Fatigue Crack Growth Behavior Under Cyclic Transient Thermal Stress*

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Thermal fatigue tests were performed using straight pipe specimens subjected to cyclic thermal shocks of liquid sodium, and crack growth behaviors were estimated using striation patterns observed clearly on any crack surface. Crack growth rate under cyclic thermal strain reaches the maximum at one depth, and after that it decreases gradually with crack depth. The peak location of crack growth rate becomes deeper by superposition of constant primary stress. Parallel cracks co-existing in the neighborhood move the peak to shallower location and decrease the maximum crack growth rate. The equivalent stress intensity factor range calculated by Walker's formula is successfully applied to the case of negative stress ratio. Fatigue crack growth rate under cyclic thermal strain agreed well with that under the constant temperature equal to the maximum value in the thermal cycle. Simplified methods for calculating the stress intensity factor and the crack interference factor have been developed. Crack growth behavior under thermal fatigue could be well predicted using numerical analysis results.

Key Words: Thermal Fatigue, Crack Growth Rate, Stress Intensity Factor, Crack Interaction, Simplified Formula.

1. Introduction

It is well known that fairly large thermal stress may be generated in the vessels and pipings of some chemical plants and power generation plants operated at elevated temperatures, in the cases of start-up, shut-down and load fluctuation. Therefore, crack initiation and growth under cyclic thermal stress should be investigated. In a liquid metal fast breeder reactor (LMFBR), liquid sodium, having good thermal conductivity, is used as a coolant. Thermal transient stress may occur cyclically in the coolant piping systems and equipment because of sodium temperature variation due to power fluctuation, reactor scram, or the mixing of cold with hot sodium at nozzles and tee-sections.

Though some studies^{(1)~(4)} have already been reported concerning the initiation and growth of cracks generated by thermal fatigue or thermal shock, few experiments have been reported where test pieces had been subjected to cyclic thermal transient stress, and crack growth behavior had been observed microscopically and quantitatively. And therefore, a method for predicting the thermal fatigue crack growth behavior has not been established yet.

In this study, thermal fatigue tests are carried out using straight pipes composed of SUS 304 steel and 2(1/4)Cr-1Mo steel. A straight pipe is subjected to severe cyclic thermal transient stress by alternating flow of hot and cold sodium inside the pipe.

After the test, crack surfaces are observed by a scanning electron microscope (SEM), and striation spacings on the fractured surface are measured. Furthermore, stress intensity factors under thermal transient conditions are calculated using the finite element method (FEM) to investigate the relationship between crack growth behavior and the stress intensity factor, including the effect of the crack interaction. Based on the test results and analyses, a simplified method is proposed to estimate fatigue crack growth

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under cyclic thermal transient stress.

2. Experimental Method

Test pieces used for the experiment were straight pipes composed of SUS 304 steel and 2(1/4)Cr-1 Mo steel. The outer and inner surfaces were machined to the dimensions shown in Fig. 1. Two or three circumferential notches were cut on the inner surface.

The chemical composition and the mechanical properties of the materials investigated are listed in Tables 1 and 2, respectively. The equipment used in the experiment was the "Piping Structure Thermal Transient Test Loop" of the Oarai Engineering Center, Power Reactor and Nuclear Fuel Development Corp. As shown in Fig. 2, a test piece was welded to the sodium piping of the test section; then hot and cold sodium was flowed alternately inside the pipe by opening and closing valves installed upstream and downstream of the test section.

On the other hand, constant axial load was added to the test piece by a dead weight loader. After the prescribed cycles of transient thermal stress, the test piece was cut out of the test section, and then submerged in alcohol to wash out the sodium.

The crack patterns and their density, location, depth and direction, were observed both macros-

copically and microscopically. Striation spacings on the fractured surface were measured by SEM, at 0.5 mm depth-wise pitches from the inside surface to the crack tip.

3. Loading Condition

The rate of temperature change of sodium flow exceeded 100°C/sec just after the beginning of thermal transient. It resulted in a large temperature difference in the wall thickness of the test piece as illustrated in Fig. 3. The temperature difference between the outer and inner surfaces of the pipe reached a maximum within 5-7 seconds after the beginning of thermal transient. The temperature distribution were approximated by a parabolic or biquadratic curve with the apex on the outer surface.

Thermal analysis is applied to the straight pipe model in which the inner surface was assumed to be the heat transfer boundary and the outer surface to be thermally insulated. Temperatures measured at the (TC) locations indicated in Fig. 1 were adopted as the temperature of the sodium. The heat transfer coefficient between the pipe surface and the sodium flow is calculated by the following equation⁽⁵⁾:

$$Nu = 5.0 + 0.025Pe^{0.8} \quad (1)$$

where Nu is the Nusselt number, and Pe is the

Table 1 Chemical compositions

Material	C	Si	Mn	P	S	Ni	Cr	Mo
SUS 304	0.04	0.51	1.65	0.025	0.001	9.50	18.55	—
2 1/4Cr-1Mo	0.10	0.39	0.45	0.025	0.008	—	2.20	0.95

(a) DW-series specimen

(b) TF-series specimen (SUS 304)

Fig. 1 Geometry of test specimen

Table 2 Mechanical properties

Material	Temp. °C	$\sigma_{0.2}$ MPa	σ_u MPa	Elongation %	Reduction of Area %
SUS 304	RT	257	628	60.2	85.3
	550	146	388	37.2	79.2
2 1/4Cr-1Mo	RT	358	504	27.0	78.0
	550	227	375	25.6	83.8

Fig. 2 Test section

Péclet number. Figure 4 shows that the calculated temperature change on the outer surface corresponded well with the measured results obtained by a chromel- almel thermocouple.

Table 3 lists the absolute value of the range of the temperature difference between the temperature of the outside surface and the temperature of the inside surface assuming moment generating equivalent linear temperature distribution (ΔT_1) and the absolute value of the range for that portion of the nonlinear thermal gradient through the wall thickness not included in ΔT_1 (ΔT_2).

Such a large temperature difference forces the inner surface of a test piece to be in a condition of plastic cycling. The axial stresses of the TF-specimens under a constant dead load were 58, 29 and 0 Mpa at the portion where the wall thickness was 7

mm.

The stress intensity factors of the circumferential and axial cracks on the inner surface were calculated by FEM under the uniform tension (internal pressure) and parabolic or biquadratic temperature distribution.

Transient thermal load causes strain-controlled type stress, and strain concentration near a crack tip is predicted well by an elastic analysis. Therefore, the stress intensity factor based on the linear fracture mechanics was applied to the estimation of crack growth in spite of the plastic cycling conditions of the inner surfaces of test specimens. Figure 5 shows the relationship between the stress intensity factor and crack depth under uniform tension (98 MPa) and parabolic temperature distribution (the temperature difference was 100°C).

The stress intensity factor becomes larger with crack depth, and is unlimited under uniform tension and internal pressure. While under the thermal transient, the stress intensity factor reaches its maximum

Table 3 Typical values of ΔT_1 and ΔT_2

ΔT (Sodium) °C	Wall Thickness mm	ΔT_1 °C	ΔT_2 °C
300	13	427	87
	10	377	72
	7	302	56
200	13	293	60
	10	261	51
	7	211	40

(a) Cold shock

(b) Hot shock

Fig. 3 Examples of temperature distribution in the wall thickness (250°C $\rightleftharpoons$ 550°C thickness 13 mm)

Fig. 4 Examples of transient temperature change (550°C $\rightarrow$ 250°C, outer surface of the inlet of test specimen)

at a crack depth of 2–5 mm, and after that depth it gradually decreases with crack depth. The stress intensity factor of the axial crack reaches the maximum at a deeper location than that of the circumferential crack. The reason may be attributed to the deformation indicated in Fig. 6 as the crack grows deeper.

4. Test Results

After thermal transient tests, the fracture surfaces of cracks initiated at geometrical discontinuities, for example, circumferential notches, were observed by an electron microscope, and clear striation patterns could be seen on them, except for the sub-surface near the inner surface of the specimen.

Transgranular cracks proceeded directly from the inner surface through the wall, and at a depth exceeding the half-thickness, they gradually turned to

Fig. 5 Relation between stress intensity factor and crack depth (thickness: 13 mm)

Fig. 6 Deformation of cylinder with longitudinal crack on the inner surface

grow along the grain boundaries. This tendency may be related to the variation in the stress intensity factor through the wall obtained by calculation. Figure 7 shows the typical relationship between the striation spacings and the crack depth in pipes of SUS 304. While striation spacings are rather scattered, their average variation through the wall thickness shows the same pattern as that of the stress intensity factor under parabolic temperature distribution, shown in Fig. 5. Figure 8 shows a comparison of the variations in the average striation spacings of the following three typical cases:

- ① Cyclic thermal load only;
- ② Cyclic thermal load plus constant axial load;
- ③ Cyclic thermal load only with interacting parallel cracks

Fig. 7 An example of the relation between striation spacings and crack depth (SUS 304)

Experiment	Prediction	Remarks
—△—	△	Cyclic thermal load only
—●—	●	Cyclic thermal load plus constant axial load
—○—	○	Cyclic thermal load only with interacting parallel cracks

Fig. 8 Variation in crack growth rate with depth (comparison of the prediction with the experiment, SUS 304, 250°C ⇌ 550°C, thickness = 13 mm)

Superposition of the constant axial load on the transient thermal load makes the location deeper where the striation spacing is widest, the variation curve of striation spacing broader, and the decreasing rate of striation spacing after the peak smaller.

When another crack exists near one crack, striation spacing reaches a smaller peak value at a shallower location than in case of an isolated crack.

5. Consideration

5.1 The relationship between stress intensity factor and crack growth rate

As mentioned in paragraph 4, striations could be observed all over the crack surface. The relationship between the crack growth rate and the stress intensity factor was estimated on the assumption that an average striation spacing at a given depth was equivalent to the crack growth per 1 cycle of the thermal load. The calculated stress intensity factor shown in Fig. 5 was used to estimate the stress intensity factor range during thermal loading. The stress intensity factor reaches the extremes, $K_{\max}$ and $K_{\min}$, during hot and cold shock, respectively, when the temperature difference between the outer and the inner surface reaches maximum. $K_{\min}$ is usually negative. Where stress ratio $R(=K_{\min}/K_{\max})$ is not zero, an equivalent

stress intensity factor range (ΔKe) was calculated by using Walker's equation⁽⁶⁾

$$\Delta Ke = K_{\max}(1-R)^n \quad (2)$$

where n is the material constant, often taken to be 0.5 for SUS304 steel and 2(1/4)Cr-1Mo steel⁽⁷⁾. Walker's equation⁽²⁾, which is certified to be valid⁽⁸⁾ for the prediction of the fatigue crack growth behavior at high temperature for $R > 0$, is herein applied for $R < 0$.

Figure 9 shows the relationship between the equivalent stress intensity factor range derived from Eq. (2), and the crack growth rate compared with the best fit curve of published crack growth data⁽⁷⁾ (the solid line in the figure). This figure reveals that fatigue crack growth rate under cyclic transient thermal stress corresponds to isothermal fatigue crack growth rate at the maximum temperature during thermal cycle.

Figure 8 compares observed crack growth behavior with estimated behaviour using the crack growth rate equation of SUS 304 at 538°C in Fig. 9. For the estimation, the biquadratic temperature distribution was assumed in the wall thickness direction, and the effect of constant axial stress was taken into consideration by using Eq. (2).

The estimation agrees well with the observation.

5.2 A simplified method for calculating the stress intensity factor

According to Stallybrass⁽⁹⁾, the stress intensity factor of an infinitely long surface-crack of depth ' a '

(a) SUS 304

(b) 2(1/4)Cr-1 Mo steel

Fig. 9 Relation between crack growth rate and equivalent stress intensity factor range

on a semi-infinite plate can be obtained by the following equation:

$$K_I = \sqrt{2\pi a} (0.7930 C_0 + 0.4829 C_1 + 0.3716 C_2 + 0.3118 C_3 + 0.2735 C_4) \quad (3)$$

where the distributed pressure $\sigma(x)$ expressed in terms of Eq. (4) works on the crack surfaces.

$$\sigma(x) = \sum_{n=0}^4 C_n \left(\frac{x}{a}\right)^n \quad (4)$$

Approximating the temperature distribution through the wall by a biquadratic curve with the apex on the outer surface, the thermal stress distribution as determined by the plate model can be expressed by the equation

$$\sigma(x) = \sigma_t \left[0.8 - 4\left(\frac{x}{t}\right) + 6\left(\frac{x}{t}\right)^2 - 4\left(\frac{x}{t}\right)^3 + \left(\frac{x}{t}\right)^4 \right] \quad (5)$$

where

$$\sigma_t = \frac{E\alpha}{1-\nu} (T_{\text{out}} - T_{\text{in}}) \quad (6)$$

E is the elastic modulus, α is the thermal expansion coefficient, ν is Poisson's ratio, T_{in} and T_{out} are the inner and the outer surface temperatures, respectively, t is the wall thickness, and x is the distance from the surface.

When the pressure distributed on the fractured surfaces is expressed by Eq. (5), the stress intensity factor can be calculated by the following equation derived from Eqs. (3) ~ (5):

$$K_I = \sigma_t \sqrt{2\pi a} \left[0.6344 - 1.9316 \left(\frac{a}{t}\right) + 2.2296 \left(\frac{a}{t}\right)^2 - 1.2472 \left(\frac{a}{t}\right)^3 + 0.2735 \left(\frac{a}{t}\right)^4 \right] \quad (7)$$

Figure 10 illustrates the stress intensity factor of a circumferential crack for a biquadratic temperature distribution with a temperature difference of 100°C between the outer and the inner surface. Calculated values using Eq. (7) agree well with FEM analysis values in the range where $a/t \leq 0.1$, while they are smaller than FEM values for $a/t > 0.3$ because of the effect of finite wall thickness. Referring to the calculation of Buchalet⁽¹⁰⁾, coefficients C_n ($n=0-4$) in the equation (4) were revised as follows:

$$0.7930 \longrightarrow 0.7930 \left[1 + 2\left(\frac{a}{t}\right)^2 \right]$$

$$0.4829 \longrightarrow 0.4829 \left[1 + 1.5\left(\frac{a}{t}\right)^2 \right]$$

$$0.3716 \longrightarrow 0.3716 \left[1 + 1.2\left(\frac{a}{t}\right)^2 \right]$$

$$0.3118 \longrightarrow 0.3118 \left[1 + \left(\frac{a}{t}\right)^2 \right]$$

$$0.2735 \longrightarrow 0.2735 \left[1 + \left(\frac{a}{t}\right)^2 \right]$$

Following this modification, coefficients in Eq. (7) were multiplied by a factor of e.g. $[1 + (a/t)^2]$. Figure 10 shows that the results obtained using this modified Eq. (7) agree well with FEM values.

5.3 Crack interaction

The growth rate of parallel cracks is often smaller than that of a single crack. The stress intensity factor of the main crack, where one or two neighbouring cracks exist, was calculated by FEM using crack spacing and crack depth as parameters. Figure 11 indicates how the stress intensity factor K_I of crack ① varies under the existence of crack ②. The numbers in the figures indicate the values of K_I/K_{I0} , where K_{I0} is the stress intensity factor of a single crack. For example, when the tip of crack ② is at point A in Fig. 10 (a), the stress intensity factor of crack ① is reduced to 40% of that of a single crack; therefore point A is on the line 0.4.

Figure 12 indicates the relationship between the stress intensity factor of the central crack and the crack interval L where three cracks of the same depth coexist at equal intervals. In the case of longitudinal cracks, the stress intensity factor of the crack ① longer than 5.5 mm is larger than that of a single crack, if the angle ϕ with two other cracks ② is larger than 120°.

An analysis of many cases of crack interaction gave the following results:

(1) The interaction effect between parallel cracks of the same depth is significant when the crack interval is within 4 times the crack depth.

(2) When two cracks are neighbouring closely, a shallow crack hardly affects the stress intensity factor of a deeper crack, while a deeper crack often relaxes

Fig. 10 K_I -value by the simplified calculation method (circumferential crack, Bi-quadratic temperature distribution, $T_{\text{out}} - T_{\text{in}} = 100^\circ\text{C}$, thickness 13 mm)

(3) The isometric lines of ratio K_I/K_{I0} (hereafter called the "iso- K_I -line") may be approximated by radial lines with the center at crack tip ①, where K_{I0} is the stress intensity factor of an isolated crack ①, and K_I is that when crack ② are neighbouring.

(4) The interaction effect of crack ② on crack ① was estimated in two cases, namely uniform tension and thermal transient temperature distribution. Where crack ② is deeper than crack ①, the interaction effect is larger in the former case; and where crack ① is equally deep or deeper than crack ②, the

interaction is larger in the latter case.

5.4 Simplified method of estimating crack interaction

The stress intensity factor of parallel edge cracks of depth ' a ' spaced at equal distances L in a semi-infinite plate under uniform tension can be obtained by Benthem's approximate equation⁽¹¹⁾

(a) Circumferential crack

(b) Axial crack

Fig. 11 Examples of crack interactions (parabolic temperature distribution, $T_{out} - T_{in} = 100^\circ\text{C}$)

(a) Circumferential crack

(b) Axial crack

Fig. 12 Crack interactions between two cracks with equal depth (parabolic temperature distribution $T_{out} - T_{in} = 100^\circ\text{C}$, $R_i = 33.5$ mm, thickness = 13 mm)

Fig. 13 Crack interaction diagram by the simplified method (circumferential crack, thickness = 40 mm)

Benthem's approximate equation⁽¹¹⁾

$$K_I = \sigma_\infty \sqrt{\pi a} \sqrt{\frac{1-s}{\pi s}} \quad (8)$$

where $s = a / \left(a + \frac{L}{2} \right)$, and σ_∞ is uniform tensile stress.

$K_I = 0.80 \sigma_\infty \sqrt{\pi a}$ at $L = 4a$. This result corresponds well with the conclusion derived from FEM analysis, that crack interaction is significant when $L \leq 4a$. Combining Eq. (8) with the result (3) in paragraph 5.3, the crack interaction factor $C (= K_I / K_{I0})$ was approximated by the equation

$$C = \sqrt{\frac{1-s}{\pi s}} \frac{\theta}{\pi/2} \quad (9)$$

where $s = a / \left(a + \frac{r}{2} \right)$. The definitions of r and θ are as shown in Fig. 13. When $C > 1$ in Eq. (9), C is taken as 1. When $\theta > \pi/2$, C is interpolated so that $C = 1$ at the surface. Figure 13 shows the crack interaction curve where the depth of crack ① is 5 mm. In Fig. 13, the crack interaction effect is estimated slightly conservatively compared with the results of FEM analysis in Fig. 11.

Equation (8) does not consider the effect of finite wall thickness so that it is applicable in the range of $a/t \leq 0.7$. Figure 8 also compares the observed crack growth behavior with the estimated behaviour using Eq. (9) for two parallel cracks. The crack shown as — and o in Fig. 8 is a shallower one of the two

parallel cracks. The retardation of crack growth rate due to crack interaction could be well estimated.

6. Conclusions

Thermal transient fatigue tests were performed using straight pipe test pieces of SUS 304 steel and 2(1/4)Cr-1 Mo steel subjected to cyclic thermal shocks by hot and cold sodium, and the crack growth behavior under thermal fatigue was investigated. The relationship between the crack growth rate and the stress intensity factor, and the effect of the interaction between neighbouring parallel cracks were studied. The following conclusions were drawn:

- (1) Transgranular cracks proceeded directly through the wall under thermal fatigue, and clear striation patterns could be seen on the crack surface.
- (2) Crack growth rate reaches maximum at one depth, and then becomes gradually smaller.
- (3) Superposing constant axial stress, the location of the maximum crack growth rate becomes deeper and the decreasing rate of the crack growth rate after the maximum becomes smaller. Where parallel cracks neighbour, the location of the maximum crack growth rate becomes shallower and the maximum value becomes smaller.

(4) Even if the stress ratio is negative, Walker's equation can be applied to calculate the stress intensity factor range. Crack growth rate under thermal fatigue corresponded well with isothermal fatigue crack growth rate at the maximum temperature during the thermal cycle.

(5) A simplified method to calculate the stress intensity factor under the transient thermal stress was proposed. A simplified equation to calculate the crack interaction factor was proposed, based on the numerical analysis. The crack growth behavior observed in the experiment could be well simulated using the numerically calculated stress intensity factor and the crack interaction factor.

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Appendix

Solid line in Fig. A shows temperature distribution through the wall thickness. Average temperature through the wall thickness, $\bar{T}$, can be obtained by the following equation

$$\bar{T} = \frac{1}{t} \int_{-t/2}^{t/2} T dx \quad (\text{A-1})$$

Broken line in Fig. A shows linear temperature distribution assuming equivalent moment generation. Under this temperature distribution temperature difference between the inner and the outer surface, ΔT_1 , can be calculated.

$$\Delta T_1 = \frac{12}{t^2} \int_{-t/2}^{t/2} T x dx \quad (\text{A-2})$$

Peak temperature difference, ΔT_2 , expresses the

Fig. A

maximum temperature difference between real and moment equivalent linear temperature distribution. It can be obtained by the equation

$$\Delta T_2 = \max \left[\left(|T_{in} - \bar{T}| - \frac{1}{2} |\Delta T_1| \right), 0, \right. \\ \left. \times \left(|T_{out} - \bar{T}| - \frac{1}{2} |\Delta T_1| \right) \right] \quad (\text{A-3})$$

Eventually, ΔT_1 and ΔT_2 indicated in Table 3 are calculated using the Eqs. (A-1)~(A-3) for the distribution of temperature range through the wall thickness during thermal cycle.