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Analytical Evaluation Method of Creep-Fatigue Crack Propagation for Surface Cracked Pipe

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ABSTRACT

This paper shows the estimated J-integrals of surface cracked pipe and elbow under creep-fatigue conditions by 3-D FEM analyses. Predictions are compared with test data and the applicability of the analytical evaluation method is discussed.

1 INTRODUCTION

Evaluation method for creep-fatigue crack propagation has been developed to apply the LBB (Leak Before Break) concept to FBR designing in Japan. Fast reactor is operated at elevated temperature, then non-linear behavior of the material must be taken into account. J-integrals are the most powerful non-linear fracture mechanics parameter to represent crack propagation behavior under creep-fatigue conditions. However, evaluation of J-integral is the crucial issue in application of non-linear fracture mechanics for designing. Finite element analysis is the practical method to calculate J-integral in the structure, however the accuracy of the results has not comfirmed for surface cracked structures yet. Then the research program has been performed to obtain experimantal data to verify the analytical evaluation method for surface cracked structure under creep-fatigue loading[1][2][3]. This paper shows the crack propagation predictions by FEM for surface cracked pipe and elbow, and the comparison with experimantal results.

2 ESTIMATION SCHEME OF CREEP-FATIGUE CRACK GROWTH

Material mainly adopted in FBR is austenitic stainless steel. Austenitic stainless steel shows the notable cyclic hardening in the operation at elevated temperature, and cyclic stress-strain hysteresis depends on strain range. Representative stress-strain relation should be chosen in the FEM modeling, and the result would be consequently affected by the modeling of stress-strain relation when cyclic stress-strain hysteresis is adopted. Authors have proposed the estimation method of creep-fatigue J-integral using cyclic stress-strain curve as shown in Fig.1[4]. Cyclic hardening is accurately modeled in the calculation of strain range, stress range, displacement range and load range with this method and fatigue J-integral ΔJ_f is given by the following equation.

$$\Delta J_f = 4 \times J \quad \cdots\cdots (1)$$

Evaluations of crack propagation rate due to fatigue $(da/dN)_f$ and that due to creep $(da/dN)_c$ are based on following Paris's equations.

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$$\left.\begin{array}{l}(da/dN)_f = C\ (\Delta J_f)^m,\ C = 1.2022\times 10^{-3},\ m = 1.4435 \\ (da/dN)_c = C'(\Delta J_c)^{m'},\ C'=0.1274,\ m'=0.877 \\ \qquad\qquad (\text{ Unit : } da/dN \cdots \text{mm/cycle},\ J \cdots \text{kgf/mm}\ )\end{array}\right\}\quad\cdots\cdots\cdots (2)$$

Crack propagation rate due to creep-fatigue is calculated by the linear sum of fatigue component and creep component.

$$da/dN = (da/dN)_f + (da/dN)_c \quad\cdots\cdots\cdots (3)$$

3 APPLICATION FOR SURFACE CRACKED PIPE

3.1 Analysis method

The object of the analyses is the surface cracked pipe under 4-points bending as shown in Fig.2. Outer diameter of the pipe is 165.2 mm and thickness is 11 mm. Semi-elliptical crack of 5.5 mm depth and 22 mm width was initially introduced at the outer surface. Material is Type 304 stainless steel and tests were performed at 550℃[3]. FEM analyses were performed for four kinds of crack geometry as shown in Table 1. 1/4 of the pipe was modeled to FEM mesh as shown in Fig.3. There was at least 5 layers both in the ligament and on the crack to obtain accurate J-integral[5].

Material constants adopted in the analyses are shown as follows.

$$\left.\begin{array}{l}\varepsilon^t = \dfrac{\sigma}{E} + \left(\dfrac{\sigma - \sigma_p}{k}\right)^{1/m} \\ \qquad E = 15691\ \text{kg/mm}^2 \\ \qquad \sigma_p = 9.39\ \ \text{kg/mm}^2 \\ \qquad k = 207.21\text{kg/mm}^2 \\ \qquad m = 0.427\end{array}\right\}\quad\cdots\cdots\cdots (4)$$

$$\dot{\varepsilon} = 1.2527\times 10^{-12}\ \sigma^{5.8128}\ (\text{mm/mm/hr})\quad\cdots\cdots\cdots (5)$$

Stress range of ±17 kg/mm^2 was applied with 5 hour tension holding in the test.

Fatigue J-integrals were calculated both by virtual crack extension (VCE) method and path integration method, and creep J-integrals (J'-integral) only by path integration. Line spring method was also applied in cases 2 and 4 which denote analyses by ABAQUS.

3.2 Analysis results

Estimated crack opening displacement renge (ΔCOD) is shown in Fig.4 compared with experimental results. ΔCODs estimated by ABAQUS are slightly larger than those by MARC, however estimated results coincide well with tested. Scatter of analytical results may be caused by the difference of mesh designing not by the difference of code.

Path independence of J-integral was confirmed in all cases except the evaluation along the closest path to the crack tip. J-integral distribution along crack front is shown in Fig.5 when applied nominal stress is 17 kg/mm^2; load is 11.1 ton. The maximum value of J-integral arises at the deepest point (θ =90 °) when crack depth is shorter than 7mm. The maximum point moves to the surface with crack grows deeper.

Solutions by line spring method are also obtained for cases 2 and 4. J-integral at the crack root could be estimated as well as that by VCE or path integration. When crack growth behavior is dominated only by J-integral at crack root, line spring method gives reasonable estimation economically.

Time histories of J'-integral during creep hold time are shown in Fig.6. Notable path dependence is observed, and it takes long time to be path-independent. Figure 7 shows J'-integral distribution along crack front at the end of 5 hr holding. J'-integrals are nearly constant along crack front, and this trend is significantly different from that under elastic-plastic condition as shown in Fig.5.

3.3 Evaluation of crack propagation rate

Estimated crack propagation rate is shown in Fig.8 compared with experimental results. There are two kinds of definition of ΔJ_c in the prediction. The first one is the ordinary time-integration of J'-integral. This ΔJ_c shows path dependence because of path dependence of J'-integral as shown in Fig.7. The second one is the simple multiplication of hold time to J'-integral at the end of 5 hr holding when J'-integral reaches path-independence. Scatter caused by the difference of evaluation method is not so large and allowable for engineering use.

4 APPLICATION FOR SURFACE CRACKED ELBOW

4.1 Analysis method

The object of the analyses is the surface cracked elbow with 165.2 mm outer diameter, 3.4 mm thickness and 228.6 mm bending radius as shown in Fig.9. Rectangular crack of 0.5mm - 2.5mm depth and 100 mm width was initially introduced for longitudinal direction at the outer surface on the both sides of elbow. Material is Type 304 stainless steel and tests were performed at 550 ℃[3]. FEM analyses were performed for four kinds of crack depth, 0.5mm, 1.5mm, 2.0mm and 2.5mm. 1/4 of the elbow was modeled to FEM mesh as shown in Fig.10. Material constants adopted in the analyses are same as those for straight pipe.

Displacement range of ±7.5mm were applied with 5 hr holding in the test.

SIMUS program[6] is used in which fatigue J-integrals are calculated by VCE method and creep J-integrals (J'-integrals) by path integration.

4.2 Analysis results

Estimated crack tip opening displacement (CTOD) and J-integral are shown in Fig.11. J-integral increase before crack reaches to 2mm and decrease beyond 2mm. Same tendency is also observed for CTOD. This seems due to displacement controlled.

Notable path dependency of J'-integral is also observed in earlier stage of holding, while path-independency at the end of 5 hr holding. J'-integral at 5 hr and average J'-integral for 5 hr are shown in Fig.12. Scatter caused by path-dependency is also shown, however scatter is relatively small.

4.3 Evaluation of crack propagation rate

Estimated crack propagation rate is shown in Fig.13 compared with experimental results Good agreement is observed between estimation and experiment for fatigue crack growth without hold time. For the creep crack propagation with hold time, estimations are affected by the definition of J'-integral. Estimation with J'-integral at 5 hr is closer to experimental results than that with average J'-integral. However scatter caused by the difference of evaluation method is not so large and allowable for engineering use.

5 CONCLUSIONS

3-D analyses for surface cracked pipe and estimation of crack propagation rate under creep-fatigue loading were performed and estimations were compared with experimental data. The conclusions obtained in this study can be summarized as follows:

(1) Crack opening behavior could be evaluated well with cyclic stress-strain curve.

(2) Path independency of J'-integral could not observed at the operation temperature of FBR. Estimated crack propagation rate is consequently affected by the definition of ΔJ_c.

(3) Estimated crack propagation rate coincide well with experimental results. Scatter caused by the difference of ΔJ_c is not so large and allowable for engineering use

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Table 1 FEM analysis conditions for pipe specimens with surface crack

Case No.	1	2	3	4
Crack depth a mm	6.5	7	8	9
Crack length 2c mm	22.6	23.4	25	26.6
Analysis code	MARC	ABAQUS	MARC	ABAQUS
Element type	20-node Solid			
Number of elements	438	334	438	334
Number of nodes	2329	1210	2329	1210
$\sigma - \varepsilon$	Multi-linear	Multi-linear	Multi-linear	Multi-linear
J-integral eval.	VCE and Path integration			
J'-integral eval.	Path integration			

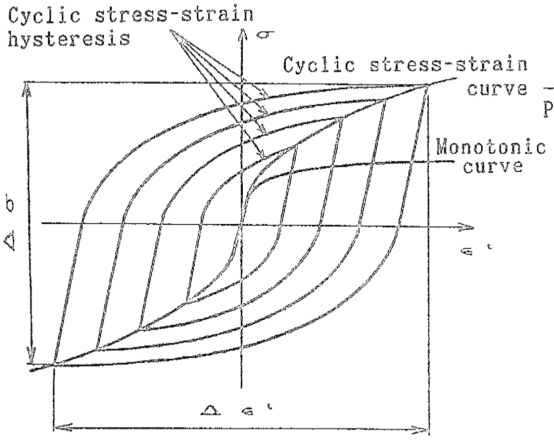

Fig.1 Cyclic stress-strain curve

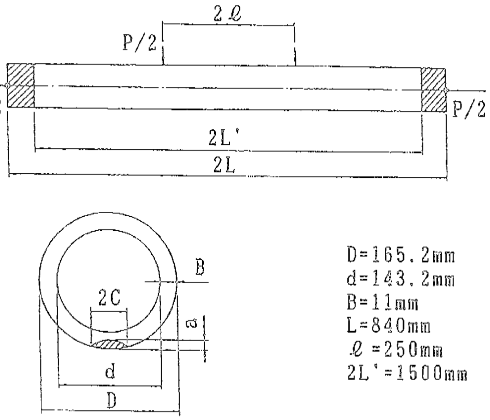

Fig.2 Surface cracked pipe

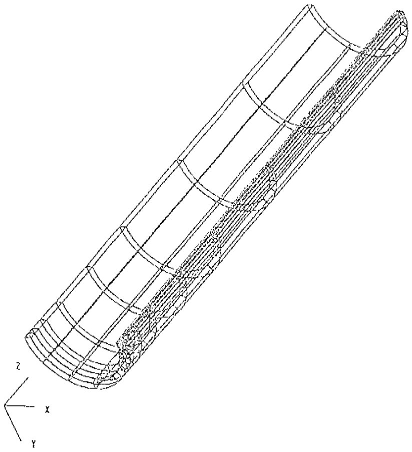

Fig.3 FEM mesh of straight pipe

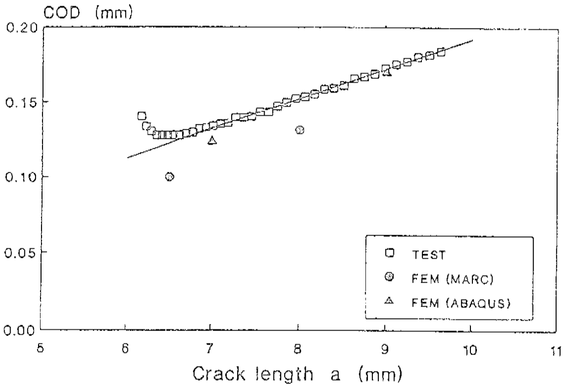

Fig.4 Comparison of COD between estimated and measured

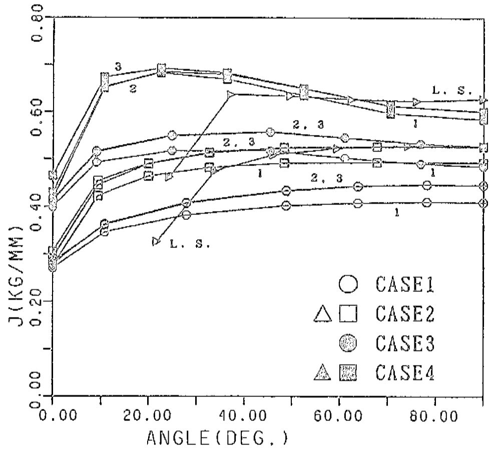

Fig.5 J-integral distribution along crack front

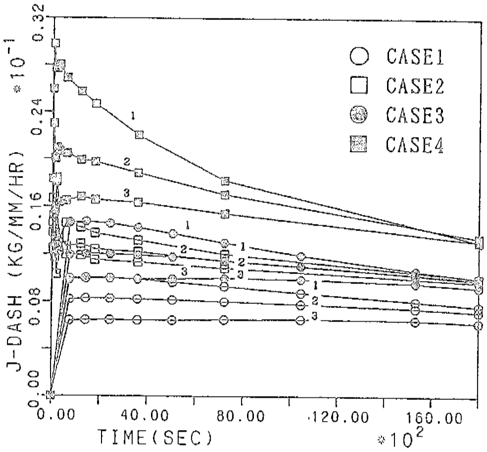

Fig.6 Time history of J'-integral

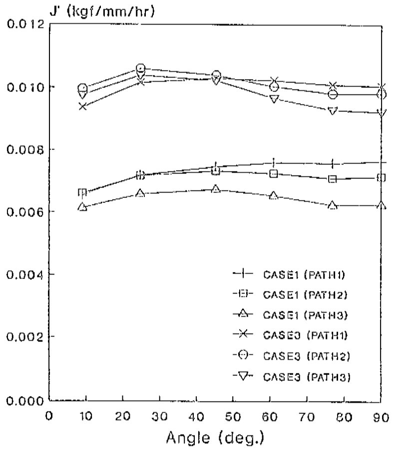

Fig.7 J'-integral distribution along crack front

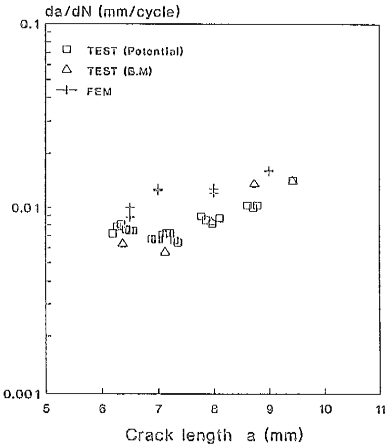

Fig.8 Comparison of da/dN between estimated and measured

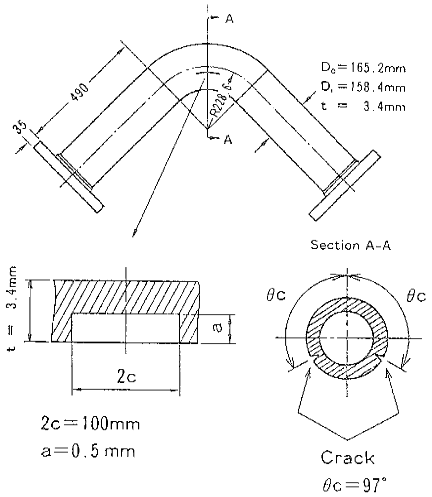

Fig.9 Surface cracked elbow

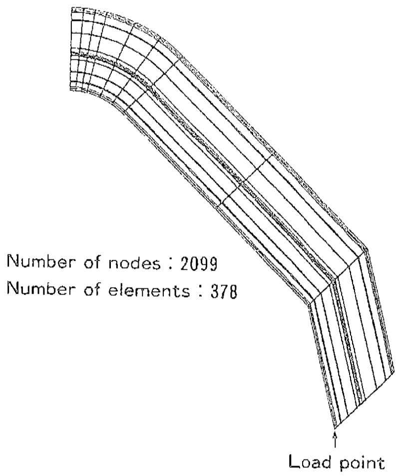

Fig.10 FEM mesh of elbow

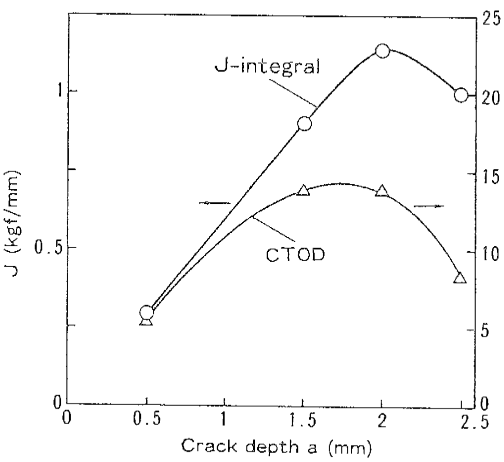

Fig.11 Relationships of J-integral and CTOD to crack depth

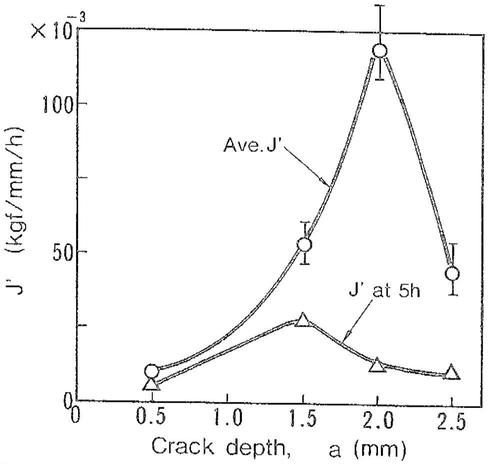

Fig.12 Relationship between crack depth and J'-integral

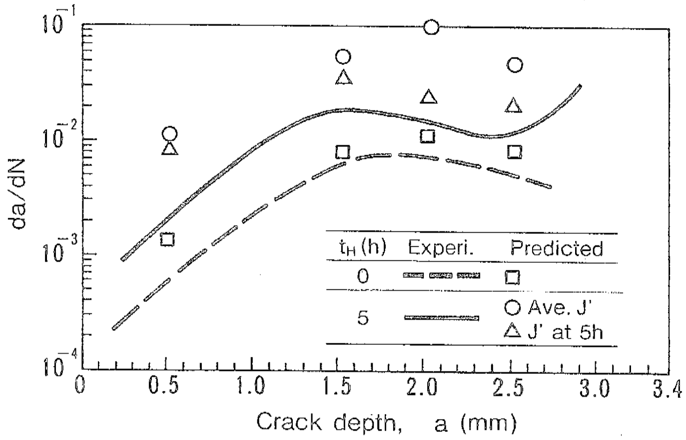

Fig.13 Relationship between crack depth and crack growth rate