LOW CYCLE FATIGUE CRACK PROPAGATION BEHAVIOR OF 1.5Cr-0.7Mo STEEL AT HIGH TEMPERATURE

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ABSTRACT

Low cycle fatigue tests were carried at high temperature on a 1.5Cr-0.7Mo steel in order to asses the remaining life of components used in aged power plants. The fatigue J-integral range, ΔJ_f, and creep J-integral range, ΔJ_c, were obtained from the results of the tests to characterize the crack propagation rates for fatigue and creep. The fatigue life at high temperature was also evaluated by use of J-integral calculated from a three dimensional finite element analysis. The results obtained from the present study are summarized as follows: (1) the characteristics of low cycle fatigue crack propagation are determined by ΔJ_f for the PP(tensile plasticity-compressive plasticity deformation) and PC(tensile plasticity-compressive creep deformation) stress waveform type and by ΔJ_c for the CP(tensile creep-compressive plasticity deformation) stress waveform type. (2) the predicted fatigue life obtained from the finite element analysis and the actual fatigue life are close, within a factor of 2.

KEYWORDS

Low cycle fatigue, crack propagation rate, fatigue J-integral range, creep J-integral range, finite element analysis, fatigue life.

INTRODUCTION

The power plants utilize high temperature and high pressure for good thermal efficiency and thus the components of a power plant such as turbine rotor, turbine casing, turbine casing bolt, steam pipe, and etc. may undergo low cycle fatigue at high temperature. Therefore it is important to estimate quantitatively the propagation behaviors of the microcracks initiated from natural or artificial defects. Ohtani et. al.(1986, 1987) reported that the characteristics of low cycle fatigue crack propagation at high temperature can be classified into two categories: the cycle-dependent fatigue causing transgranular fatigue fracture and the time-dependent fatigue causing intergranular creep fracture. Crack propagation rates are determined by the fatigue J-integral range and creep J-integral range, respectively. In this study, characteristics of low cycle fatigue at high temperature for the material of turbine casing bolts used in power plants, are examined. By using ΔJ_f and ΔJ_c, the relationships between crack propagation rates for fatigue and creep are studied. Finally, the fatigue life is estimated by using the J-integral obtained from finite element analysis.

EXPERIMENTAL PROCEDURE

The specimens were machined from 1.5Cr-0.7Mo steel which is widely used in thermal power plant turbines and they are of a hollow cylindrical type. A hole of 0.6 mm diameter was machined at the center of the gage length and the inner and outer surfaces were well polished to minimize the influence of surface roughness. An electro-servo dynamic fatigue testing machine was used. Crack opening displacements were measured at the center of a crack in the specimen's horizontal part using a 10 mm contact extensometer. The temperature was obtained using the thermocouple which was spot-welded on the center of specimen. Crack lengths were measured using a travelling microscope with 60 magnifications. The low cycle fatigue tests at high temperature were performed under the load-controlled conditions. Crack propagation measurements were made at 300, 425, and 550℃. The applied stress was chosen as a 45~75% of yield stress with a stress ratio of R=-1. Stress waveforms of the PP type with no hold time and of the CP and PC type with hold time were used. The loading time applied were: 1 second in tension, 1 second in compression, with a hold time of 300 seconds were used. Table 1 shows the experimental conditions of the low cycle fatigue tests at high temperature.

FINITE ELEMENT ANALYSIS

The finite element model used for calculating J-integral is an 1/4 of the hollow cylindrical specimen. Three dimensional 20 node hexahedral parametric elements were employed. The total number of elements were 510~610 and the total number of nodes were 3120~3180. The quarter point singular elements are used to model the strain singularity at the crack tip. A crack length, applied stress and temperature were chosen as parameters. The analysis was performed by varying crack length, i. e., a=2, 4, 6, 8, 10 mm, and by using the experimental temperature, i. e., T=300, 425, 550℃. The J-integral values for three different paths around the crack tip were calculated.

J-integral, ΔJ_f, as shown in Fig. 4. Accordingly the crack propagation of PC stress waveform type has the characteristics of cycle-dependent fatigue, and the crack propagation rate can be obtained as

$$d(2a)/dN = 5.65 \times 10^{-4}\ \Delta J_f^{1.56} \tag{5}$$

From Eqns. (2), (4) and (5) the low cycle fatigue test results can be summarized into a single crack propagation law:

$$d(2a)/dN = C_i(\Delta J_i)^{m_i} \tag{6}$$

where the index i corresponds to f for cycle-dependent fatigue, and c for time-dependent fatigue, respectively, and C_i and m_i are material constants. Note that the above relationship is independent of temperature or stress.

From the finite element analysis, it appears that the plastic zone size increases with increasing temperature. The increase in the plastic zone size results in an increasing crack propagation rate. Therefore, the crack propagation rate increases with increasing temperature. The result of J-integral value obtained from finite element calculations is shown in Fig. 5. The solid line in the figure represents experimental results which are obtained from the crack propagation law equation (Eqn.(2)). From the comparison between experimental data and finite element results for the crack propagation rate versus J-integral range, it is shown that the analytical and experimental results are fairly close to each other. The predicted life obtained by the finite element analysis and the actual life from experimental data are compared for the PP stress waveform type in Fig. 6 indicating a range within a factor of 2. Thus, it may be possible to estimate the fatigue crack propagation rate at high temperature by the calculation of J-integral from finite element analysis, so that this results can be used for the quantitative life assessment of components in power plants.

CONCLUSION

The results from the tests and finite element analysis are summarized as follows;

(1) The characteristics of low cycle fatigue at high temperature are determined by the fatigue J-integral range, ΔJ_f and the creep J-integral range, ΔJ_c, that are cycle-dependent and time-dependent, respectively. The crack propagation law is given as $d(2a)/dN = C_i(\Delta J_i)^{m_i}$

(2) The characteristics of low cycle fatigue crack propagation at high temperature are determined by ΔJ_f for the PP and PC stress waveform type and by ΔJ_c for the CP stress waveform type, respectively.

(3) The crack propagation law of low cycle fatigue at high temperature can be obtained by J-integral calculated using the finite element method and, therefore, it can be used to examine crack propagation behavior.

(4) The fatigue life at high temperature was evaluated using the results of the

RESULTS

The characteristics of low cycle fatigue crack propagation are classified into two categories: cycle-dependent fatigue and time-dependent fatigue that is the crack propagation rates, $d(2a)/dN$, are determined by fatigue J-integral range, ΔJ_f, and creep J-integral range, ΔJ_c. The crack propagation rate for the PP stress waveform type with no hold time is expressed in terms of fatigue J-integral range. But the crack propagation rate for the CP and PC stress waveform type is expressed by both ΔJ_c and ΔJ_f to include the creep effect because it is affected by creep due to hold time at the maximum or minimum stresses. The ΔJ_f is obtained from the hystersis loop between load and crack opening displacement, which is given as

$$\Delta J_f = \Delta K^2 / E + S_p / (Bb) \tag{1}$$

where S_p is the plastic deformation area of hysteresis loop as shown in Fig. 1, B is the specimen thickness, and b is the ligament length. ΔK is the range of stress intensity factor. The ΔJ_f means the sum of elastic deformation energy and plastic deformation energy dissipated per unit increment in the cracked area accompanied by crack extension. The experimental results obtained from the PP stress waveform type are shown in Fig. 2. Where the following rate equation is valid:

$$d(2a)/dN = 7.20 \times 10^{-4}\ \Delta J_f^{0.94} \tag{2}$$

with $2a$ as the total crack length including the hole diameter. This is the cycle-dependent fatigue.

For the CP stress waveform type ΔJ_c is expressed as

$$\Delta J_c = S_c / (2Bb) \tag{3}$$

where S_C is the creep deformation area of the hysteresis loop as shown in Fig. 1. The ΔJ_c is the plastic deformation energy dissipated per unit increment in the cracked area accompanied by crack extension. For the CP stress waveform type with hold time at the maximum stress, the crack propagation rate is not related linearly with ΔJ_f when it is expressed in terms of ΔJ_f and ΔJ_c, but it is related linearly with ΔJ_c in a log-log scale, as shown in Fig. 3. Thus the crack propagation for the CP stress waveform type is characterized as time-dependent fatigue and $d(2a)/dN$ is given in terms of the creep J-integral, ΔJ_c, as:

$$d(2a)/dN = 1.46 \times 10^{-2}\ \Delta J_c^{1.63} \tag{4}$$

For the PC stress waveform type with hold time at the minimum stress, the crack propagation rate is not related linearly with ΔJ_c when it is expressed in terms of ΔJ_f and ΔJ_c. However it is related linearly with the fatigue

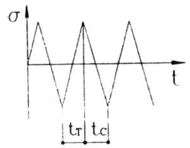
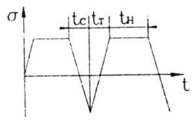
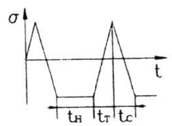
finite element analysis. It appears that the predicted life and the actual life are within a factor of 2.

REFERENCES

Ohtani, R. and T. Kitamura (1986). Crack propagation under creep-fatigue interaction condition, Trans. Japan Soc. Mech. Eng. Ser. A, Vol. 52, No. 480, 1816-1823.

Ohtani, R., T. Kitamura and N. Tada (1987). High-temperature fatigue crack propagation under cyclic temperature, Trans. Japan Soc. Mech. Eng. Ser. A, Vol. 53, No. 490, 1030-1036.

Table 1 Test conditions for low cycle fatigue.

No	Specimen No.	Symbol	Temp. (℃)	Max. stress (MPa)	Stress ratio	Stress waveform	Loading time (sec)		
							t_T	t_H	t_C
1	PP350	○	300	359.9	-1		1	-	1
2	PP355	⊙		395.9					
3	PP450	-○-	425	338.1					
4	PP455	⊕		371.9					
5	PP545	ϕ	550	267.7					
6	PP550	●		297.4					
7	CP370	⚒	300	503.9			1	300	1
8	CP375	*		539.9					
9	CP470	+	425	473.3					
10	CP550	☆	550	297.4					
11	CP555	★		327.1					
12	CP560	✡		356.9					
13	PC375	-●-	300	539.9			1	300	1
14	PC470	⌀	425	473.3					
15	PC475	●		507.1					
16	PC560	✹	550	356.9					

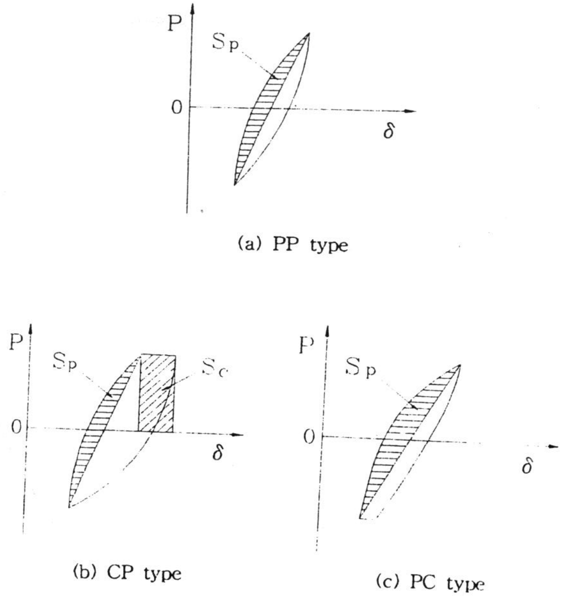


Fig. 1 Schematic hysteresis loops of load and crack opening displacement.

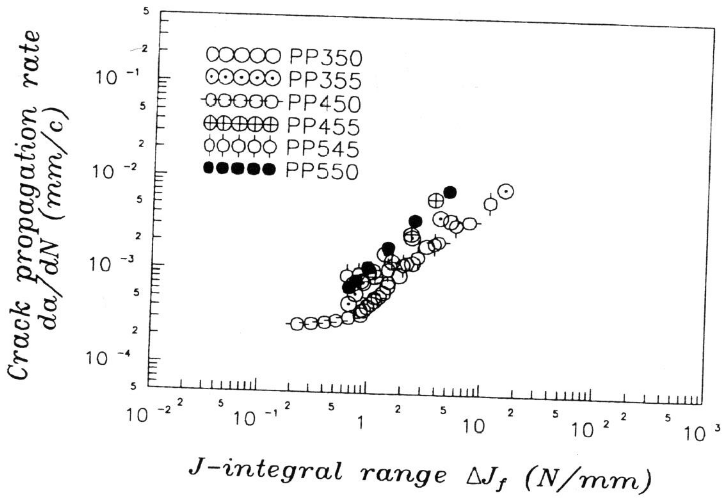


Fig. 2 Relation between crack propagation rate and fatigue J-integral range (PP type).

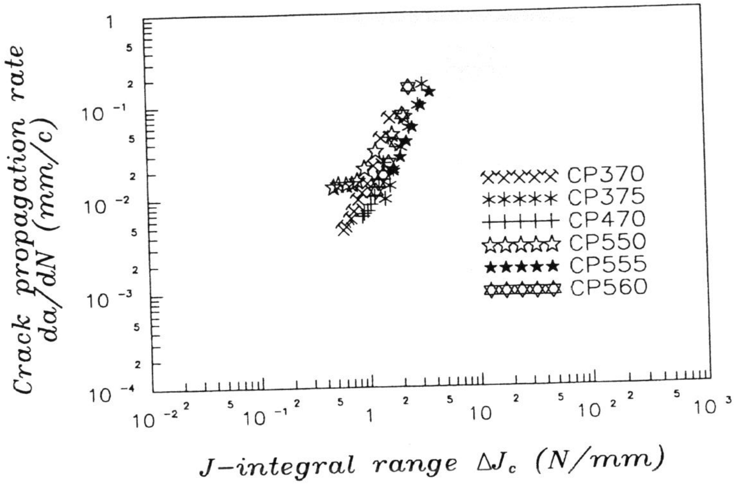


Fig. 3 Relation between crack propagation rate and creep J-integral range (CP type).

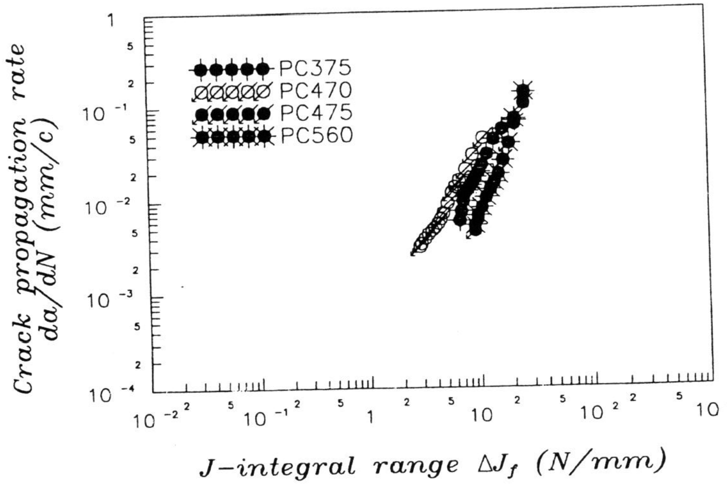


Fig. 4 Relation between crack propagation rate and fatigue J-integral range (PC type).

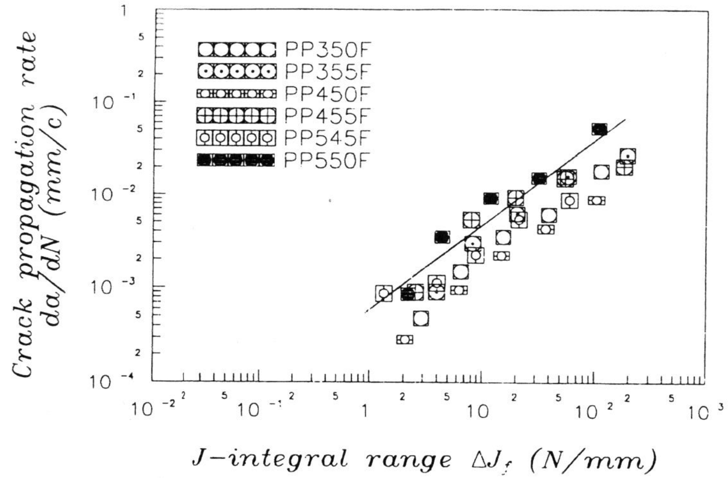


Fig. 5 Comparison between calculated results by FEM and experimental data for crack propagation rate vs J-integral range.

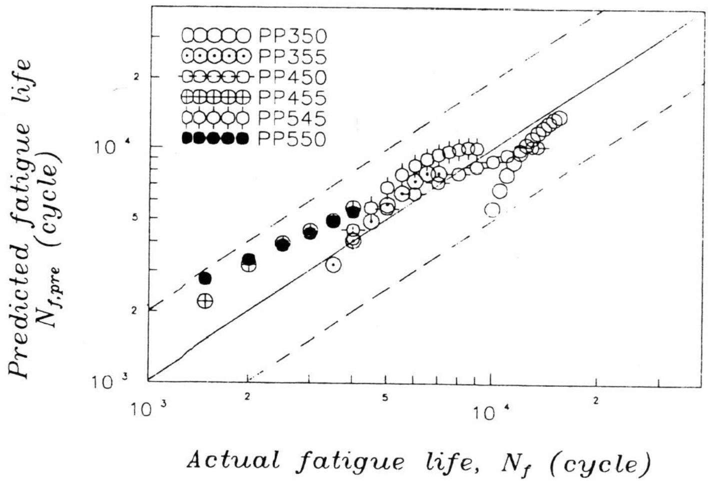


Fig. 6 Comparison between predicted and actual fatigue life.