



Fatigue lives of stainless steels in PWR primary water

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ABSTRACT

The series of strain controlled fatigue tests on stainless steels in simulated PWR primary water were conducted to examine the effects of water environment, strain rate, temperature, dissolved oxygen, thermal aging/sensitization on fatigue life of several steels. The effects of water environment, strain rate and temperature on fatigue life of stainless steels were substantial.

1. INTRODUCTION

The fatigue design curves in ASME Sec. III were determined from the best fit curves of fatigue data which were obtained in room temperature air taking account of 20 times factor on fatigue life and 2 times factor on stress. The effect of water environment was not included in these factors although the other effects such as size, surface condition, scatter of fatigue data and atmosphere were included. Recently, some researches on the effect of water environment on fatigue life have been carried out in Japan[1],[2] and USA[3] and the quantitative methods which could account the effect of water environment on fatigue life have been proposed. However, the major parts of fatigue data were those of carbon steels and low alloy steels and there are not enough fatigue data of stainless steels especially in PWR primary water.

The strain controlled fatigue tests on stainless steels were carried out in simulated PWR primary water. The material tested were austenitic stainless steel JIS SUS316, SUS304 and duplex stainless steel JIS SCS14A. The effects of strain rate, test temperature, dissolved oxygen content in water, thermal aging of duplex stainless steel and sensitization of austenitic stainless steel on fatigue life in PWR primary water were examined.

2. EXPERIMENTAL PROCEDURE

(1) Material

The materials tested were austenitic stainless steels SUS316, SUS304 and duplex stainless steel SCS14A (equivalent to CF8M). The chemical compositions of the materials are listed in Table 1. Each stainless steel consisted of three heats of base-metal. The heat treatment and mechanical properties are listed in Table 2. FN in the tables showed ferrite number of cast pipe. One of three heats of SUS316 and SUS304 were heavily sensitized and one of three heats of SCS14A was thermally aged. The other materials were tested as solution heat treated condition.

(2) Specimen and test apparatus

The hollow cylinder specimen was used for fatigue tests as shown in Fig.1. The outer diameter and thickness were 12 mm and 3 mm, respectively. The specimens were machined with the axis coinciding with that of piping or forging direction of plate. The outer and inner surface of the specimens were polished in the same direction as the specimen with emery

Table 1 Chemical composition of material tested

		C (%)	Si (%)	Mn (%)	P (%)	S (%)	Ni (%)	Cr (%)	Mo (%)
SUS316(A)	pipe	0.06	0.61	1.69	0.025	0.01	13.06	16.55	2.08
SUS316(B)	forged plate	0.07	0.5	1.48	0.031	0.006	11.06	17.6	2.3
SUS316(C)	sensitized pipe	0.057	0.64	1.64	0.026	0.006	13.02	16.48	2.07
SUS304(A)	plate	0.06	0.59	0.83	0.023	0.002	9.17	18.89	
SUS304(B)	pipe	0.061	0.58	1.74	0.026	0.003	9.6	18.35	
SUS304(C)	sensitized plate	0.06	0.55	0.9	0.026	0.004	8.87	18.38	
SCS14A(FN11.4)	cast pipe	0.048	0.64	0.84	0.028	0.005	10.46	20.01	2.16
SCS14A(FN19.7)	cast pipe	0.053	0.95	0.8	0.03	0.005	9.52	20.52	2.2
SCS14A(FN25.6)	cast pipe	0.05	1.3	0.84	0.028	0.017	9.32	20.75	2.3
		N (%)	Co (%)	Cu (%)	V (%)	Nb (%)	O (ppm)	H (ppm)	FN (%)
SCS14A(FN11.4)	cast pipe	0.05	0.09	0.21	0.04	0.01	75	3.8	11.4
SCS14A(FN19.7)	cast pipe	0.045	0.06	0.13	0.06	0.02	78	5.2	19.7
SCS14A(FN25.6)	cast pipe	0.042	0.08	0.12	0.04	0.02	129	4.9	25.6

Table 2 Heat treatment and mechanical properties of material tested

	Solution Heat Treatment	Aging / sensitization	Temp.	0.2% proof stress (MPa)	Tensile stress (MPa)	elongation (%)	reduction of area (%)
SUS316(A)	1060°C×30min. WQ	-	RT	234	550	63.0	81.1
			325°C	153	465	47.4	73.1
SUS316(B)	1050°C×40min. WQ	-	RT	264	569	58.5	81.5
			325°C	171	476	48.3	77.7
SUS316(C)	1055°C×30min. WQ	700°C×100hrs.	RT	250	555	50.5	67.6
			325°C	163	463	40.3	56.9
SUS304(A)	1050°C×10min. WQ	-	RT	246	604	57.4	70.4
			325°C	161	447	42.4	64.7
SUS304(B)	1060°C×30min. WQ	-	RT	222	551	64.4	80.0
			325°C	130	427	49.4	77.0
SUS304(C)	1040°C×5min. WQ	650°C×20hrs.	RT	267	614	54.7	69.2
			325°C	173	460	42.3	67.5
SCS14A(FN11.4)	1100°C×5hrs. WQ	-	RT	259	521	48.6	77.6
			325°C	160	416	35.9	80.0
SCS14A(FN19.7)	1100°C×5hrs. WQ	-	RT	300	611	45.3	74.6
			325°C	197	505	38.7	67.5
		465°C×25200hrs.	RT	312	715	24.9	32.9
			325°C	201	544	17.7	24.0
SCS14A(FN25.6)	1100°C×5hrs. WQ	-	RT	352	644	43.3	69.0
			325°C	235	543	36.2	60.1

paper.

The test apparatus was arranged as shown in Fig.2. The corrosive environment was formed inside the hole of the specimen. The water chemistry was controlled in the tank. The flow rate was about 10 l/hr and average fluid velocity at test section was about 0.3 m/sec.

(3) Fatigue test

Fully reversed axial strain controlled fatigue tests were carried out. The strain rate in rising phase was varied from 0.00001 to 0.4 %/sec and that in falling phase was always kept 0.4 %/sec. The test water was 100°C~360°C simulated PWR primary water which contained boric acid and lithium hydroxide. The dissolved oxygen (DO) and hydrogen were kept less than 0.005 ppm and 30 cc/kg · H₂O in almost test and DO was kept 8 ppm in the limited test to examine the effect of DO on fatigue life.

The fatigue life was defined as N_{LEAK} , which was the number of cycles to the full thickness penetration of a crack in this study.

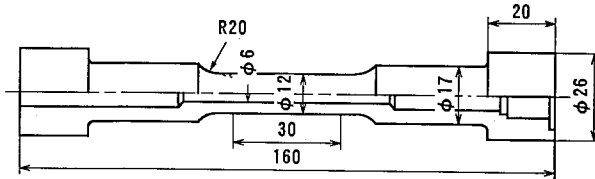


Fig. 1 Configuration of specimen

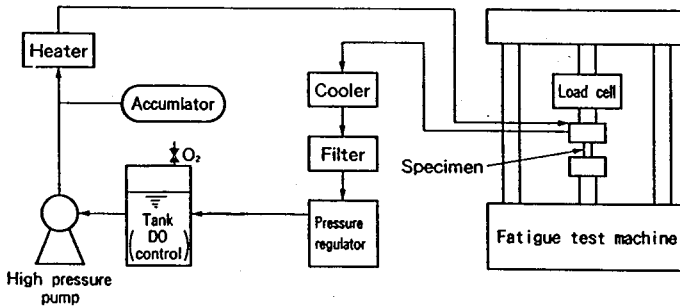


Fig. 2 Outline of test apparatus

3. RESULTS AND DISCUSSION

(1) Effect of environment

The fatigue life of SUS316, SUS304 and SCS14A(un-aged) in 325°C air and PWR primary water are shown in Fig.3~Fig.5, respectively. The fatigue life of all materials in water was shorter than in air and substantial effect of water environment was observed. This observation indicated that the environmental effect of PWR primary water on fatigue life of stainless steels must be accounted for the accurate fatigue evaluation of actual components.

(2) Effect of strain rate

Relation between strain rate in rising phase and fatigue life at 325°C is shown in Fig.6. In all materials, the fatigue life was decreased with a decrease of strain rate and good linear relation between logarithmic strain rate and logarithmic fatigue life was observed. In SUS316, the clear threshold strain rate, below which effect of strain rate on fatigue life was saturated, was observed at 0.004 %/sec when strain amplitude was 0.6 %. The same threshold strain rate of SUS304 was observed at 0.0004%/sec although that of SCS14A was not observed in the range from 0.00001 %/sec to 0.4 %/sec. The threshold strain rate at lower strain amplitude was almost as same as at strain amplitude of 0.6 % in SUS316 and this observation showed that effect of strain amplitude on threshold strain rate was not prominent.

The threshold strain rate was observed in the fatigue tests of carbon steel in oxygenated water[3] and its value was 0.001 %/sec. However, in the other fatigue tests using the other carbon steel the threshold strain rate was not observed in the range from 0.0001 %/sec to 0.4 %/sec[1]. Although the reason why the threshold strain rate exists is not determined, these observations suggested that the threshold strain rate could vary among the materials or heats, and indicated the importance of these kind of fatigue data.

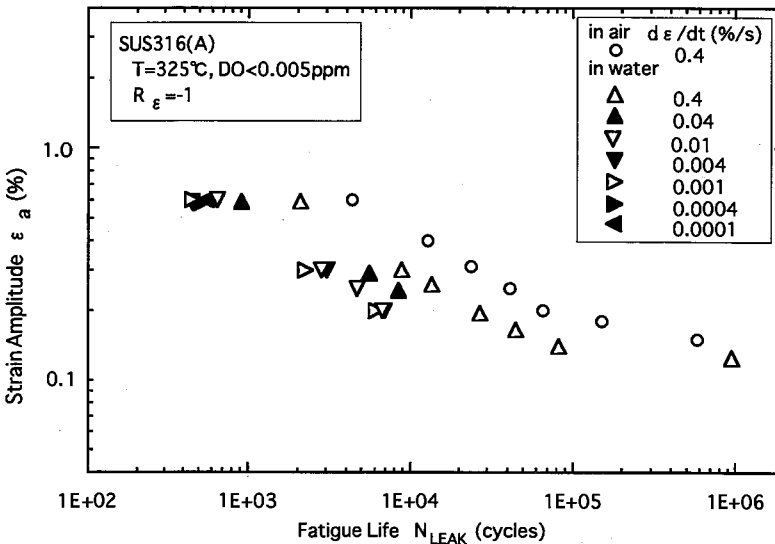


Fig.3 Effect of PWR primary water on fatigue life of SUS316 at 325°C

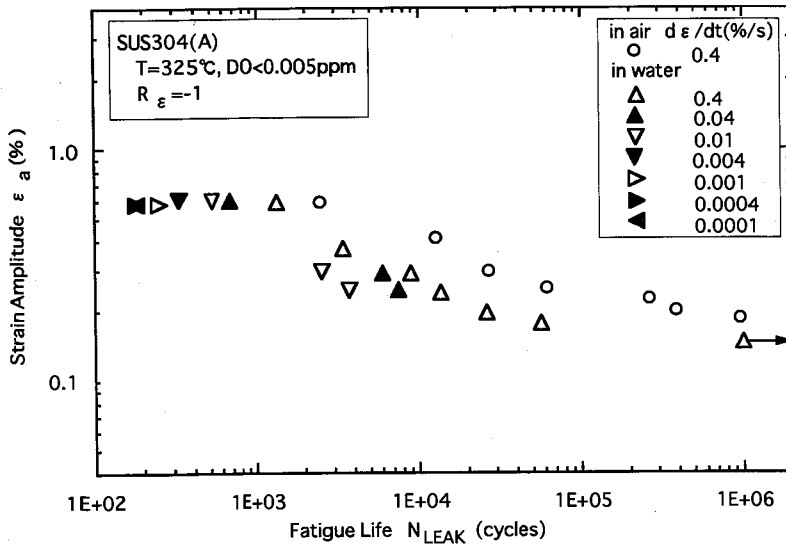


Fig.4 Effect of PWR primary water on fatigue life of SUS304 at 325°C

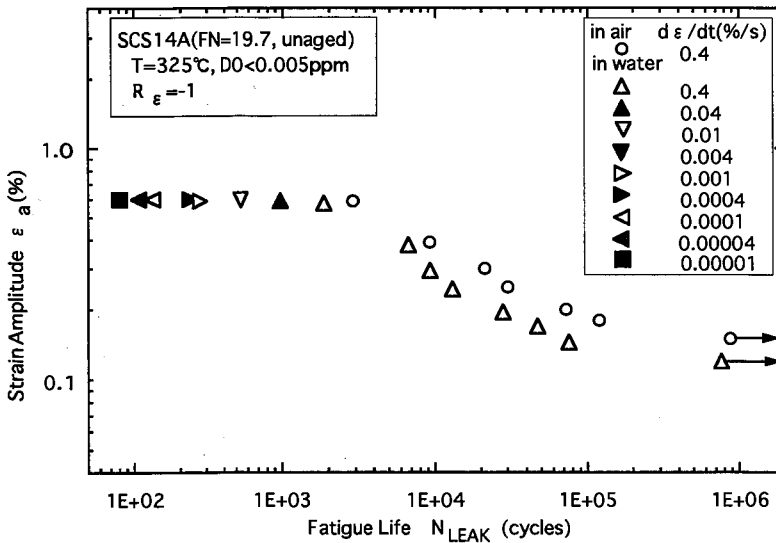


Fig.5 Effect of PWR primary water on fatigue life of SCS14A(unaged) at 325°C

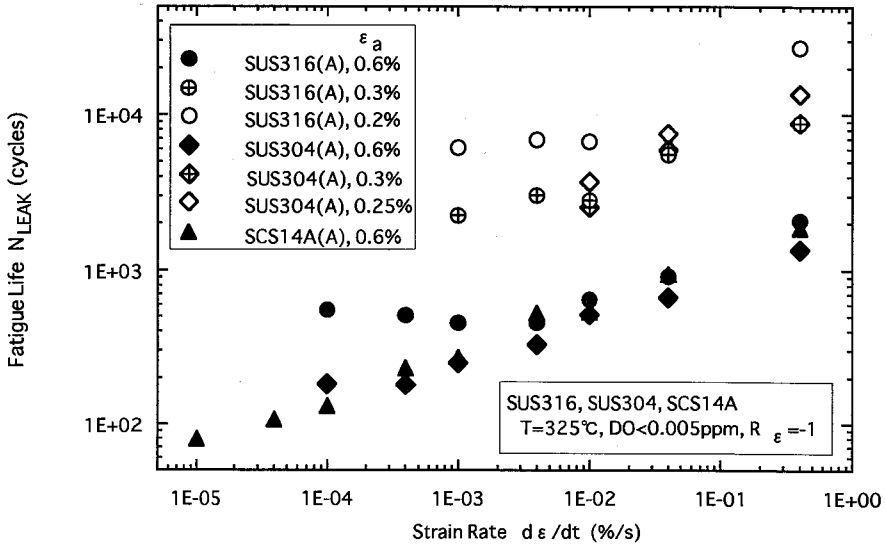


Fig.6 Effect of strain rate on fatigue life of stainless steels at 325°C

(3) Effect of temperature

The SN curve and relation between strain rate in rising phase and fatigue life of SUS316 at various temperature were shown in Fig.7 and Fig.8, respectively. The difference of fatigue life among various temperature was small at fast strain rate of 0.4 %/sec. However, prominent effect of temperature on fatigue life was observed at slower strain of 0.01 %/sec and the fatigue life was decreased with an increase of temperature. The same tendency of temperature was observed in the fatigue tests of SUS304.

(4) Effect of dissolved oxygen

The SN curves of SUS316 at DO<0.005 ppm and 8 ppm were shown in Fig.9. Although the fatigue life of SUS316 at DO<0.005 ppm was slightly shorter than that at DO=8 ppm at strain rate of 0.01 %/sec, the effect of dissolved oxygen on fatigue life was not prominent in this study. In the case of SUS304, the difference of fatigue life between DO<0.005 ppm and DO=8 ppm was smaller than SUS316.

In the tests of carbon steels and low alloy steels, the substantial effect of DO on fatigue life was observed[1],[2],[3]. The difference of DO tendency between carbon steels/low alloy steels and stainless steels suggested that the mechanism of fatigue life reduction of stainless steels was not the same as that of carbon steels/low alloy steels although the same kind of strain rate and temperature tendencies were observed among these three materials.

(5) Effect of thermal aging on fatigue life of SCS14A

The comparison of fatigue life between un-aged and aged SCS14A in air and water was shown in Fig.10 and relation between strain rate in rising phase and fatigue life of un-aged and aged SCS14A was shown in Fig.11. The ductility of material tested decreased very much after long heat treatment as shown Table 2 and the substantial effect of thermal aging was observed. However, the fatigue life of aged material was the same as that of un-aged material both in air and in PWR primary water and the difference of strain rate dependency was very small.

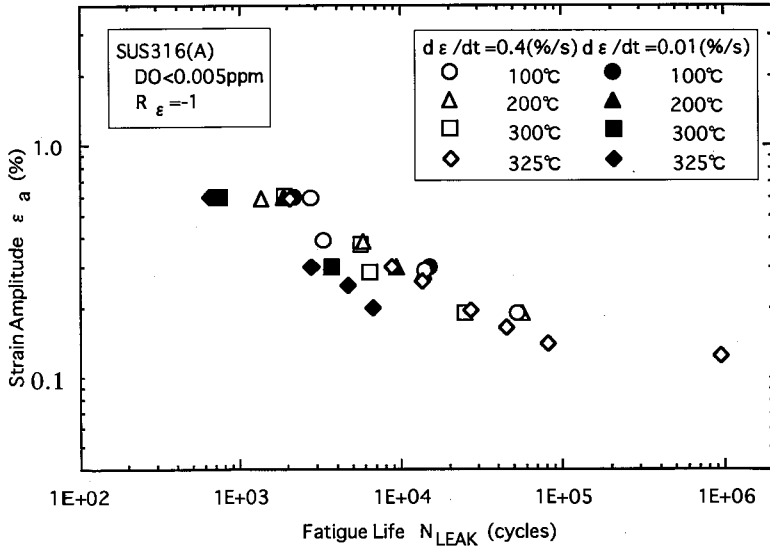


Fig.7 Effect of temperature on fatigue life of SUS316

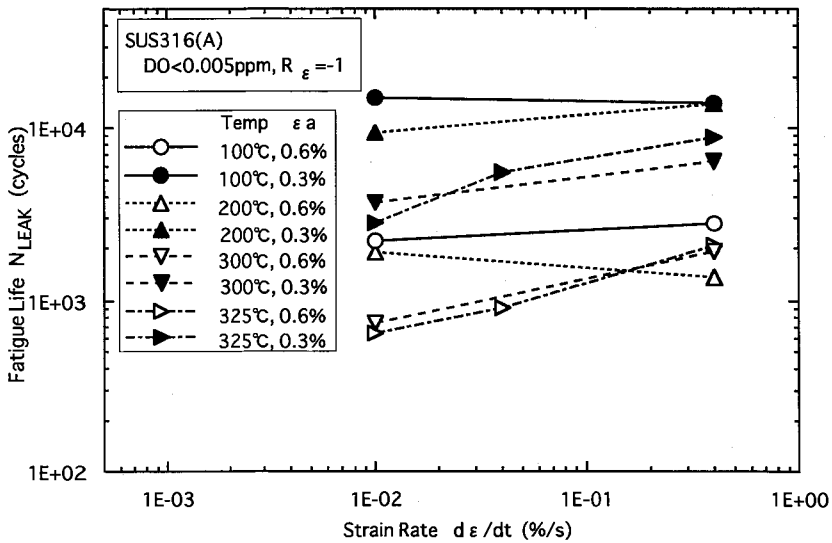


Fig.8 Effect of temperature on strain rate dependency of SUS316

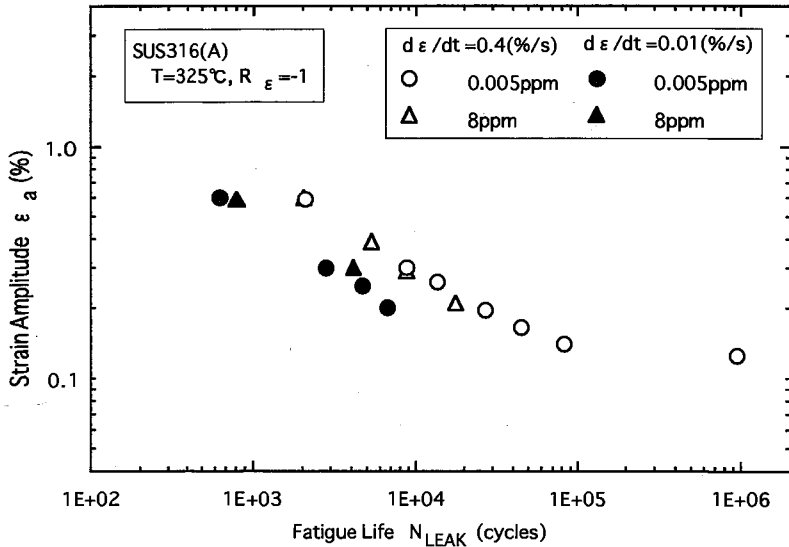


Fig.9 Effect of dissolved oxygen content on fatigue life of SUS316

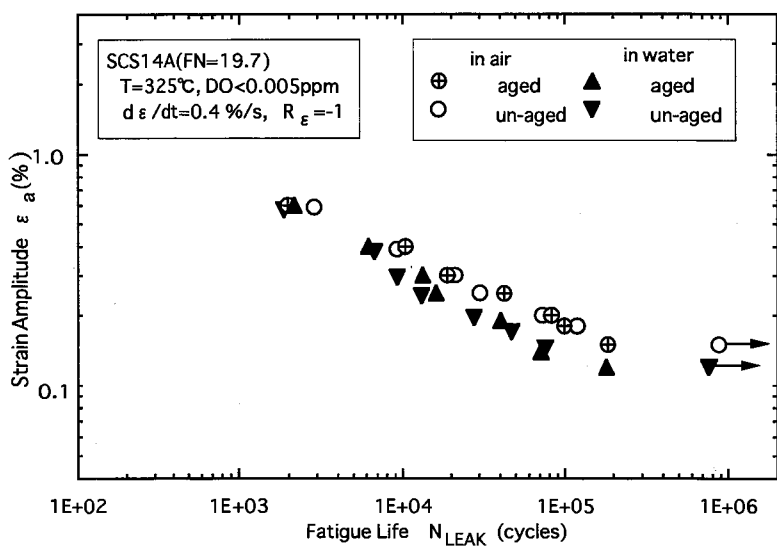


Fig.10 Effect of thermal aging on fatigue life of SCS14A

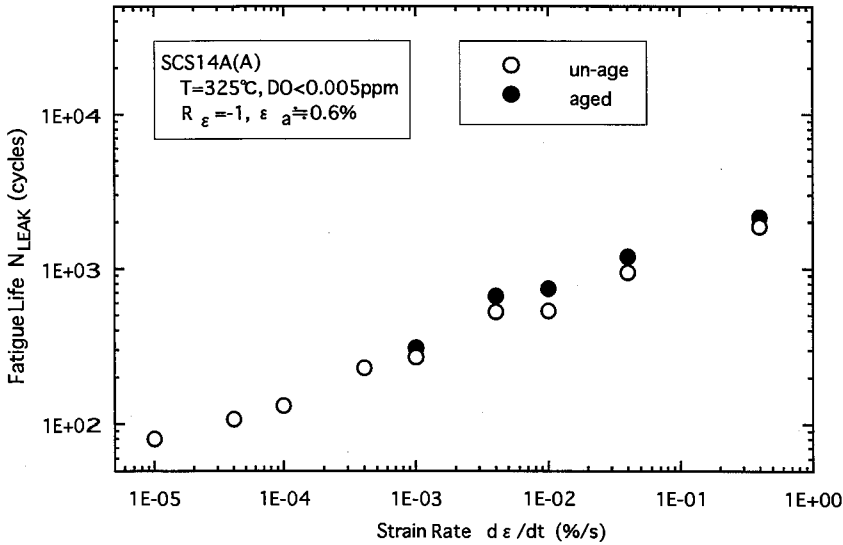


Fig.11 Effect of thermal aging on strain rate dependency of SCS14A

(6) Comparison between three heats

The SN curves of three heats of SUS316 are shown in Fig.12. SUS316(A) was solution heat treated pipe, SUS316(B) was solution heat treated forged plate and SUS316(C) was heavily sensitized pipe, as shown in Table 2. The difference of fatigue life among three heats was small in this figure and the same tendency was observed in the fatigue tests of SUS304 and SCS14A. This observation showed that the difference of products form, sensitization and ferrite content did not influence the fatigue life of stainless steels in PWR primary water.

(7) Strain rate dependency factor

Good linear relation between logarithmic strain rate and logarithmic fatigue life was observed above the threshold strain rate and this relation could be formulated[1],[4] as follows;

$$N_{LEAK} = A(d\epsilon/dt)^P \quad (1)$$

where N_{LEAK} was fatigue life, $d\epsilon/dt$ was strain rate in rising phase, P and A was constant. "P" was called as strain rate dependency factor and the substantial strain rate effect, that is environmental effect, exists when P is large.

In this study, only temperature was the most influential factor on fatigue life except strain rate and the other factors such as dissolved oxygen, thermal aging, sensitization and difference of heats were not influential factors. Then, P were calculated by least square method for all condition and relation between P and temperature was shown in Fig.13. P value increased with an increase of temperature. P was about 0.3 above 300°C although it varied from 0.1 to 0.43.

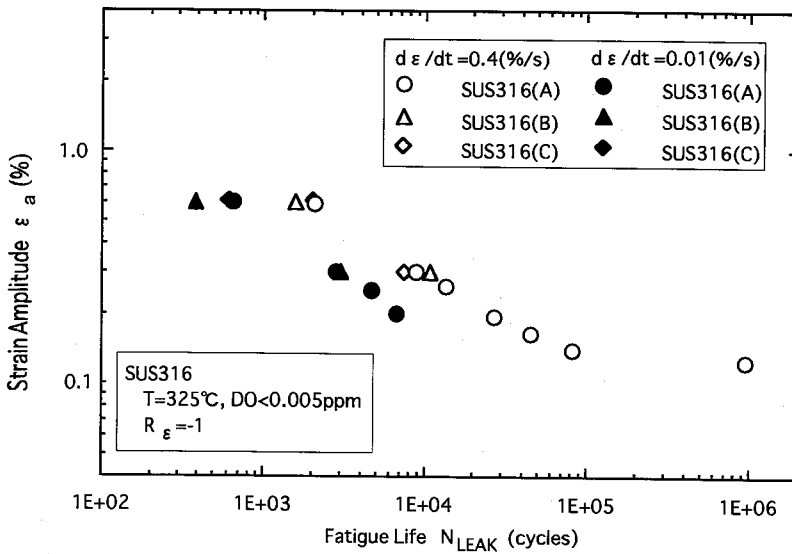


Fig.12 Comparison of fatigue life among three heats of SUS316

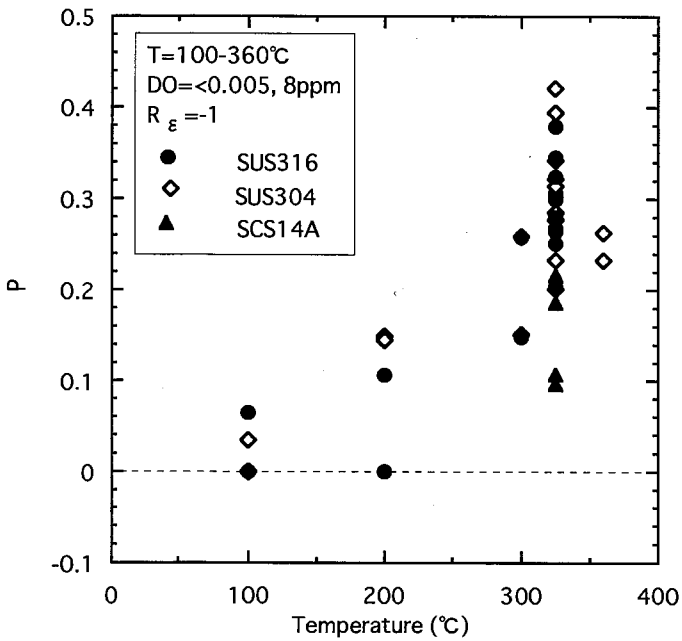


Fig.13 Relation between temperature and P value of stainless steels

4. CONCLUSION

The series of strain controlled fatigue tests on stainless steels in simulated PWR primary water were conducted to examine the effects of water environment, strain rate, temperature, dissolved oxygen, thermal aging/sensitization on fatigue life of several steels. The obtained results were as follows;

- a. The fatigue life of stainless steel in simulated PWR primary water was shorter than that in air and substantial effect of water environment was observed.
- b. The fatigue life in water decreased with a decrease of strain rate and linear relation between logarithm of strain rate and that of fatigue life was observed.
- c. The threshold strain rate were observed below which the effect of strain rate was saturated in SUS316 and SUS304.
- d. The prominent effect of test temperature was observed in water and the fatigue life decreased with an increase of test temperature.
- e. The effects of dissolved oxygen content in water and thermal aging on fatigue life were small.

5. ACKNOWLEDGMENT

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6. REFERENCES

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