Ductile Fracture Behavior of Stainless Steel Wide Plates under High Temperature

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ABSTRACT

In the development of fast breeder reactors (FBRs), structural integrity must be assured for nuclear components which are subjected to high temperatures. Nonlinear fracture mechanics is one of the most effective approaches to evaluate the structural integrity of the reactor vessel based on ductile fracture behavior. In this study, large scale wide-plate tests were conducted at room temperature and 550℃ to investigate the fracture behavior and criteria of type 304 stainless steel.

1 INTRODUCTION

Safety assurance is one of the most crucial issues in the design and maintenance of nuclear power plants. Nonlinear fracture mechanics is one of the effective approaches to estimate the behavior of crack growth and unstable fracture under many thermal and mechanical conditions. According to the recent progress in fracture mechanics, a variety of material database and analytical methods have been developed to evaluate the cracked structures of piping and vessels.

In 1987, CRIEPI started a 7-year research program on evaluating structural integrity of high-temperature components under the sponsorship of the Japanese government. One of the objectives of this program is to develop and demonstrate the nonlinear fracture mechanics approach which is effective and applicable to evaluating safety of fast breeder reactor (FBR) components.

In this program, large wide-plate fracture tests were conducted at room temperature and elevated temperature (550℃) to study ductile crack growth behavior of type 304 stainless steel base metal and weld joint. Evaluation methods for fracture loads were also investigated.

2 TEST METHOD

2.1 Test facilities

Fig. 1 shows a schematic of the large test facilities newly developed at CRIEPI. This test system provides a maximum loading capacity of

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9800kN and a maximum stroke of ±250mm. For high-temperature tests, wide-plate specimens were heated to 550℃ by an electric furnace, which can provide a maximum temperature of 800℃.

2.2 Materials and specimens

Materials were type 304 stainless steel base metal and TIG weld joint with 46 to 50mm thickness, nearly equal to one of the design values of the vessel wall. The weld joint specimens were fabricated with a double U butt weld using the TIG multi-pass process. The welded part was 12 to 14mm wide on the specimen surface. Chemical compositions and mechanical properties of the materials are shown in Tables 1 and 2.

Fig. 2 and Table 3 show the geometry and dimensions of the specimens. They were fabricated to make the loading direction coincide with the rolling direction of the base metal. A through-wall or a surface notch was introduced by electric-discharge machining at the central part of the specimen. Notch width was approximately 0.2mm. For the weld joint, the loading direction was perpendicular to the weld-line and the initial notch was located in the middle part of the weld metal. In Table 3, material for specimen 01-A-05 is base metal aged at 650℃ for 147hrs. For specimen 01-B-01 and 01-W-02, a

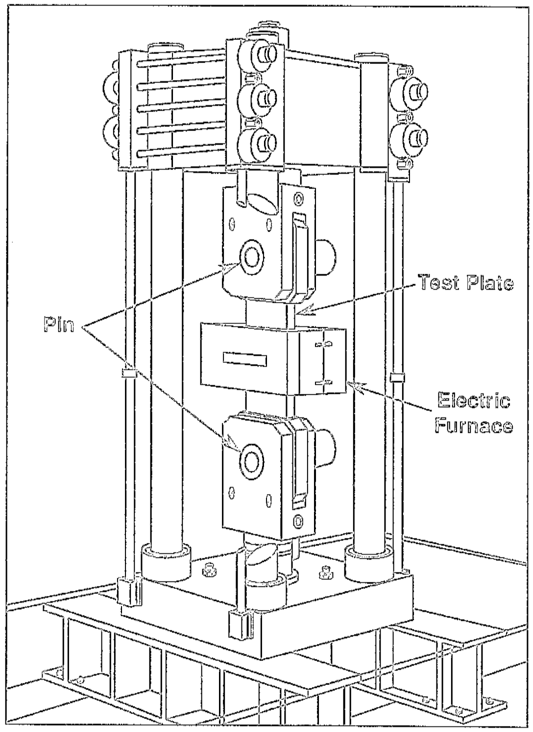

Fig. 1 Overview of Wide-Plate Test Facilities

Table 1 Chemical Composition of Type 304 Stainless Steel (wt%)

C	Si	Mn	P	S	Ni	Cr	Mo	V	N	Co	B	O
0.05	0.52	0.81	0.025	0.003	9.10	18.44	0.11	0.03	0.035	0.09	0.0005	0.0033

Table 2 Mechanical Properties of Type 304 Stainless Steel

Material	Temperature [C]	0.2% Yield Stress [MPa]	Ultimate Strength [MPa]	Elongation [%]	Reduction in Area [%]
Base Metal	R.T.	246	642	71.5	79.7
	550	138	393	43.1	75.9
Weld Metal	R.T.	370	606	52.4	72.1
	550	249	340	29.5	67.5

creep-fatigue crack was introduced instead of an artificial notch to investigate the effect of the crack tip geometry. A typical creep-fatigue crack geometry is shown in Fig. 3.

2.3 Test conditions and method

Fracture tests were conducted for two specimens at room temperature and ten specimens at high temperature (550℃). In high-temperature tests, temperature was kept constant in a 75mm-width strip of the central part of specimens with an accuracy of ±5℃. All of the test conditions are summarized in Table 3.

Fracture tests were conducted under displacement-controlled conditions with a stroke rate of 3.0 to 6.0mm/min, which was regarded as quasi-static monotonic loading.

Experimental data of load, stroke, COD (Crack Opening Displacement, gage length=6mm) were automatically gathered at intervals of 1 to 1.5 seconds. Crack deformation and growth were monitored on both the front and the back surface of the specimen and recorded by video-tape through two observation windows of the electric furnace.

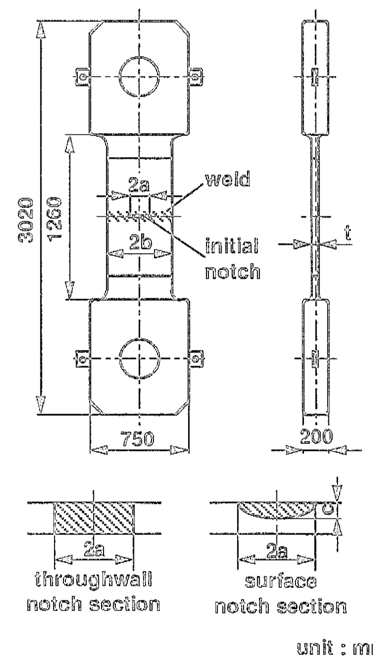

Fig. 2 Wide-Plate Test Specimen

Table 3 Specimen Dimensions and Experimental Maximum Load

Test No.	Material	Temp. [C]	Notch Type	Dimension of Specimen: Width 2b [mm]	Thickness t [mm]	Notch Length 2a [mm]	Notch Depth c [mm]	Experimental Pmax [kN]
63-B-01	Base Metal	R.T.	Through-wall	500	50.0	150	50.0	7213
63-B-02			Surface	500	50.0	150	25.0	10628
63-B-03		550	Surface	500	50.0	150	25.0	7556
63-B-04			Surface	500	50.0	210	35.0	5954
63-B-05			Through-wall	500	50.0	150	50.0	5410
63-B-06			Surface	500	50.0	210	35.0	5694
01-B-01			Through-wall**	400	46.9	281/125***	46.9	2622
01-W-02	Weld Joint		Surface**	399	46.2	357/101***	42.4	2592
01-W-03			Surface	500	49.6	150	25.0	6987
01-W-04			Surface	500	49.9	210	35.0	5282
01-A-05	Aged Base*		Surface	499	50.7	210	35.0	4694
01-W-06	Weld Joint		Through-wall	500	50.7	150	50.7	5478

* : Aging Condition 650℃ × 147hr

** : Introduced Creep-Fatigue Crack as Initial Notch

*** : 2a at Front Surface / 2a at Back Surface

3 TEST RESULTS

3.1 Load-COD relation

Figs. 4(a) and (b) show the example of measured load-COD relations for through-wall and surface notch tests. All the results show that load changes smoothly with displacement before and after the maximum load. For through-wall notch tests (Fig. 4(a)), load decreases gradually after the maximum load; for surface notch tests (Fig. 4(b)), maximum load was generated just before crack penetration, and it seems that load increases slightly again after maximum load.

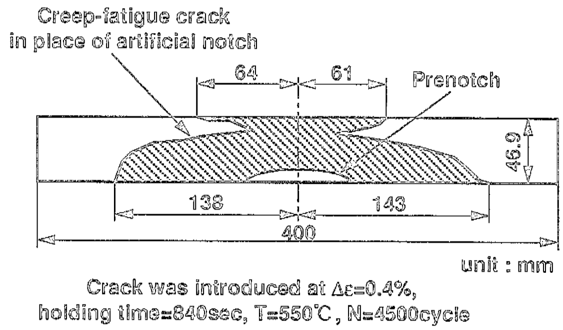

Fig. 3 Initial Creep-Fatigue Crack
(TP No. 01-B-01, Base Metal, 550℃)

3.2 Crack extension

Crack extension was stable, and a bilateral symmetric crack profile was observed on both front and back surfaces of all specimens except 01-B-01 and 01-W-02, which have an asymmetric initial crack. In surface notch tests, the crack propagated in the depth direction and the fracture surface was flat until crack penetration. After penetration, the crack propagated along the surface direction. At that time, the fracture surface was shear for base metal and flat for weld joint. These differences of fracture behavior are supposed to be due to stress triaxiality, restraint conditions , material inhomogeneity etc. These problems are complicated and should be considered further.

The penetration of the surface crack was observed immediately after the maximum load (Fig. 4(b)).

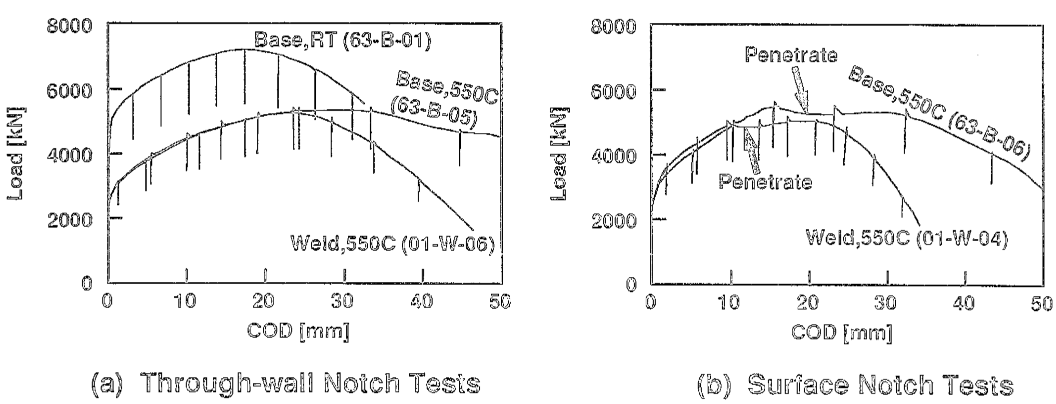

Fig. 4 Load-COD Relations for Wide-Plate Tests

3.3 J-resistance relation

Fig. 5 shows apparent J-resistance curves for wide-plate specimens. These curves were calculated based on the experimental relationship between load, COD and crack extension. J was estimated by use of Rice's method. J values of the base metal at room temperature are a little higher than that at 550℃. At 550℃, the weld joint had a higher J-R curve than the base metal. However, no significant difference was observed, so J-R curves converge on a band.

4 EVALUATION OF FRACTURE LOAD

Fig. 6 shows the relation between the net-section stress at the maximum load (σ_{net}) and the ratio of initial crack depth to thickness. σ_{net} is normalized by the flow stress (σ_{flow}), which is defined as the mean value of 0.2% yield stress and ultimate strength. It is apparent that experimental σ_{net}s are higher than or nearly equal to σ_{flow}. It seems that surface notch tests yield larger $\sigma_{net}/\sigma_{flow}$ values than through-wall notch tests, and base metal tests show larger $\sigma_{net}/\sigma_{flow}$ values than weld joint tests.

For highly ductile material, the fracture load can be generally predicted by net-section collapse criterion. The above result for base metal supports this prediction. Analytical method to evaluate fracture load for inhomogeneous material such as weld joint has not been established, and investigations are now being conducted. However, according to the material in this study, it is apparent that net-section collapse criterion is approximately valid for base metal and weld joint.

5 CONCLUSIONS

To study ductile crack growth behavior of type 304 stainless steel base metal and weld joints, fracture tests were conducted at room temperature and 550℃ using large wide-plate specimens. Methods of evaluating fracture loads were also investigated. Conclusions are as follows:

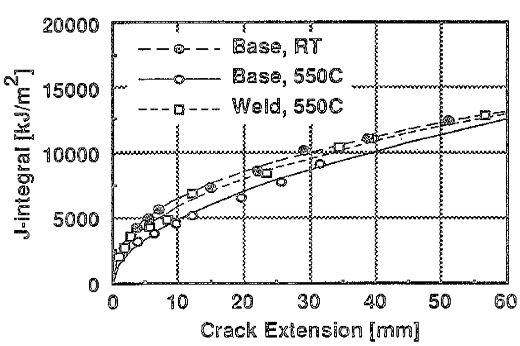

Fig. 5 J-Resistance Curves for Wide-Plate Tests

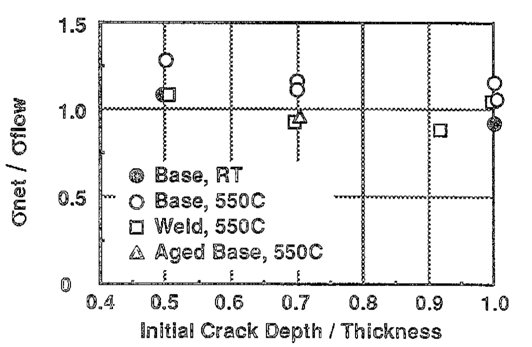

Fig. 6 Fracture Net Stress for Wide-Plate Tests

- Surface cracks propagate in the depth direction until crack propagation.
- Penetration of surface crack is observed immediately after the maximum load.
- Fracture load can be predicted based on net-section collapse criterion for both base metal and weld joint for any initial notch geometry.

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