SMiRT-12 / K. Kussmaul (Editor)

FG16/2

EVALUATION OF SURFACE CRACK PROPAGATION AT ELEVATED TEMPERATURE

H. Takahashi, H. Yoshizawa and T. Uno

Toshiba Corporation, Kawasaki, Japan

1 INTRODUCTION

In structural integrity assessments of a fast breeder reactor (FBR) piping system, it is necessary to understand the three-dimensional surface crack propagation behavior in the creep temperature range and to establish estimation methods by the fracture mechanics approach. Though it is possible, at present, to estimate the crack propagation behavior in components according to fracture mechanics, there are few applications of the method to FBR structures in practice.

In a study carried out in the FCC II Subcommittee of the Japan Welding Engineering Society, crack propagation tests at elevated temperatures using structural models, such as pipes and plates, were carried out. A series of data on crack propagation and the aspect ratio were acquired and the applicability of the electrical potential method for predicting the surface crack configuration has been confirmed [1]. And it has also been confirmed that the J-integral can be estimated by simplified methods such as the reference stress approach [2][3].

In the present study, elevated temperature crack propagation tests were carried out using CT specimens and surface cracked plates which were the same material as the surface cracked pipes under 4-point bending [1]. The estimated J-integral by the simplified method for surface cracks were compared with experimental results obtained with CT specimens. The applicability of the evaluation method that the J-integral for a surface cracked pipe can be calculated by substituting formulas for a surface cracked plate has been experimentally discussed.

2 CRACK PROPAGATION TESTS

2.1 Surface cracked pipe test

The test material used in this study was type 304 stainless steel pipes. The chemical composition and mechanical properties are shown in Table 1 and Table 2, respectively. Table 3 shows the results of creep tests.

The test specimens for the 4-point bending test were a straight pipe, 165.2 mm in outside diameter, 11 mm in wall thickness, and 1500 mm in length, with a semi-elliptical surface notch at the center. The notch formed using an electro-discharge machining method was about 5.5 mm deep (a_0) and 22 mm wide ($2c_0$).

Fig.1 is a drawing of the experimental set-up. The end of the pipe specimen was bolted to a flange, which was pin-jointed to its supporting structure. The load point distance was 500 mm, and the support point distance was 1680 mm. Tests were carried out using a hydraulic fatigue testing machine under load-controlled conditions. The maximum nominal stress value was 13 kgf/mm^2, and the stress wave was a completely reversed triangular wave. The specimens were heated with electric heaters, installed inside the specimen. The temperature was 650℃.

Fig.2 shows the fracture surface showing the beach marks. A delay in crack propagation was observed near the surface of the test specimen. As for the crack width (c), the maximum length inside the surface was measured. Fig.3 shows the relationship between the crack length measured from the beach marks on the fracture surface and the number of cycles. The reproducibility of crack propagation was good for the two pipe specimens.

2.2 CT test

The crack propagation tests were carried out using CT specimens, which were made from a material of the same lot as the pipe specimen in order to obtain the crack propagation properties of the tested material. The specimen thickness was 8 mm. The specimens were heated with an induction coil and the temperature was 650℃. The crack length was measured by visual observation using a telescope of 20 times magnification. The load line displacement was measured by using a high temperature clip-gage of 5 mm in gage length. The load was applied under completely reversed triangular waves and trapezoidal waves with a 10 minute load holding. The fatigue J-integral range (ΔJ_f) and the creep J-integral range (ΔJ_c) were calculated using the measured relationship between the load and the load line displacement. Fig.4 (a) and (b) show the relationship between the crack propagation rate (da/dN) and the fracture mechanics parameters (ΔJ_f and ΔJ_c), respectively.

2.3 Surface cracked plate test

In the case of a simplified J-integral estimation of a surface cracked pipe, calculation had already been carried out by using formulas for a surface cracked plate in the FCC II study [3]. In order to experimentally verify the effect of the pipe curvature, a crack propagation test was carried out using a plate specimen made from the pipe specimen. Fig.5 shows the configuration of the surface cracked plate specimen. The width (2W) was 26 mm and the thickness (t) was 8 mm. A semi-elliptical surface notch formed using an electro-discharge machining method was about 1.2 mm deep (a_0) and 6 mm wide ($2c_0$). The maximum nominal stress value was 13 kgf/mm^2 and the stress wave was a completely reversed triangular wave. The specimen was heated with an induction coil and the temperature was 650℃.

Fig.6 shows a fracture surface showing beach marks. Fig.7 shows the relationship between the crack length measured from beach marks on the fracture surface and the number of cycles. Fig.8 shows the relationship between the aspect ratio (a/c) and the crack depth ratio (a/t) with the result of the surface cracked pipe tests. As for the plate specimen, the aspect ratio gradually increased up to 0.8 and then took a constant value. Concerning the pipe, the aspect ratio did not reach a constant value, because the initial crack was deep (a/t=0.5). It was considered that the aspect ratio reached up to about 0.8 similar to the plate specimen, because the bending stress components in the pipe was small compared with the axial stress components (about σ_b/σ_m = 1/14).

3 SIMPLIFIED J-INTEGRAL ESTIMATION

3.1 Estimation method

In the FCC II study [3], four kinds of simplified J-integral estimation methods were discussed. As for the elastic-plastic J-integral, the differences among the predicted values for the various method were small, so the reference stress approach was applied in this study. The J-integral was expressed by the following equation.

$$J = J_e E \varepsilon_r / \sigma_r \qquad (1)$$

where J_e is the elastic part of the J-integral determined from the stress intensity factor of the surface crack (Raju-Newman equation), σ_r is the reference stress expressed by the following equation in the case of tensile loading and ε_r is the reference strain corresponding to σ_r.

$$\sigma_r = L_r \sigma_y = \{Wt/(Wt-ac)\} \sigma_m \qquad (2)$$

where L_r is the ratio of the present load to the limit load corresponding to plastic collapse. The following cyclic stress-strain equation, based on the stable cyclic peak stress-strain relationships in the vicinity of $1/2N_f$ [4], was used.

$$\sigma = E\varepsilon \qquad (\sigma < \sigma_y) \qquad (3)$$
$$\sigma = K\varepsilon_p{}^m + \sigma_y \qquad (\sigma \geqq \sigma_y) \qquad (4)$$
$$E = 14700 \ \mathrm{kgf/mm^2}$$
$$K = 93.72 \ \mathrm{kgf/mm^2}$$
$$\sigma_y = 8.74 \ \mathrm{kgf/mm^2}$$
$$m = 0.345$$

3.2 Estimation results for the J-integral

The relationship between the crack propagation rate (da/dN, dc/dN) and the estimated J-integral range (ΔJ_f) for the surface crack is shown in Fig.9 compared with the experimental data for the CT specimen. Here, the fatigue J-integral range ΔJ_f was given by the following equation.

$$\Delta J_f = 4 \times J \qquad (5)$$

The ΔJ_f value of the surface crack calculated by the simplified method was almost located on the data band of the CT specimen, so it has been verified that the present methods give good estimates. As for the ΔJ_f for the surface direction (c-direction) of the pipe, slightly large (conservative) estimated results were obtained. To confirm whether this was the effect of curvature, it was necessary to be investigated by numerical FEM analysis. There have been very few papers on the effect of curvature on surface cracked pipes, and the following shell parameter was obtained in the case of a through-wall crack by the traditional shell theory [5].

$$\lambda = 12(1-\nu^2)c^4/(R^2t^2) \qquad (6)$$
$$f(\lambda) = 1+(\pi/64)\lambda^2 \qquad (\lambda < 1) \qquad (7)$$

where c is the half crack length, R is the radius of the pipe, and t is the wall thickness. In the case of calculating $f(\lambda)$ ($=\sigma_{shell}/\sigma_{plate}$) by treating as a through-wall crack of the same length as the original semi-elliptical surface crack, it was considered that the predicted value was conservative. The value of $f(\lambda)$ was almost equal to 1 when applied to the specimen configurations in this study, so it has been confirmed that no revision of the curvature was necessary in the elastic analysis. It seems that the elastic-plastic fracture mechanics evaluation for the surface crack considering the revision of the curvature may be the next problem when the shell parameter is not small (λ>>1).

4 CONCLUSIONS

Elevated temperature crack propagation tests were carried out using CT specimens, surface cracked plates, and surface cracked pipes. The estimated J-integral by the simplified method for surface cracks were compared with experimental results. The following conclusions have been obtained.
(1) The J-integral was estimated well by simplified methods.
(2) The J-integral for a surface cracked pipe can be approximated by that for a surface cracked plate when the shell parameter is small.

REFERENCES

[1] Takahashi,H. et al., (1991), Creep-Fatigue Crack Behavior in Surface Cracked Pipe, SMiRT-11, L09/2, 193.
[2] Shimakawa,T. et al., (1991), Analytical Evaluation Method of Creep-Fatigue Crack Propagation for Surface Cracked Pipe, SMiRT-11, L09/4, 205.
[3] Iwasaki,R. et al., (1991), Application of Simplified J-estimation Methods to Surface Cracked Structures under Creep-Fatigue Loadings, SMiRT-11, L10/2, 217.
[4] Wada,Y. et al., Analytical Representation for the Cyclic Stress-Strain Hysteresis Loops of Type 304 Austenitic Stainless Steel, Computational Mechanics 86, IV-25.
[5] Folias E.S., (1969), On the Effect of Initial Curvature on Cracked Flat Sheets, Int.Journ.of Fracture Mech., 5, 327.

Table 1. Chemical composition of tested 304 stainless steel (wt.%)

C	Si	Mu	P	S	Ni	Cr	Co
0.05	0.66	1.65	0.027	0.007	9.06	18.92	0.152

Table 2. Mechanical properties of tested 304 stainless steel

Temperature (℃)	0.2% proof stress (kgf/mm2)	Tensile strength (kgf/mm2)	Elongation (%)	Reduction of area (%)
R.T.	25	61	62	65

Table 3. Results of creep tests

Temperature (℃)	Stress (kgf/mm2)	Rupture Time (hr)	Elongation (%)	Minimum creep rate (%/hr)
650	15.0	217	76.4	1.47×10^{-1}
650	13.0	655	84.0	4.88×10^{-2}
650	11.0	>1510	–	5.19×10^{-3}

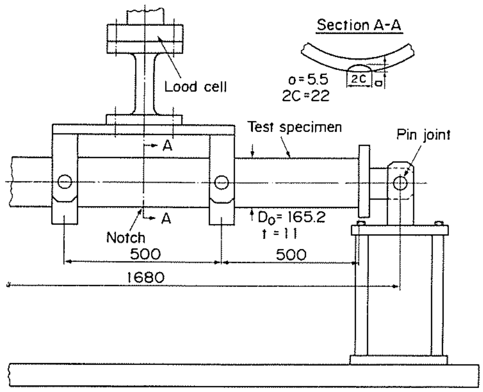

Fig.1 4-point bending test apparatus and notch configuration

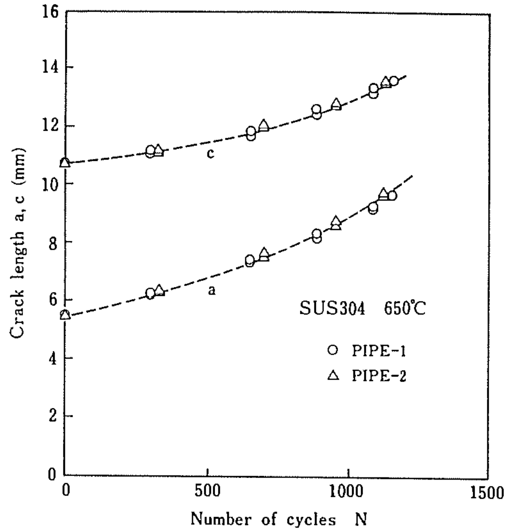

Fig.3 Relationship between crack length and number of cycles (surface cracked pipe)

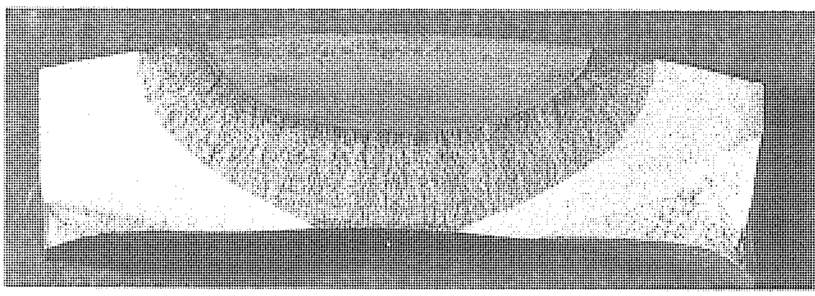

Fig.2 Fracture surface (surface cracked pipe)

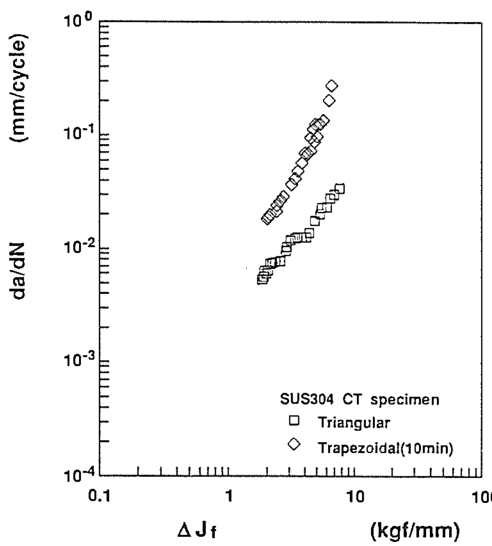

Fig.4 (a) Relationship between da/dN and ΔJ_f

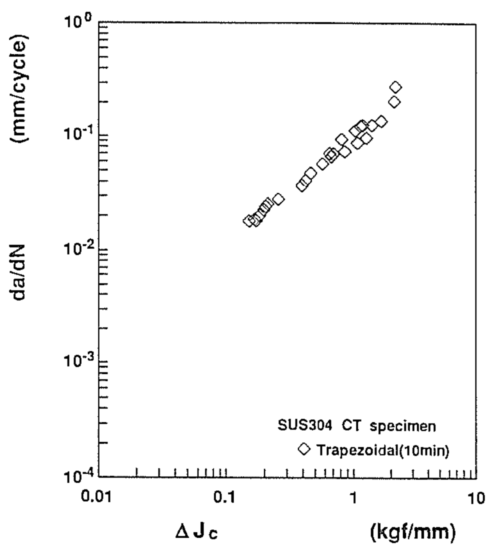

Fig.4 (b) Relationship between da/dN and ΔJ_c

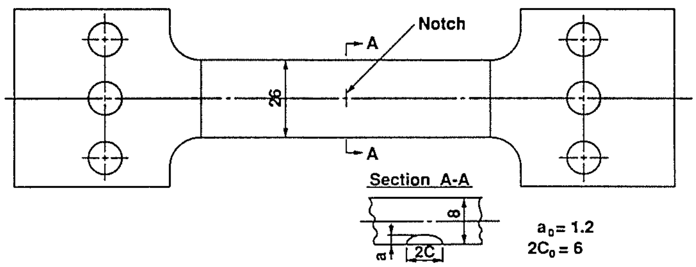

Fig.5 Configuration of surface cracked plate specimen

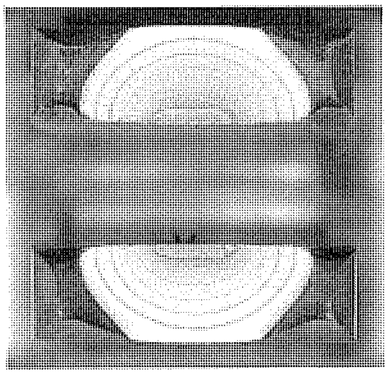

Fig.6 Fracture surface (surface cracked plate)

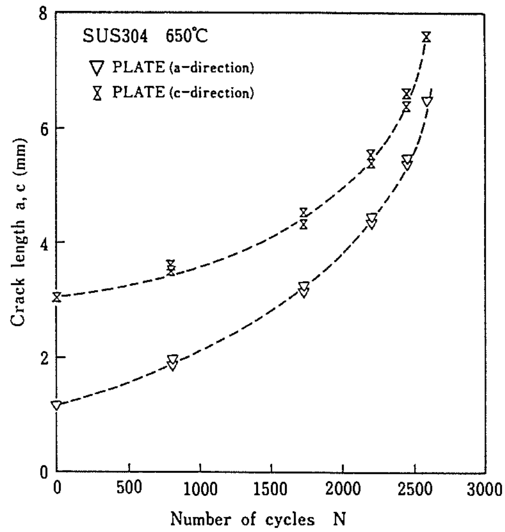

Fig.7 Relationship between crack length and number of cycles (surface cracked plate)

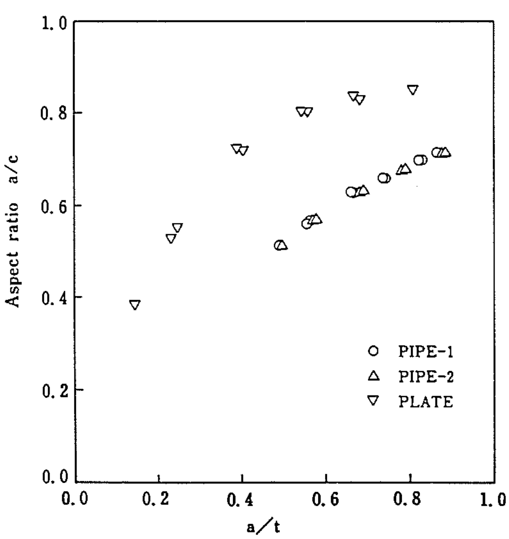

Fig.8 Relationship between aspect ratio (a/c) and crack depth ratio (a/t)

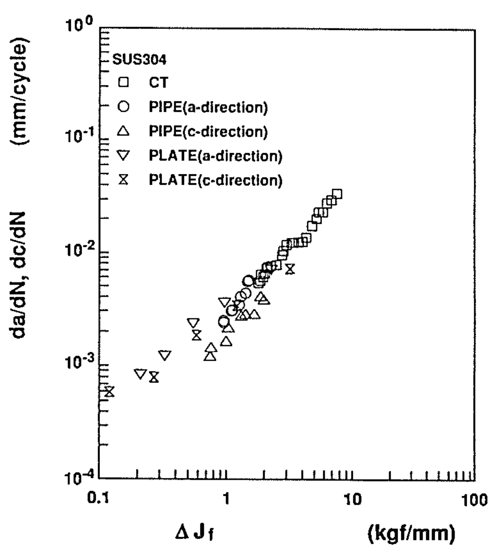

Fig.9 Relationship between da/dN and ΔJ_f (estimated by simplified method and measured with CT specimen)