Hz to 2×10^{-3} Hz, from 0.5 stress ratio to 0.2 stress ratio and from 288°C to 150°C. Trapezoidal waveform tests were also carried out to identify stress corrosion cracking contribution to crack growth rates during corrosion fatigue tests. Furthermore, some specimens were tested in 288°C air-saturated steam environment. Fatigue crack growth rates in room temperature air were obtained for each specimen as the reference to those in water and steam environment as above. The test conditions are summarized in Table 2.

Crack extension was monitored by a compliance method and crack growth rates were determined by seven points incremental polynomial method in most of the tests. All the rates were plotted against applied cyclic stress intensity factor range, ΔK, in double logarithm scales.

3 RESULTS AND DISCUSSION

Fatigue crack growth rates obtained in room temperature air condition are shown in Fig.1. There was not any noticeable difference in crack growth rates between STS42 and STS49 pipes. No difference was also found in crack growth rates between the base material and the weld metal. These crack growth rates in low ΔK range exceeded the reference curve for carbon and low alloy steels in air of ASME Code Sec. XI (ASME 1983) as shown in Fig.1.

Crack propagation rates obtained in 288°C pure water under triangular waveform at 2×10^{-2} Hz and 2×10^{-3} Hz are also shown in Fig. 1. ΔK dependency of the crack growth rate was complicated. It seems that only the rates in low ΔK range followed Paris law relationship and the rates in high ΔK range were retarded or remained unchanged In some cases, the crack growth rate decreased followed by another increase. All the obtained crack growth rates except those under 2×10^{-3} Hz triangular waveform were located within the ASME code reference curve in water at stress ratio $R \geq 0.65$. In 2×10^{-3} Hz triangular waveform test, the rates were several times higher than the rates at 2×10^{-2} Hz at high stress intensity factor range and the rates were beyond the ASME code reference curve.

Crack growth rates in 288°C 8 ppm DO water under 2×10^{-3} Hz and 2×10^{-4} Hz trapezoidal waveform are shown in Fig.2. Note that no detectable crack growth was obtained under 2×10^{-4} Hz trapezoidal waveform until stress intensity factor range ΔK exceeding about 30 $MPa.m^{1/2}$ for both pipe steels.

The 2×10^{-3} Hz trapezoidal waveform test and the 2×10^{-2} Hz triangular waveform test did not give any noticeable differences in crack growth rates, however, the 2×10^{-4} Hz trapezoidal waveform test showed slightly higher crack growth rates at around ΔK=30 $MPa.m^{1/2}$. In the trapezoidal waveform tests, the waveforms at 2×10^{-3} Hz and 2×10^{-4} Hz were composed by holding for 450 seconds and 4950 seconds at the top load in the 2×10^{-2} Hz triangular waveform test, respectively. Therefore, crack growth rate acceleration in the 2×10^{-4} Hz trapezoidal waveform test was due to stress corrosion cracking for top load holding periods of 4950 seconds. Subtraction of crack growth rates under 2×10^{-2} Hz triangular waveform from those under 2×10^{-4} Hz trapezoidal waveform could give a stress corrosion cracking propagation rate (Kawakubo 1980). The rates from 3×10^{-10} m/s to 8×10^{-10} m/s are calculated at around K=60 $MPa.m^{1/2}$ as stress corrosion cracking propagation rates of carbon steel in 288°C 8 ppm DO water.

As for stress ratio, decrease from 0.5 to 0.2 shifted the crack growth rate curve to a high ΔK direction as shown in Fig.3. An effective cyclic stress intensity factor, K_{eff}, instead of ΔK, seemed to be available for plotting different sets of rates at stress ratios of 0.5 and 0.2.

Temperature change from 288°C to 150°C under 2×10^{-2} Hz triangular waveform apparently lowered the crack growth rate as shown in Fig.4. temperature air.

Table 1. Chemical Composition of STS 42 and 49 Carbon Steel

(Wt%)

	C	Si	Mn	P	S
STS 42	0.22	0.30	1.20	0.025	0.012
STS 49	0.20	0.33	1.16	0.026	0.012

Table 2. Test Conditions of Corrosion Fatigue Tests

Material	Environment			Temperature(C)			Dissolved Oxygen	Stress Waveform		Stress ratio		Frequency (Hz)		
	Water	Steam	Air	288	150	RT	8(ppm)	Triangular	Trapezoidal	0.5	0.2	2×10^{-2}	2×10^{-3}	2×10^{-4}
STS 42 20B Sch 100	O			O			O	O		O		O		
	O			O			O	O		O			O	
	O			O			O	O			O	O		
	O			O			O		O	O			O	
	O			O			O		O	O				O
	O				O		O	O		O		O		
		O		O			O	O		O		O		
		O		O			O		O	O			O	
			O			O		O						
STS 49 26B Sch 80		O		O			O	O		O		O		
			O			O		O		O				
Weld Metal	O			O			O	O		O		O		
			O			O		O		O				

Environmental change from 8 ppm dissolved oxygen containing water to air-saturated steam lowered the crack growth rate as shown in Fig.5. Changing stress waveform from 10^{-2} Hz triangular to 10^{-3} Hz trapezoidal did not give any noticeable increase in growth rate in steam environment as well as that in 288°C 8 ppm DO water. And the rate in steam environment is generally lower than that in 288°C 8 ppm DO water.

Therefore, crack growth in steam environment can be evaluated conservatively by the rate in 288°C 8 ppm DO water.

Crack growth rate of weld metal in 288°C 8 ppm DO water under 2×10^{-2} Hz triangular waveform are shown in Fig.6. The growth rate is almost equal to or lower than those of the base materials.

4 CONCLUSION

Fatigue crack growth rates of carbon steels are obtained using compact tension specimen in high temperature water and in steam environments and the results are summarized as follows.

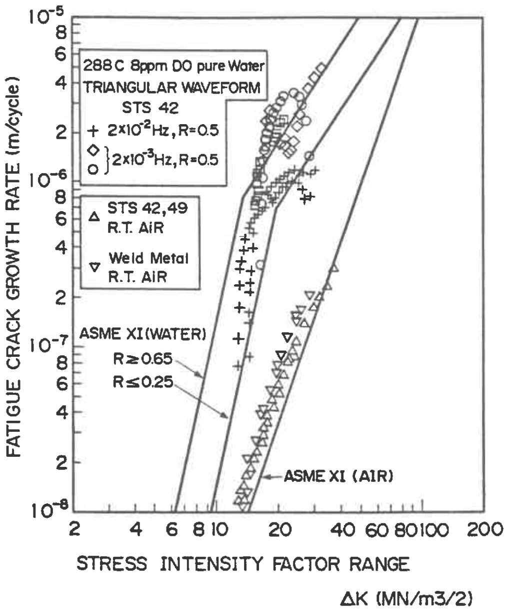

Fig.1 Crack growth rates for STS 42 carbon steel obtained in triangular waveform tests

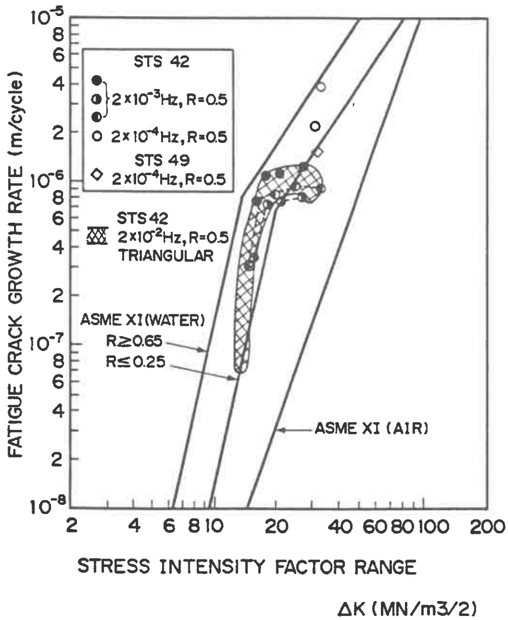

Fig. 2 Crack growth rates for STS 42 and STS 49 carbon steels in trapezoidal waveform tests (288°C 8ppm DO, pure water)

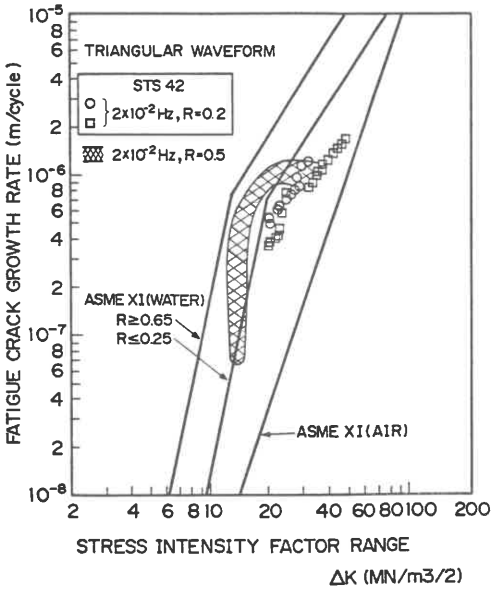

Fig. 3 Crack growth rates for STS 42 carbon steel under stress ratio R=0.2 in 288°C 8ppm DO water

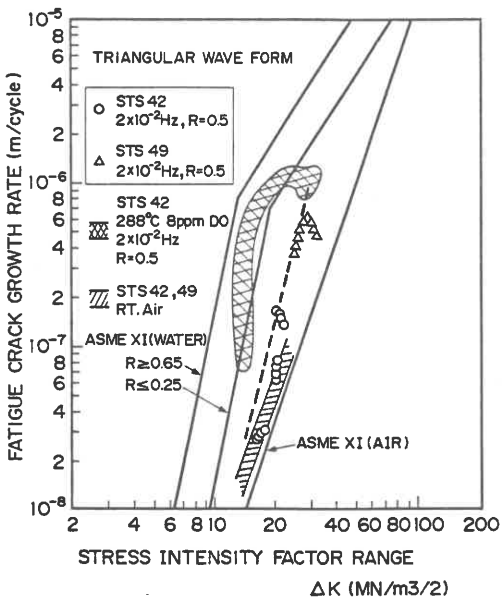

Fig. 4 Crack growth rates for STS 42 and STS 49 carbon steels in 150°C 8ppm DO water

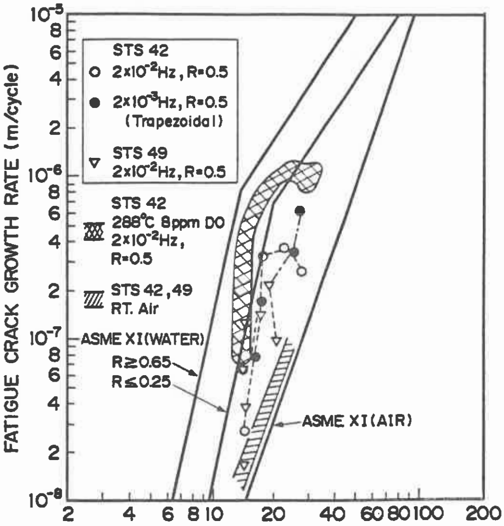

Fig. 5 Crack growth rates for STS 42 and STS 49 carbon steels in 288°C air-satulated steam

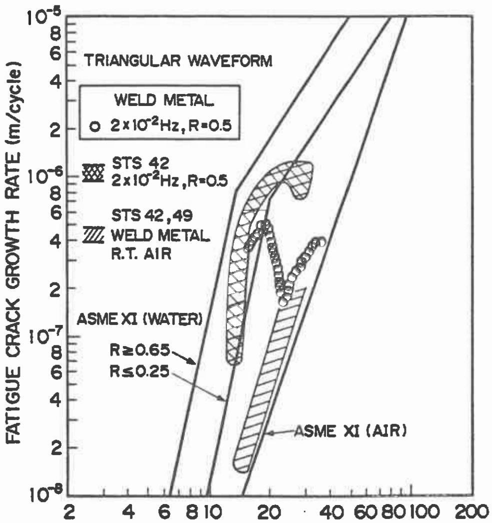

Fig. 6 Crack growth rates for weld metal in 288°C 8ppm DO water

(1) Crack growth rates strongly depended on the frequency in triangular waveform. The rates became higher as the frequency lowered from 2×10^{-2} Hz to 2×10^{-3} Hz.
(2) Crack growth rate are almost equal under 2×10^{-3} Hz Trapezoidal waveform and under 2×10^{-2} Hz triangular waveform.
(3) Crack growth rate are lowered as stress ratio decreased from 0.5 to 0.2.
(4) Temperature change from 288°c to 150°C apparently lowered the crack growth rate.
(5) 288°C 8 ppm DO water environment gave much higher acceleration on crack growth rate than 288°C air-saturated steam.
(6) Crack growth rate for weld metal in 288°C pure water are almost equal to or lower than that of base metal.

ACKNOWLEDGEMENTS

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