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CREEP-FATIGUE DEFORMATION ON CURVED TUBES OF HASTELLOY XR UNDER IN-PLANE AND OUT-OF-PLANE BENDING

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ABSTRACT

Both completely reversed in-plane and out-of-plane bending fatigue tests were carried out at 900°C. The effects of the loading-direction and the carvature-radius of the elbow on the deformation of the curved tube under creep-fatigue conditions at elevated temperature were examined experimentally and analytically. Main crack was observed at the lower side of the elbow in the in-plane bending fatigue tests. In the out-of-plane bending fatigue tests, main crack was observed in the side of the elbow and extended in the direction of 45° to the axis of the test tube. The position and direction of the main crack were in fairly good agreement with those by the analytical results. The inelastic analyses are conducted by using the creep constitutive equation. A comparison between the predicted fracture lives based on analyses and the experimental ones of the test tubes are tried.

1. INTRODUCTION

The intermediate heat exchanger (IHX) is necessary for the process heat applications of the high temperature gas-cooled reactor (HTGR). The heat transfer tubes of the IHX are subjected to thermal stresses due to a restriction of thermal expansion during start-up and shut-down transients. Especially, curved tubes must be one of weak points in the IHX structures. A safety margin for the structural life of heat transfer tubes should be ascertained because they belong to the important pressure boundary for the reactor coolant.

Therefore, the authors developed a high-temperature curved-tube bending test apparatus and carried out deflection-controlled in-plane and out-of-plane bending tests at elevated temperature. The experimental results were compared with the analyzed ones by a general purpose FEM code ABAQUS.

2. EXPERIMENTAL PROCEDURE

2.1 Test specimen

Material of the test tubes was a nickel-base superalloy Hastelloy XR, a modified version of Hastelloy X. Test tubes were hot-extruded. The chemical composition and mechanical properties are shown Table 1. Some of the test tubes were specimens with TIG-welded joint. The shape of test tube is shown in Fig. 1. The position of the TIG-welded joint is between straight and elbow tube. The dimensions of the test tubes were 31.8mm in outer diameter, 3.5mm in thickness, and 160mm and 250mm in radius of carvature of the elbow.

Table 1. Chemical compositions and mechanical properties of Hastelloy XR

Chemical compositions (wt%)

C	Mn	Si	Cr	W	Mo	Fe	Ni	Co	Al	Ti	B	P	S	N
0.07	0.95	0.34	22.25	0.48	8.87	17.86	Bal.	0.02	<0.01	<0.01	<0.0001	<0.001	0.002	0.007

Material properties at 900°C

Tensile strength (MPa)	0.2% proof strength (MPa)	Creep rupture test		
		Stress (MPa)	Time (h)	Elongation (%)
210.8(698.2)	179.5(333.4)	51.0	245	24

( ): strength at room temperature

2.2 Test apparatus and test

In the test apparatus, push-pull loads were applied to the one end of the test tube by a servo-controlled hydraulic machine under deflection-controlled condition. The cross sectional view of the test apparatus is shown in Fig. 2. The furnace has three separate heaters and the temperature of the test tube is controlled within ±5°C of the desired temparature. The apparatus enables in-plane and out-of-plane bending tests at elevated temperature by replacing the support of the apparatus. The type of loading direction in the apparatus is shown in Fig. 3. In this paper, the loading direction in in-plane and out-of-plane bending fatigue tests were I-1, I-2 and O-1 in Fig. 3, respectively.

The experimental conditions and results are shown in Table 2. In the test, both completely reversed in-plane and out-of-plane bending fatigue tests for both base and welded materials were carried out at 900°C in air. The out-of-plane bending fatigue tests with holding time were carried out to research the effect of holding time on the number of cycles to failure.

After the bending fatigue tests, observation of the surface and the cross section was performed by means of a microscope to research the microstructure of the fractured test tubes.

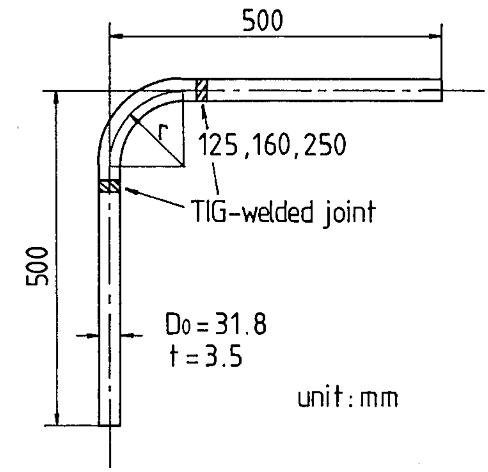


Fig. 1 Shape of test tube

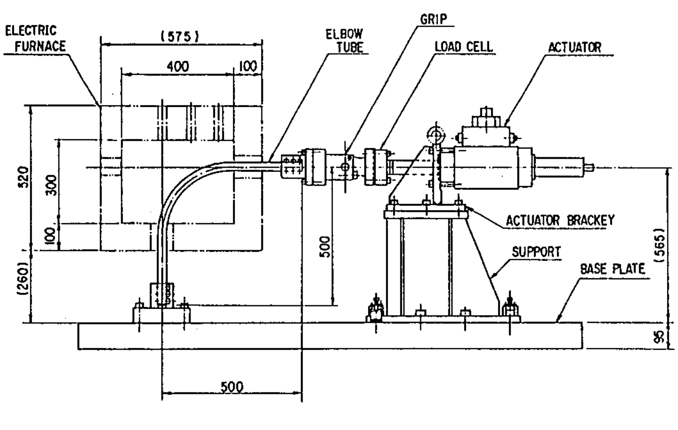


Fig. 2 Cross section of the test apparatus

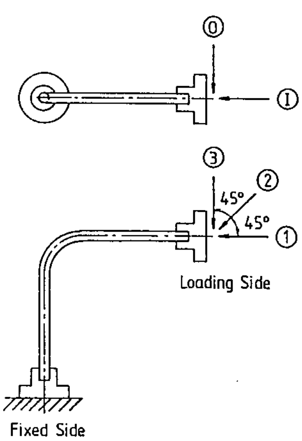


Fig. 3 Loading direction

Table 2 Experimental conditions and results

No.	Test temp. (oC)	Material	Curvature-radius of elbow (mm)	Loading-direction	Deflection range (mm)	Deflection rate (mm/s)	Holding time (s)	Number of cycles to failure
XRA-1			160	In-plane(I-2)	30	0.6	0	849
XRA-2			160		14.4	0.6	0	19472
XRC-4		Base	250	In-plane(I-1)	60	3	300	149
XRB-3			160	out-of-plane(O-1)	60	3	300	4000*
XRC-5	900		250		60	3	300	3667
XRC-3			250		60	3	0	200635*
XRC-1			250		40	3	300	11285*
WJB-1		Weld	160	In-plane(I-2)	30	0.6	0	795
WJA-2			125		14.4	0.6	0	14001

* : No fracture

3. ANALYTICAL PROCEDURE

3.1 Material properties

Constant-stress creep tests were done by a balanced weight inside an electric-heated furnace at 900°C in air. Tests were carried out under assumption of invariable volume within the gauge length measured by a extensometer. A next Norton type creep constitutive equation was established for the further analyses of creep deformation.[1)]

$$\dot{\varepsilon}_c = 1.9761 \times 10^{-14} \sigma^{6.083} \quad (1)$$

where $\dot{\varepsilon}_c$ is creep strain rate (1/h), σ is applied stress (MPa).

Young's modulus and Poisson's ratio at 900°C was taken to be $E=1.285 \times 10^5$ MPa and $\nu=0.3$, respectively.

3.2 FEM analysis by ABAQUS

The elastic and inelastic analysis were performed by the ABAQUS (version 4.9)[2)] in which the update Lagrangian formulation is adopted and the change of the load-direction caused by the deformation is taken into account. The test tube was modeled by both three dimensional 3-node beam elements and 8-node shell elements. Number of nodes and elements in beam model were 26 and 15, respectively. For example, a finite element model for using shell elements in in-plane bending fatigue test is shown in Fig. 4. Number of nodes and elements in the shell model were 2908 and 905, respectively.

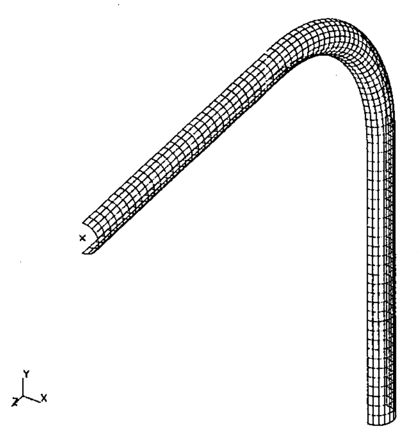


Fig. 4 Finite element model (shell model)

4. RESULTS AND DISCUSSION

Preliminary tests were carried out to examine the performance of the test apparatus at room temperature. Local strains of the elbow were measured with strain gages. The elastic analyses were performed by the FEM and the effect of the boundary conditions in the test tube's end were examined. As an example, relationship between axial strain and displacement is shown in Fig. 5. These experimental results were measured at the point of maximum axial strain in the in-plane bending test. It is confirmed that one end of the test tube is rigid-jointed and the other pin-jointed in the apparatus. Figure 6 shows relationship between deflection range and number of cycles to failure in both in-plane and out-of-plane bending fatigue tests at 900°C. It is observed that the effect of the loading-direction on the fracture lives of the test tubes is very large under identical

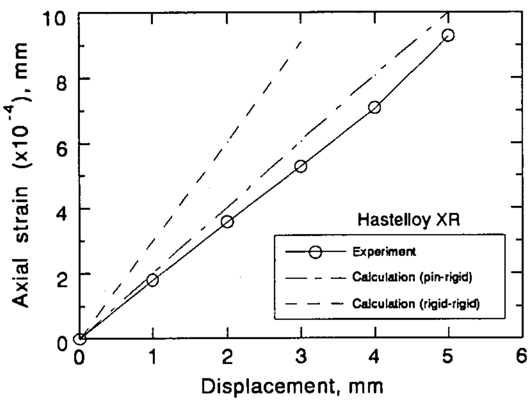


Fig. 5 Preliminary test result

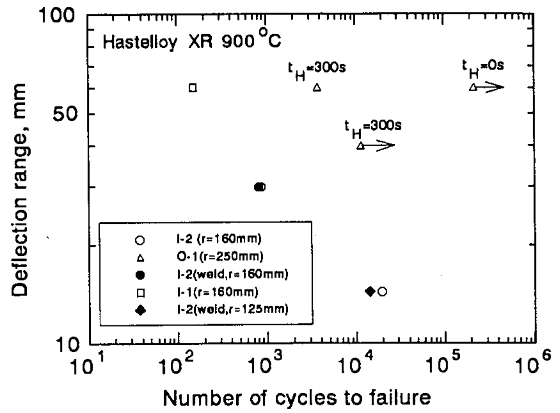


Fig. 6 Number of cycles to failure

conditions. In the in-plane bending fatigue test, experiments were carried out for using both base metal and welded elbow under identical conditions. It is found that the fracture life of welded elbow is a little shorter than the base one. But the deformation mode and the position of the main crack on welded elbow were same as the base elbow. The micro-crack was not seen on the welded-joint of the elbow. In the out-of-plane bending fatigue test, the experiments were conducted under the same deflection range and deflection rate condition to examine the effect of holding time. The fracture life with holding time was much shorter than the without holding time. The test tube without holding time was not fractured under the out-of-plane bending condition, though number of cycles was larger than 10^5.

Even if the deflection range is same, the generated strain and stress become different due to the loading-direction. The maximum value of the residual-load range in the in-plane bending fatigue test (XRC-4) is much larger than the out-of-plane bending fatigue test (XRC-5) under identical conditions as shown in Fig. 7. That is reason why the fracture life of XRC-4 is much shorter than that of XRC-5. Figure 8 shows relationship between residual-load range and number of cycles for base and welded materials under in-plane bending conditions. The value of residual-load range in base material is a little smaller than the welded one because of constraint of welded joints and then the number of cycles to failure in base material becomes larger than the welded one.

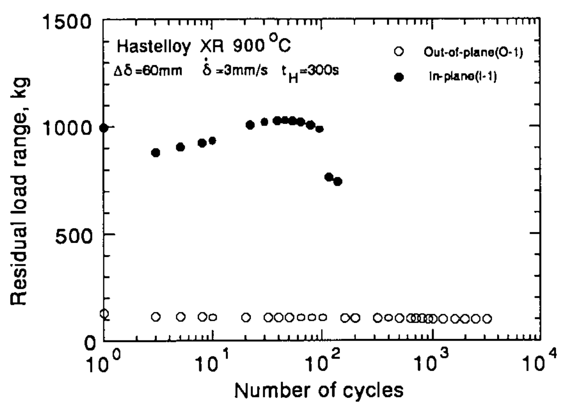


Fig. 7 Effect of loading-direction on residual load range

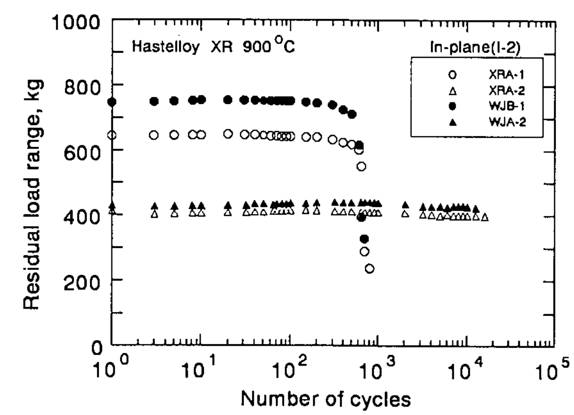
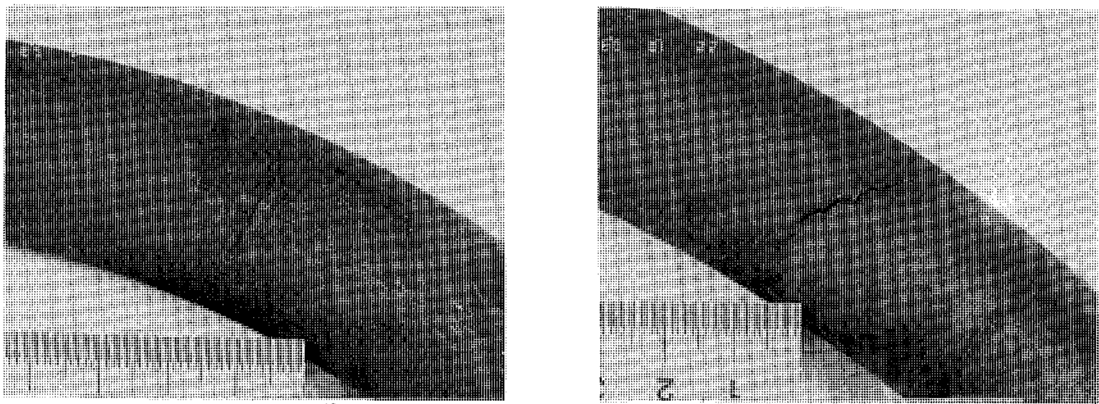


Fig. 8 Effect of weldment on residual load range

Figure 9 shows the appearance of the fractured test tube. In the in-plane bending fatigue test, main crack is observed in the lower side of the elbow. On the other hand, main crack is observed in the side of the elbow and extends in the direction of 45° to the axis of the test tube in out-of-plane bending fatigue test. Figure 10 shows the schematic illustrations of the fractured elbow in both in-plane and out-of-plane bending fatigue tests. The position of the main crack is in fairly



(a) In-plane bending (b) Out-of-plane bending

Fig. 9 Appearance of the fractured tube

good agreement with the results of elastic analysis in both in-plane and out-of-plane bending fatigue tests. It is indicated that longitudinal stress is dominant on the deformation under in-plane bending condition and shear stress is dominant under out-of-plane bending condition.

The typical example of cross-sectional view of the fractured test tube for both in-plane and out-of-plane bending fatigue tests is shown in Fig. 11. In the in-plane bending fatigue tests, the mixed fracture mode consisted of trans-granular and intergranular cracking is observed around most of the crack propagation region. And the fracture surface in the in-plane bending fatigue tests is flat as compared with that of the out-of-plane bending fatigue tests. It is considered to be attributed to the mixed mode consisted of time dependent mechanism and cycle dependent mechanism. On the other hand, intergranular fracture is observed from crack initiation to propagation region in the out-of-plane bending fatigue tests. The cracks are observed to have grown along the grain boundary inside the fractured tubes and the fracture surface is very rough.

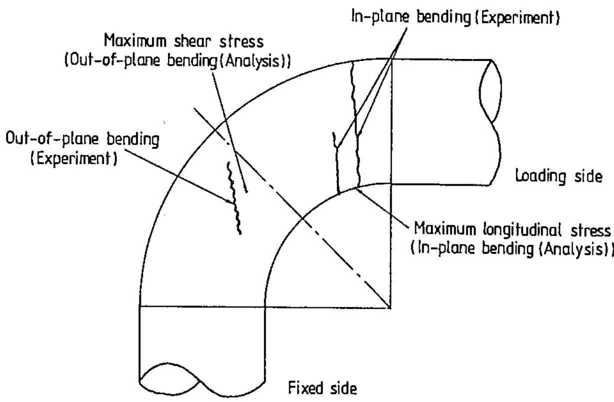
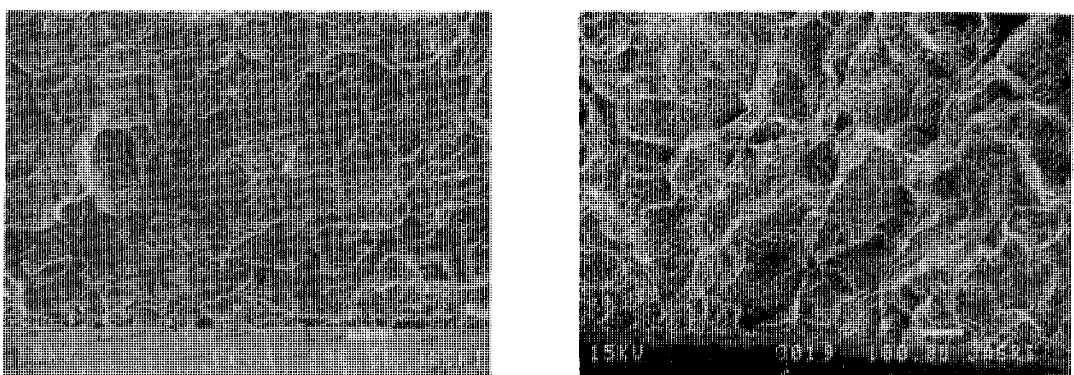


Fig. 10 Schematic illustration of the fractured tube



(a) In-plane bending (b) Out-of-plane bending

Fig. 11 Cross sectional view of the fractured tube

Prediction of fracture lives was conducted for all the test conditions by using the inelastic analysis results using the beam model in the FEM code ABAQUS and tim[illegible] ry conditions in this analysis were that one end of the test tube was rigid-jointed and the other pin-jointed. Temperature of the test tube is assumed 900°C except the grip of the tube. Creep rupture datas in time fraction rule were given by the experimental results under constant stress condition for bar-type specimen at 900°C. Figure 12 shows the comparison between predicted and experimental fracture lives including the results of the welded tubes. Most of predictions are very conservative as compared with the experimental fracture lives. It is considered that the creep constitutive equation in the FEM code is Norton type equation which does not consider the primary creep and so the estimation of creep damage in a cycle is very large and the prediction of the fracture lives is conservative in this case.

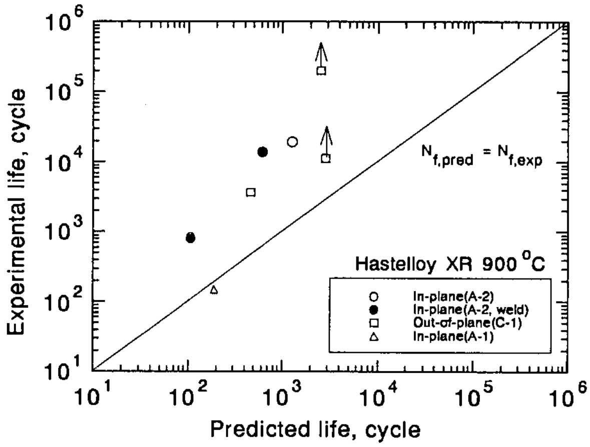


Fig. 12 Comparison between experimental and predicted life

5. CONCLUSIONS

Both completely reversed in-plane and out-of-plane bending fatigue tests were performed at 900°C in air. The effects of the loading-direction and the carvature-radius of the elbow on the deformation of the curved tube under creep-fatigue conditions were examined experimentally and analytically. And prediction of fracture lives was performed by using the inelastic analysis. The following conclusions were derived from the present study.

(1) The effect of loading-direction on the fracture lives of test tubes is very large under identical conditions.

(2) The position and direction of the main crack in both in-plane and out-of-plane bending fatigue tests were in fairly good agreement with those by the analytical results.

(3) Most of predictions of fracture lives are very conservative as compared with the experimental fracture lives.

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