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FATIGUE CRACK GROWTH BEHAVIOR OF WELD HEAT AFFECTED ZONE OF TYPE 304 STAINLESS STEEL IN HIGH TEMPERATURE WATER

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Abstract

Fatigue crack growth behavior of weld heat affected zone(HAZ) of type 304 stainless steel in simulated BWR water environment was investigated to make clear the effects of welding residual stress, cyclic frequency(f) and thermal aging on crack growth rate. It was observed that the crack growth rate of HAZ was lower than that of base metal owing to the compressive residual stress in both 288°C water and ambient air. The effect of welding residual stress on crack growth rate of HAZ can be evaluated separately from the environmental effect through the crack closure behavior. High temperature water increased the crack growth rate at $f=0.0167\text{Hz}$, but did not much affect it at $f=3$ and 5Hz . The crack growth behavior of thermally aged HAZ at 400°C for 1800hrs was almost the same as those of unaged material tested at the frequency of 0.0167 and 5Hz .

1. INTRODUCTION

There are many investigations on the stress corrosion cracking and corrosion fatigue of structural steels, for example low alloy steel, austenitic stainless steel, Ni base alloy and so forth in the high temperature water, which assess the structural integrity of LWR power plant. Fatigue crack growth behavior of these materials in the high temperature water is becoming clear by many efforts. However, the crack growth behavior of weld joint is more complicated due to the combined effect of welding residual stress and microstructural change introduced by welding. Then it is important to clarify the mechanism of acceleration of fatigue crack growth rate(FCGR) of HAZ for understanding of fatigue crack growth of weld joint and an accurate plant life prediction. Furthermore, structural materials used for main components of LWR are thought to be degraded by neutron irradiation, thermal aging, fatigue and other mechanisms.

In this paper, the crack growth behavior of HAZ of type 304 stainless steel in the high temperature water was studied in view of crack closure due to welding residual stress and the effect of thermal aging on it was discussed.

2. EXPERIMENTAL PROCEDURE

Specimens used for the tests were prepared from type 304 stainless steel plate of 40mm thickness which received solution heat treatment at 1100°C for 0.8hrs. Chemical compositions and mechanical properties of the material are shown in Table 1 and 2, respectively. Weld joints were made by butt SAW with 308L weld metal so that fusion line is parallel to the rolling direction of the plate, and some of joints were thermally aged at 400°C for 1800hrs to simulate the thermal aging caused by long term plant operation.

Table 1 Chemical compositions of type 304 stainless steel tested (wt%)

Material	C	Si	Mn	P	S	Ni	Cr	Mo	N	Fe
type 304	0.06	0.65	0.91	0.030	0.002	8.99	18.50	0.13	0.039	Bal.

Table 2 Mechanical properties of solution treated type 304 stainless steel

Material	σ_Y (MPa)	σ_B (MPa)	ϵ_t (%)
type 304	231	579	66

Table 3 Loading condition for fatigue crack growth test

Material		Environment	Stress ratio	Cyclic frequency(Hz)	Procedure
Base metal	Unaged	R.T. in air	0.1	5	ΔK increase
HAZ	Unaged	R.T. in air	0.1	5	ΔK increase
		288°C water	0.1	0.0167 and 3 5	ΔK increase
	Aged	288°C water	0.1	0.0167 and 5	ΔK decrease
			0.5	0.0167	ΔK increase

Side grooved 1T-compact tension(CT) specimens of HAZ were prepared from both aged and unaged joint as shown in Fig.1 so that the crack grows in HAZ along the fusion line. Fatigue crack growth test was conducted using electro-hydraulic testing machine with an autoclave. Specimens were loaded in the simulated BWR water, which temperature was 288°C, pressure 7.8MPa, D.O. 0.2ppm and average conductivity $0.2 \mu\text{S/cm}$. Loading conditions are shown in Table 3. All the tests for unaged material and a test for aged material at $R=0.5$ were conducted by the ΔK increasing method, but for aged material at $R=0.1$, the ΔK decreasing method was utilized and cyclic frequency was changed from 0.0167Hz to 5Hz for the single specimen. Crack lengths were estimated by the unloading compliance method through measuring the crack opening displacement by a COD gage mounted at the mouth of the specimen. To evaluate the effect of welding residual stress on the crack growth of HAZ, crack closure level was measured in some specimens.

3. RESULTS and DISCUSSION

3.1 Crack growth behavior in high temperature water

Fig.2 shows the relationships between crack growth rate, da/dN and stress intensity factor range, ΔK . This figure also shows the crack growth data obtained by Hishida et al.^[1] for base metal of type 304 stainless steel in the similar testing condition. The fatigue crack growth rate at 0.0167Hz is predominantly higher than others in the high temperature water. The FCGR at $f=3\text{Hz}$ in the water is lower than those at $f=5\text{Hz}$ in the water and in ambient air. The effect of cyclic frequency decreases with increasing ΔK and the FCGR is not affected by cyclic frequency and/or environment at ΔK above $45\text{MPa}\sqrt{\text{m}}$. In air, the FCGR of HAZ is lower than that of base metal. Comparing the present results with that of Hishida et al.^[1], it is found that the FCGR of HAZ at $f=0.0167\text{Hz}$ is also lower than that of base metal at $f=0.02\text{Hz}$ in the water. The lower FCGR at $f=3\text{Hz}$ in the water than that in air is thought to be caused by the difference of welding residual stress as discussed later. It also seems that the lower FCGR of HAZ than base metal is due to welding residual stress.

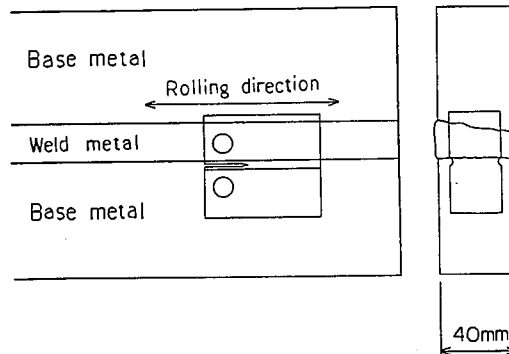


Fig.1 Preparation of HAZ specimens

Fig.3 shows the effect of stress ratio on the FCGR of HAZ in the high temperature water with the data by Hishida et al.. It is observed that the FCGR at R=0.5 is higher than that at R=0.1 and the effect of stress ratio decreases with increasing ΔK . The effect of stress ratio on the FCGR of HAZ is greater than that of base metal. The difference in the FCGR between HAZ and base metal at R=0.5 is not so remarkable rather than that at R=0.1. Although the crack closure level was not measured at R=0.5, the crack opening ratio(U) generally becomes higher with increasing stress ratio. Then the effect of residual stress on the crack closure at R=0.5 may be smaller than that at R=0.1. At such high R, the difference in the FCGR of HAZ and base metal depending on residual stress must be smaller.

3.2 Crack closure behavior in HAZ

It is found that the FCGR of HAZ is lower than that of base metal in both high temperature water and ambient air. A residual stress introduced by welding is thought to be cause of the lower FCGR of HAZ than that of base metal. Fig.4 shows the residual stress distributions of butt weld joint and specimens taken from it^[2]. It is understood from this figure that the crack tip is always in a compressive residual stress field in the CT specimen provided in the test. When the material undergoes cyclic loading, the residual stress is thought to affect the crack closure behavior. So the crack closure level has been measured by using the unloading compliance method during the fatigue crack growth tests.

Fig.5 shows the relationships between crack opening ratio(U) and ΔK . It is found that the crack closure level of HAZ is lower than that of base metal. The value of U increase with ΔK and becomes to the unity at ΔK above 45MPam^{1/2}. Crack closure level of unaged HAZ tested in the water is lower than that of aged HAZ in water and unaged HAZ in air. For unaged HAZ tested in the water at f=0.0167 and 3Hz using single specimen, both data can be recognized to be located on the same trend curve. Since the clear effect of cyclic frequency on the crack closure level is not observed, the environmental effect, e.g. wedge effect by oxide, is negligible in these frequency ranges tested. Then the difference in observed crack closure level between unaged and aged HAZ in water may be considered to be caused by the variation of residual stress. The value and distribution of residual stress of specimen may depend on the location of specimen cut out from the weld joint.

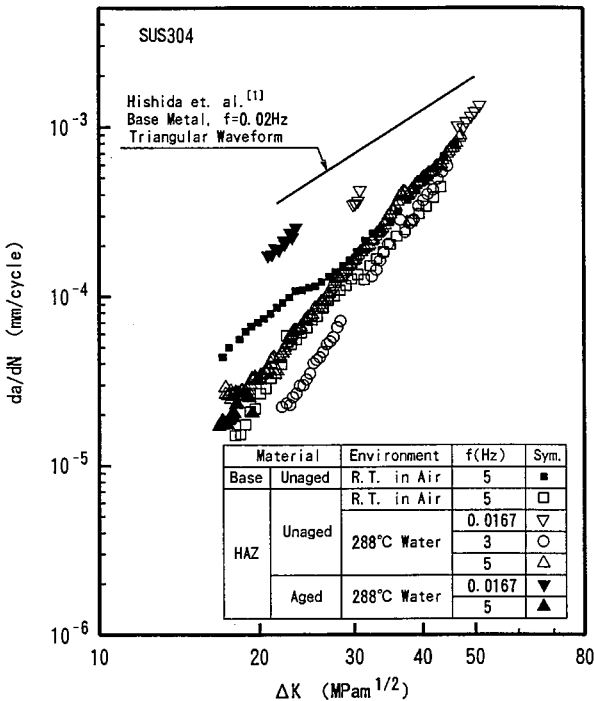


Fig.2 Effect of cyclic frequency and thermal aging on the fatigue crack growth behavior of HAZ of type 304 stainless steel

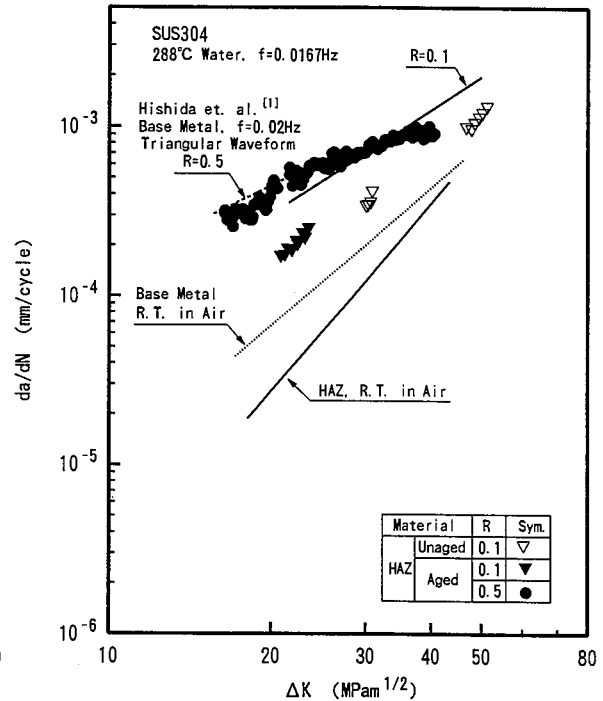


Fig.3 Effect of stress ratio on the fatigue crack growth behavior of HAZ of type 304 stainless steel

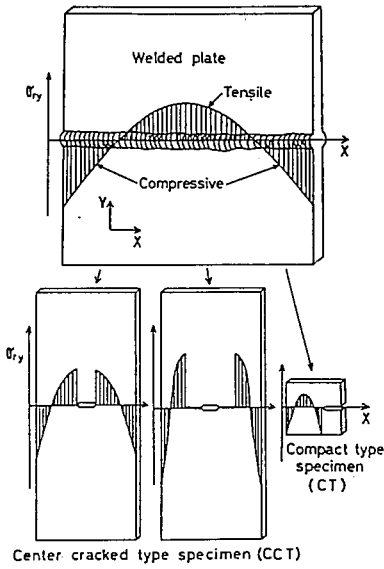


Fig.4 Residual stress distribution of butt weld joint and specimen prepared from joint⁽²⁾

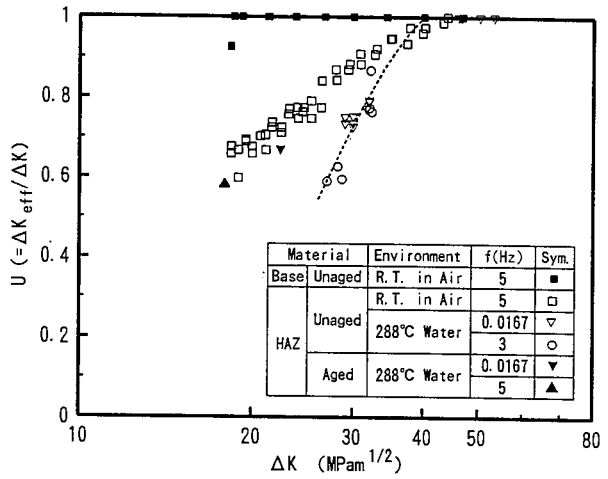


Fig.5 Crack closure behavior of HAZ of type 304 stainless steel

Fig.6 shows the relationships between crack growth rate, da/dN and effective stress intensity factor range, ΔK_{eff} that is considered to be the true driving force for fatigue crack growth. It is found that the FCGR of HAZ is almost the same as base metal in ambient air. And the FCGR at $f=3\text{Hz}$ in the water is slightly higher than that in ambient air. The environmental effect on the FCGR is clearly recognized in Fig.6 through the FCGR dependence on cyclic frequency. It is also found that the thermal aging does not much affect the $da/dN-\Delta K_{eff}$ relationships.

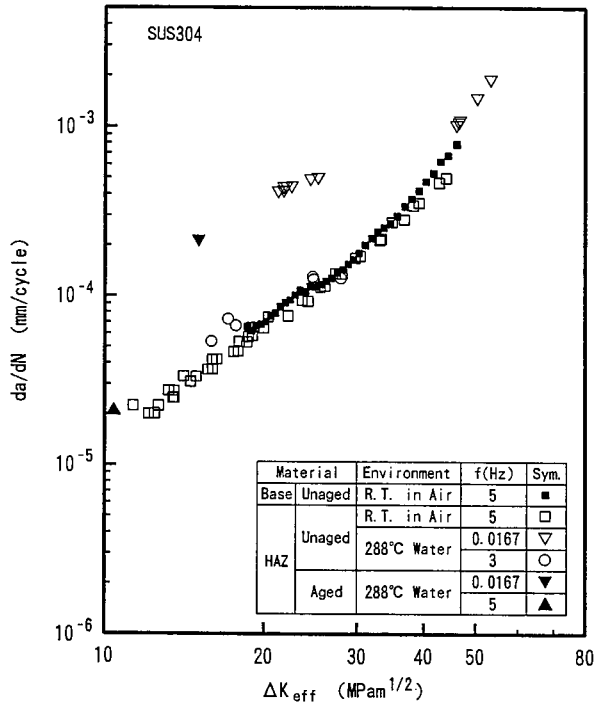


Fig.6 da/dN vs. ΔK_{eff} relationships of HAZ of type 304 stainless steel

3.3 Sensitization by welding and thermal aging

Comparing the results of fatigue crack growth tests for aged HAZ with unaged HAZ, it can be recognized that the effect of thermal aging at 400°C for 1800hrs on FCGR is not remarkable. The EPR change was measured before and after aging for both base metal and HAZ to evaluate the degree of sensitization(DOS). Two specimens with 1–4 points measurements were performed about both materials. The location of measurements for HAZ is about 2mm from the fusion line. Table 4 shows the DOS of each measurement and their average value for each condition. These DOS values are defined as ratio of I_r/I_a , in which I_r is peak current density during the potential rising process and I_a is peak current density during the potential dropping process^[3]. In this table, in spite of a little data scatter, the average value shows the development of sensitization by welding and thermal aging. As a DOS value over 5% means that type 304 stainless steel is sensitized, thermally aged HAZ was sensitized, but not so much to cause the influence on the crack growth behavior. This is consistent with the fracture appearance in which no remarkable differences are observed between the aged and the unaged materials as shown in the next.

Table 4 Result of degree of sensitization measurement

Material		DOS(%)	
Unaged	HAZ	3.9	Average 3.0
		2.9	
		2.3	
		2.5	
3.2			
Base Metal	0.0	Average 0.7	
	1.3		
Aged	HAZ	2.2	Average 10.2
		14.1	
		17.1	
		8.6	
		9.1	
	Base Metal	0.1	
5.3			

3.4 Crack path and fracture surface observation

It was found that thermal aging at 400°C for 1800hrs does not much affects the FCGR of HAZ in the water, but changes DOS slightly. Then the crack path and fracture surface of the specimens were observed to investigate the influence of environment and thermal aging on micro-structural aspect of fracture. Fig.7(a)–(c) show the crack paths of unaged HAZ in air, unaged HAZ at $f=5\text{Hz}$ in the water and aged HAZ at $f=0.0167\text{Hz}$ in the water respectively. It is understood that the fracture surface formed in ambient air is flat from Fig.7(a). On the contrary, the fracture surface is rough and branched in the water. In spite of the difference in the FCGR and DOS, no distinct difference in fracture appearance is observed between unaged HAZ at $f=5\text{Hz}$ and aged HAZ at $f=0.0167\text{Hz}$.

Fig.8(a)–(c) show the fracture surfaces observed by SEM corresponding to Fig.7. These figures show that surfaces formed in water is rougher than that obtained in air. From Fig.7 and 8, it is clear that the crack grows transgranularly and does not cause any difference in fracture morphology between unaged and aged HAZ in the high temperature water.

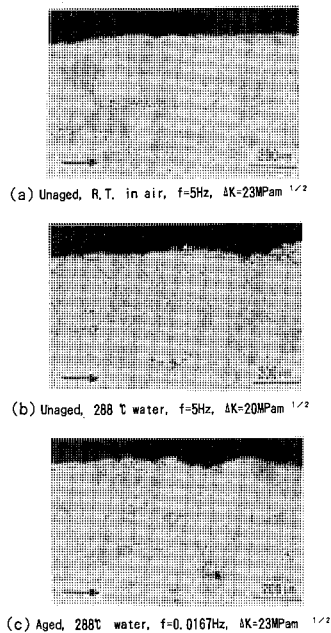


Fig.7 Crack path of HAZ formed in ambient air and high temperature water

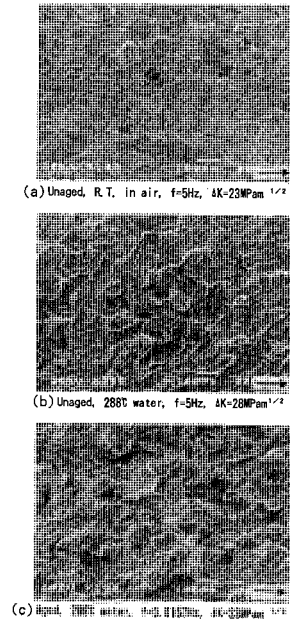


Fig.8 Fracture surface of HAZ formed in ambient air and high temperature water

4. CONCLUSIONS

Fatigue crack growth behavior of HAZ of type 304 stainless steel was investigated by using CT specimens prepared from the butt weld joint in view of the effect of welding residual stress and cyclic frequency. The influence of thermal aging is also discussed. Then the following conclusions are obtained.

- (1) The FCGR of HAZ is lower than that of base metal, since the crack tip of HAZ is always in the compressive residual stress field.
- (2) Effective stress intensity factor range, ΔK_{eff} is a reasonable factor to evaluate the fatigue crack growth behavior in residual stress field and useful to understand the environmental effect on the acceleration of the FCGR.
- (3) The FCGR of HAZ increases with stress ratio, R and is more sensitive to R than that of base metal because of the compressive welding residual stress.
- (4) Thermal aging at 400°C for 1800hrs causes the sensitization of HAZ, but does not so much affect the fatigue crack growth behavior.
- (5) Fracture surface observations are made to examine the frequency dependency of FCGR of HAZ. It was found that the fatigue crack grows transgranularly and branched in high temperature water. No distinct difference of fracture appearance was observed under influence of thermal aging and cyclic frequency in spite of FCGR change.

References

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