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Effect of Loading Variables and Temperature on Fatigue Crack Propagation in SA508 Cl.3 Nuclear Pressure Vessel Steel

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원자로압력용기강에서 하중변수와 온도가 피로균열진전에 미치는 영향

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Abstract

The effect of loading variables and temperature on fatigue crack growth rate in SA508 Cl.3 nuclear pressure vessel steel was investigated in air environment. Crack growth rate tests on compact tension specimen of thickness 12mm were conducted by using sinusoidal waveform. The crack length was monitored by compliance method. Test conditions were at 0.1 and 0.5 of load ratio, at 1 and 10 Hz of loading frequency, and at room temperature to 400°C. At the lower temperatures, the fatigue crack propagation was not affected by the frequency and temperature, while at the higher temperatures above 120°C, fatigue crack growth rate increased with decreasing loading frequency and increasing temperature. This accelerated fatigue crack propagation was associated with the increase of oxidation rate at the ahead of crack tip. Fatigue crack growth rate increased with increasing the load ratio. The effect of load ratio was more significant at the lower temperature, while the dependence on load ratio decreased with increasing temperature. The sensitivity of load ratio to temperature can be explained by crack closure with the oxidation process.

요 약

SA508 Cl.3 원자로 압력용기강에서 하중변수와 온도가 공기 중에서 피로 균열성장률에 미치는 영향에 대하여 조사하였다. 피로 균열성장률 시험은 12.7mm 두께의 CT(compact tension) 시편을 이용하였으며, 균열길이 측정은 컴플라이언스 방법을 사용하였다. 시험은 0.1, 0.5 하중비와 1, 10Hz의 하중주파수로 상온에서 400°C까지 온도를 변화시키면서 수행하였다. 120°C 이하의 비교적 낮은 온도에서는 피로균열전파속도는 하중주파수와 온도에 영향을 받지않았지만, 120°C이상의 경우 피로 균열성장률은 온도가 높을수록, 하중주파수가 낮을수록 증가하였다. 이러한 피로균열진전속도의 빨라짐은 균열선단에서의 산화속도의 증가로 인한것으로 생각된다. 또한 하중비의 영향으로 균열닫힘과 산화의 상호작용으로 피로 균열성장률은 상온에서 두드러졌다.

1. Introduction

The nuclear pressure vessels are subjected to repeated thermal stresses during start-up and shut-down or variations in operating conditions, so that the nuclear pressure vessel steels are degraded by cyclic load and a careful study of fatigue behavior is needed [1]. On the basis of the fracture mechanics approach to the fatigue analysis, an understanding of the crack growth characteristics of the reactor pressure vessel steels is essential to manage the plant life and evaluate the period of in-service inspection under appropriate service conditions [2].

The effect of load ratio (R), loading frequency and environments on fatigue crack propagation has been examined for a number of engineering materials ; low alloy steels [3−7], austenitic stainless steels [9, 10] and Ni-based superalloys [11]. Musuva et al.[12] investigated that the loading frequency had only a little influence on crack growth rate at low R-ratio, while the crack growth rate was significantly higher than that at low frequencies at high R-ratio at a low alloy structural steel at room temperature air. Logsdon and Liaw [13] reported the effect of temperature on the fatigue crack propagation of SA508 and 533 steel of nuclear pressure vessels at the temperatures of 22°C and 288°C in air environment. It was found that temperature significantly increased the rate of fatique crack propagation. However, there are only a few limited works on the effect of the loading variables and temperature on the fatigue behavior of reactor pressure vessel steels.

The objective of this work is to examine the effect of testing variables such as R-ratio, loading frequency and temperature on fatigue crack growth rate of SA 508 Cl. 3 pressure vessel steel in air environment.

2. Experimental

ASME SA508 Cl.3 forging steel of 250mm thickness for nuclear pressure vessels was cut from a cylindrical shell manufactured by Korea Heavy Industrial and Construction Co. Ltd. The chemical compositions are given in table 1. Standard compact tension specimens of 51mm width, 12.5mm thickness, and 17.85mm notch length were employed for crack growth tests, and the orientation of crack was normal to the maximum general membrane stress (in this case, normal to the hoop direction).

Table 1. Chemical Compositions of SA508 Forging Steel.

Element	Fe	C	Mn	Mo	Ni	Cr	Si
Weight Percent	Bal.	0.18	1.48	0.54	0.91	0.21	0.03

Table 2. Arbitrary Plastic Zone Size and Yield Stress.

Temperature(°C)	RT	120	288	400
Yield stress(MPa)	454	424	407	390
r_p	1.0*	1.14	1.24	1.36

* arbitrary reference

Air environmental fatigue tests were conducted on a closed-loop servo-hydraulic testing machine (Instron model 8501). A Hewlett Packard 3852A data acquisition system was used to obtain the experimental data. For the high temperature tests, the specimens were heated in three zones controlled split furnace. The test temperatures were between room temperature (approximately 20°C) and 400°C, and the humidity of laboratory was 62%. The R-ratios are 0.1 and 0.5. A sinusoidal waveform was utilized at frequency of 1 and 10Hz. All of the specimens were precracked in accordance with ASTM E647-89 [14]. To initiate the crack at the machined notch, load range was stepped down with reducing 20% from maximum load. Crack length was monitored by the elastic compliance method. In order to calibrate crack length, traveling microscopy was used with compliance method. To measure compliance, 100 sets of simultaneous load and displacement were obtained on the rising load portion of alternate cycles. The linear least squares' line was fitted to the upper linear portion from 40% to 95% in load-displacement curve. Then the slope was averaged over 1300 cycles and then a calibration equation for the compliance vs. relative crack length was determined based on the two-dimensional elastic analysis for compact tension specimens proposed by Saxena and Hudak, Jr. [15]. From the relation between crack length and number of cycles, fatigue crack growth rates were calculated using the seven point incremental polynomial method recommended by ASTM E647. Fractured surfaces after fatigue testing were examined by Philips 515 scanning electron microscope.

3. Results

3.1. Fatigue Crack Growth Behavior

Fig. 1 shows the relation between crack length and number of elapsed cycles of the specimen tested in room temperature air. The cyclic load range (ΔP) has a significant effect on fatigue crack propagation. Relatively small variations in the cyclic load range produce large changes in the number of cycles required to grow to a certain crack length.

To investigate the temperature effect, fatigue tests were conducted at $R=0.5$ and $f=1$ Hz over the temperature range from room temperature to 400°C. Fig. 2 shows the fatigue crack growth rate is nearly the same at room temperature and 120°C. However, at the above 120°C, the fatigue crack growth rate was accelerated with increasing temperature. This result agrees well with the results that the fatigue crack growth rate of SA533 Gr. B pressure vessel steel and SA508 Cl. 2 forging steel increased with increasing test temperature ranging between room temperature and 288°C [16].

The effect of frequency on fatigue crack propagation is illustrated in fig. 3 at room temperature and in fig. 4 at 288℃, respectively. Fatigue crack growth rate at room temperature was independent of frequency within the tested ΔK range. However, at 288℃, fatigue crack growth rate increased with decreasing frequency from 10 to 1Hz. This dependence on frequency confirms that the influence of frequency on fatigue crack propagation increases at higher temperatures. The effect of frequency on fatigue crack growth rate would then be related to oxidation rate [17] such as ;

- the amount of active atoms such as oxygen available at the surface per cycle

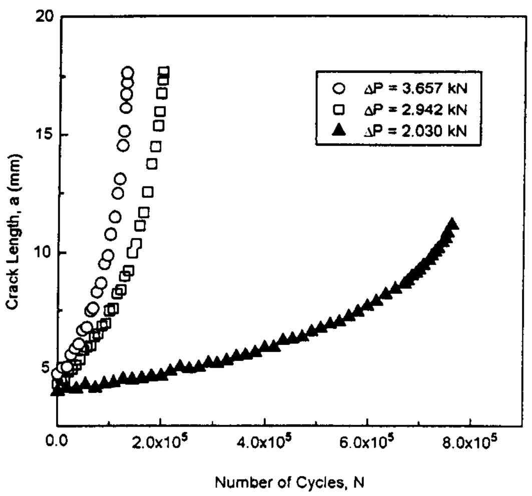

Fig. 1. Effect of Cyclic Load Range on Fatigue Crack Growth Rate of SA508 Cl.3 Pressure Vessel Steel at Room Temperature.

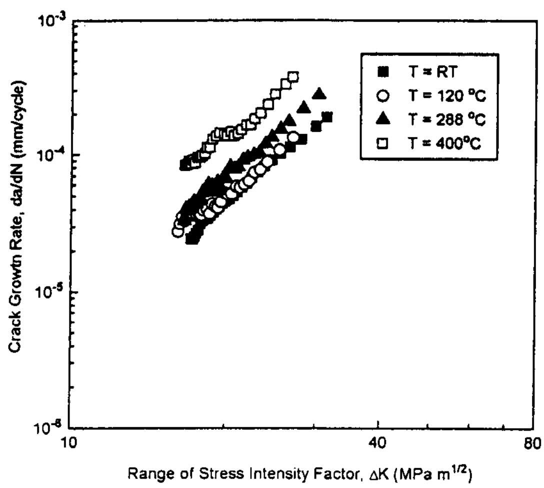

Fig. 2. The Influence of Temperature on Fatigue Crack Growth Rate at R=0.5 and f=10Hz.

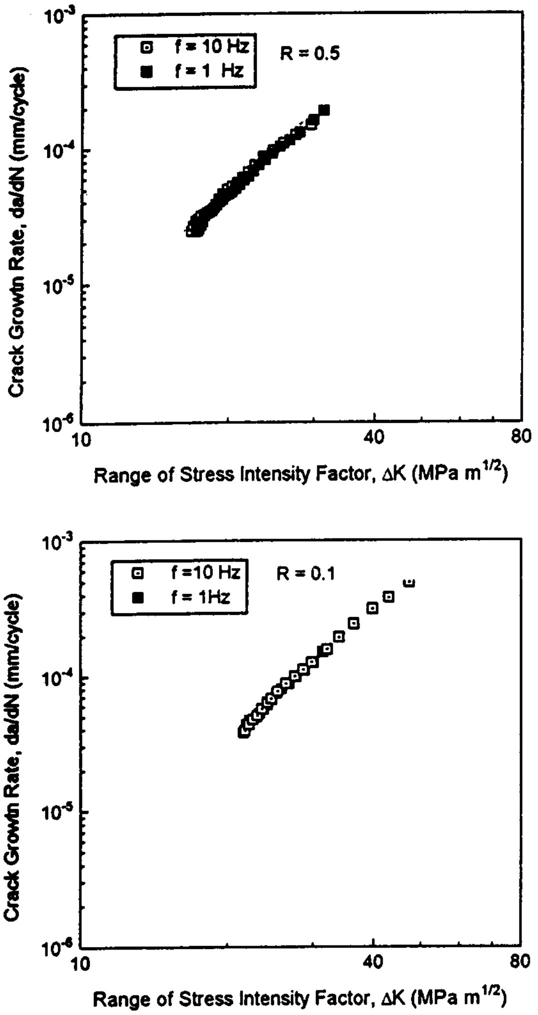

Fig. 3. The Influence of Frequency on Fatigue Crack Growth Rate at Room Temperature.

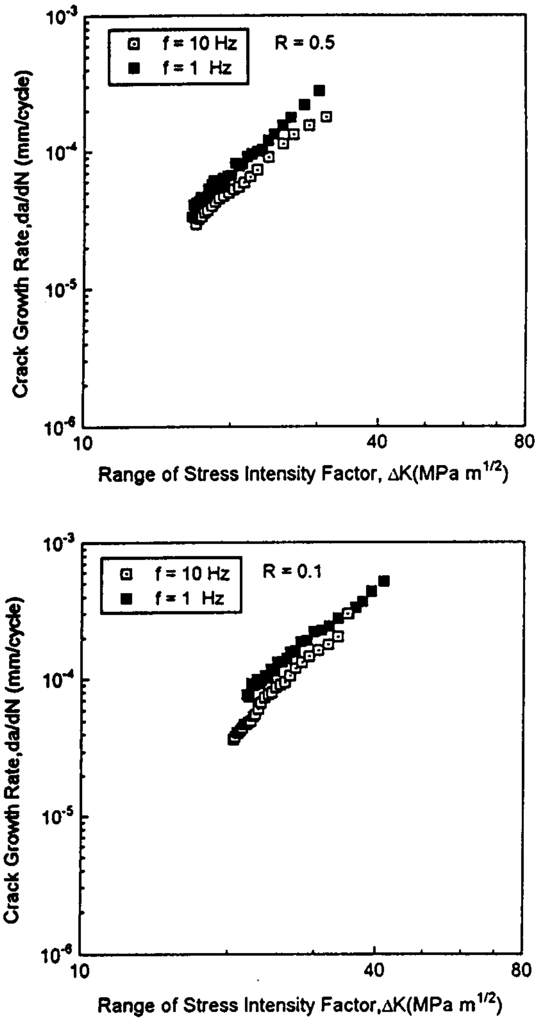

Fig. 4. The Influence of Frequency on Fatigue Crack Growth Rate at 288°C.

- the depth into the vicinity of the crack tip that the active element can be transported per cycle

This is consistent with the observation of other investigators [18, 19], in which fatigue crack propagation is related to environmental effects as well as mechanical effect.

To investigate the effect of R-ratio on the fatigue crack propagation, figs. 5 and 6 show fatigue crack propagation behaviors at room temperature and at 288°C, respectively. The R-ratio effect on the fatigue crack propagation is distinguishable at different testing conditions (frequency and temperature). The increase of R-ratio from 0.1 to 0.5 accelerated fatigue crack growth rate at room temperature. However, the effect of R-ratio on fatigue crack propagation disappeared with increasing temperature. This disappearance indicated that the R-ratio effect was related with the test temperature. Therefore, based on a reduced R-ratio effect at the higher temperature, the fatigue crack propagation is dependent on R-ratio in addition to the environmental conditions.

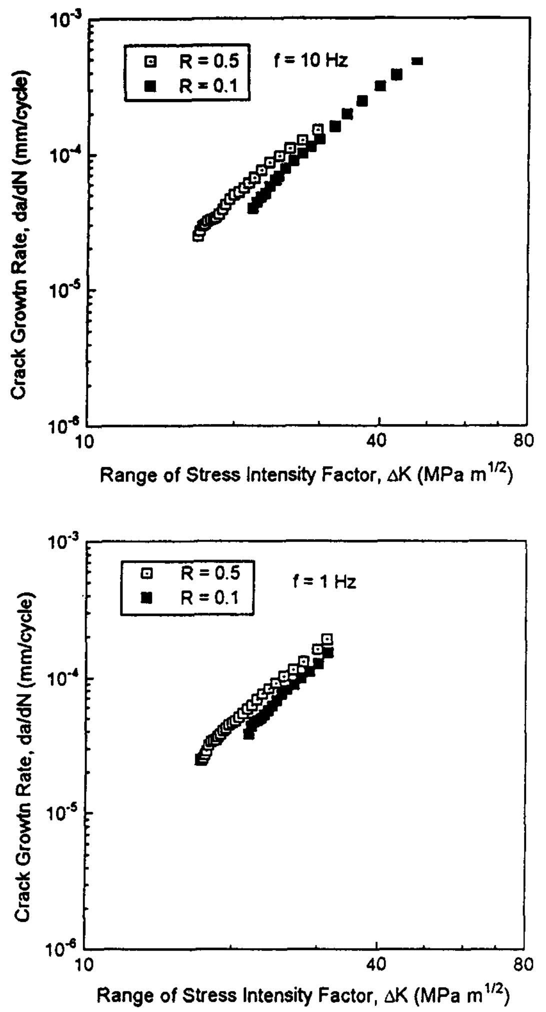

Fig. 5. The Influence of R ratio on Fatigue Crack Growth Rate at Room Temperature.

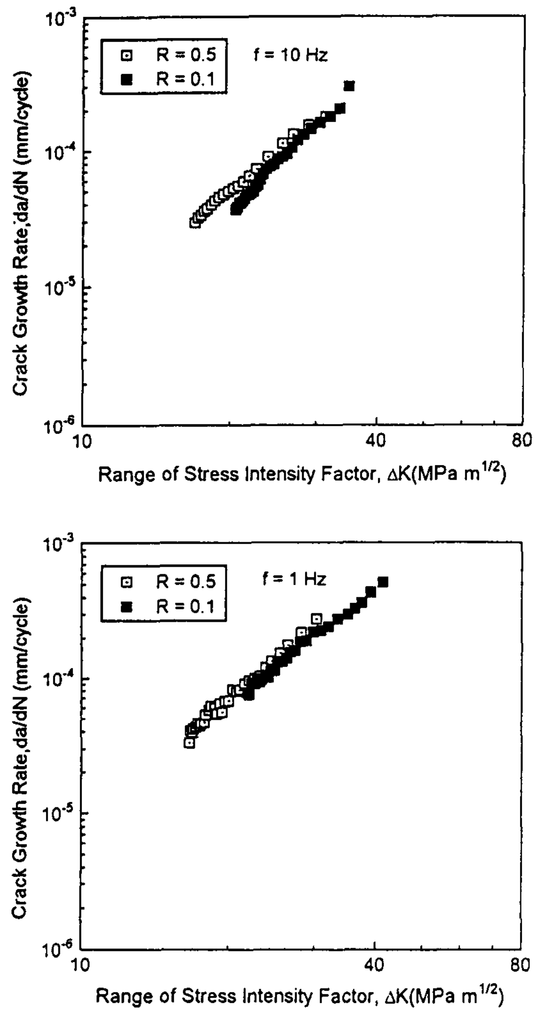

Fig. 6. The Influence of R ratio on Fatigue Crack Growth Rate at 288℃.

3.2 Comparing the Present Testing Results with ASME XI Code

Fig. 7 shows the comparison of the fatigue crack propagation properties of SA508 Cl.3 with the reference curve in ASME Boiler and Pressure Vessel Code Sec. XI Appendix A [20], which represents an upper bound for two ferritic reactor pressure vessel steels in air and at ambient temperature. At the higher ΔK range, fatigue crack growth rate is nearly the same or under the ASME code curve, while the fatigue crack propagation behavior did not satisfy the ASME code at the lower ΔK range.

3.3. Fractographic Examination

The fracture surfaces of the fatigued specimens at R=0.5 and f=1.0Hz were examined by scanning electron microscope. Fig. 8 shows the degree of oxidation and the striations on fracture surface with in-

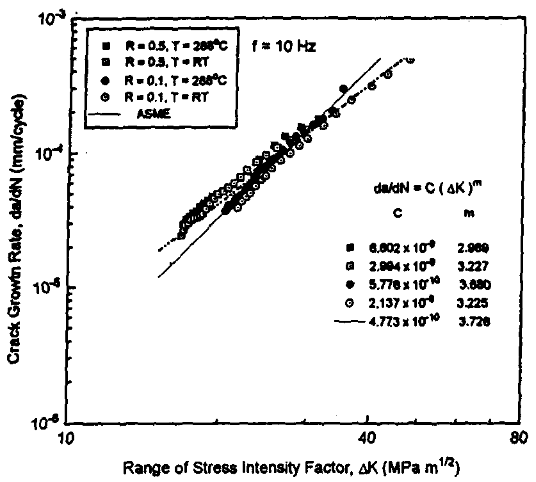

Fig. 7. Comparison the Present Data with the ASME Reference Curve.

creasing test temperature. No distinct difference was observed on fracture surface at room temperature and 120°C at which the striation widths were almost equal to 1.0μm. However, at above 120°C, the degree of oxidation and the width of striations on fracture surface increased at the higher temperature. The striation widths were approximately 3μm at 288°C and 5μm at 400°C. The degree of oxidation and striation width are in good agreement with the trend of fatigue crack propagation in fig. 2, which shows no difference at room temperature and 120°C, but faster crack propagation at 400°C than at 288°C. On the basis of the observed SEM micrographs, the fracture mode in the specimens is a ductile striated growth associated with environmental effects due to oxidation at the ahead of the crack tip.

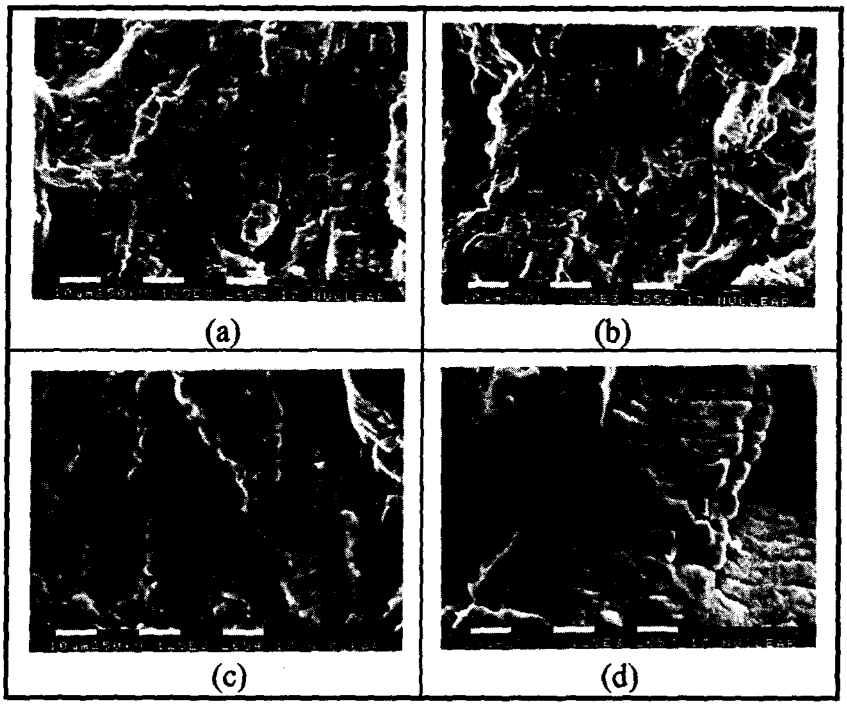

Fig. 8. Scanning Electron Micrographs for Fractured Surfaces after Fatigue Crack Propagation Test at Different Temperatures ;
(a) RT (b) 120 (c) 288 (d) 400°C

4. Discussion

In this investigation, significant effects of loading variables and temperature on fatigue crack propagation behaviors have been found in nuclear pressure vessel steel. Fatigue crack growth rate increased with increasing temperature and R-ratio, and decreasing frequency.

The influence of R-ratio on fatigue crack propagation was rather clear at room temperature. The R-ratio has been mainly treated in the threshold region (stage I), while it has been neglected in the Paris' linear region (stage Ⅱ) [21]. However, the effect of R-ratio in the present study of stage Ⅱ was clearly observed in figs. 5 and 6, so that R-ratio should be considered even in stage Ⅱ to understand the fatigue behavior of the SA508 pressure vessel steel. The sensitivity of fatigue crack propagation to R-ratio at room temperature is caused by crack closure [12], which occurs under the tensile load by plastic deformation in the wake of a propagating crack. However, the R-ratio effect on the fatigue crack propagation was different with testing conditions (frequency and temperature) as shown in figs. 5 and 6. Since fatigue crack propagation at room temperature is more sensitive than that at the 288°C, the crack closure concept alone does not explain why the R-ratio effect disappeared with increasing test temperature. It is possible that the effect of R-ratio on the fatigue crack propagation could be connected with oxidation effects. The main influence of the environment is to supply the active atoms such as oxygen to the vicinity of the crack tip and to increase the protective oxide film on the surface of the specimen. Rupture of the protective oxide film after cycling provides an active path for chemical attack. Furthermore, the cracking of the brittle oxide film, by itself, may lead to the growth of a fatigue flaw. Therefore, fatigue crack growth rate is faster as the oxidation at the ahead of crack tip increases with increasing the temperature and decreasing the loading frequency. In addition, the closure effect by R-ratio at the high temperature is compensated by the oxidation, so that the fatigue crack propagation behavior is insensitive to the R-ratio. This suggests that the dominant effect is the change in yield strength and dislocations mobility resulting from thermal activation, rather than mechanism such as oxide-induced closure or coarsening of carbide phases [22].

On the other hand, the accelerated growth rates are explained by the plastic zone size in view of fracture mechanics theory [23]. The size of localized plastic zone, r_p, at the crack tip is directly dependent on the squared ratio of the applied stress intensity to yield strength such as

$$r_p \propto \left(\frac{\Delta K}{\sigma_{YS}}\right)^2$$

where σ_{YS} is yield stress.

The fatigue crack propagation increases as the plastic zone size increases. The plasticity increases with increasing test temperature, thereby lowering the residual compression stress in plastic zone size, which may reduce crack closure effect and thus a faster crack growth rate is observed. The fact that the yield strength of SA508 Cl.3 decreases with increasing test temperature [24] indicates that the plastic zone size at the higher test temperatures is larger than that at the lower temperature; the increased crack growth rate behavior at higher temperature is in accordance with plasticity considerations. The calculated plastic zone sizes at the arbitrary reference and yield stresses are listed in table 2. The variation of plastic zone size is in good agreement with the trend of crack propagation at fig. 2. Brothers and Yukawa [25] have also found that the variations of yield strength of Cr-Mo-V and Ni-Cr-Mo-V steel significantly affect the fatigue crack propagation under identical test conditions. Their results consistently showed that the crack growth rate decreased as the yield strength increased. Assuming that the toughness of a given material decreases with increasing yield strength, these data indicate that the fatigue crack propagation at a given ΔK level decreases as the plastic zone size decreases.

Therefore, the accelerated fatigue crack propagation at the high temperature is believed to be caused by the increase of oxidation rate and plasticity by reduction of yield strength.

5. Conclusions

The fatigue crack propagation behavior of ASME SA508 Cl.3 for a nuclear pressure vessel in the range of temperature from room temperature to 400°C has been studied in order to clarify the effect of loading variables and oxidation. The results obtained are as follows.

(1) At the lower temperatures, the fatigue crack propagation was not affected by the loading frequency and temperature, while at the higher temperatures above 120°C, fatigue crack growth rate increased with decreasing loading frequency and increasing temperature. This accelerated fatigue crack propagation is due to the increased oxidation rate at the ahead of crack tip.

(2) Fatigue crack growth rate increased with increasing the R-ratio. It is more significant at the lower temperatures. The effect of load ratio can be explained by crack closure with accompanied oxidation process.

References

1. W.H. Bamford and D.P. Jones, ASTM STP 738, 281(1981)
2. J.G. Bjeletch and T.M. Morton, ASTM STP 536, 439 (1973)
3. R.D. Achilles and J.H. Bulloch, Int. J. Press. Ves. & Piping, 30, 375 (1987)
4. J.H. Bulloch, Int. J. Press. Ves. & Piping, 49, 139 (1992)
5. Kumar, Int. J. Press. Ves. & Piping, 42, 303 (1990)
6. S. Turner and J.H. Bulloch. Int. J. Press. Ves. & Piping, 31, 141 (1988)
7. R.D. Achilles and J.H. Bulloch, Int. J. Press. Ves. & Piping, 35, 363 (1988)
8. P. Shahinian, H. H. Smith and H. E Watson, ASTM 520, 387 (1973)
9. J. H. Bulloch, Int. J. Press. Ves. & Piping, 33, 27 (1988)
10. J. Bressers and M. Steen, Int. J. Press. Ves. & Piping, 47, 217 (1991)
11. W.G. Clark, Jr. and H.E. Trout, Jr., Eng. Fract. Mech, 2, 107 (1970)
12. J.K. Musuva and J.C. Radon, Fatigue Engng. Mater. and Struct., 1, 457 (1979)
13. W.A. Logsdon and P.K. Liaw, Eng. Fract. Mech., 22, 509 (1985)
14. ASTM E647 (1989)
15. A. Saxena and S.J. Hudak, Jr., Int. J. of Fracture, 14, 453 (1978)
16. P.C Paris, R.J. Bucci, E.T. Wessel, W.G. Clark, and T.R. Mager, ASTM STP 513, 141 (1972)
17. H. Sehitoglu and W. Sun, J. of Engineering Materials and Technology, 113, 31 (1991)
18. J. Llorca, Fatigue Fract. Eng. Mater. Struct., 15, 655 (1992)
19. R.C. McClung, Fatigue Fract. Eng. Mater. Struct., 14, 455 (1991)
20. ASME Boiler and Pressure Vessel Code, Sec. XI App. A, American Society of Mechanical Engineers, New York (1989)
21. D. Taylor, Fatigue thresholds, Butterworth (1989)
22. A. Puskar and L. Varkoly, Fatigue Fract. Engng Mater. Struct. 9, 143 (1986)
23. G.R. Irwin, Pro. 7th. Sagamore Ordance Mater. Res. Conf. (1960)
24. Soon-Pil Choi and Jun-Hwa Hong, KAERI, "Test and Evaluation of Mechanical Characteristics in Reactor Core Shell" (1988. 4)
25. A.J. Brothers and S. Yukawa, J. Bas. Eng. ASME Paper No. 66-Met-2 (1966)