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Comparison of the CEA and JNC approaches for creep-fatigue evaluation of weldment
(3) Benchmark analysis of a vessel subjected to thermal transients

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Abstract

To establish rational evaluation methods of weldments, France and Japan have compared data and ideas under the framework of CEA/JNC cooperation in fast reactor technology. Design evaluation procedures of both countries have some differences caused from CEA approach based on material data analysis and JNC one with mechanical analysis, which are described in the associated paper. Evaluation results of both procedures have been quantitatively compared through two benchmark analyses. One of benchmarks that provided by JNC is creep-fatigue evaluation of a welded vessel subjected to cyclic thermal transient loading. The objective of this problem is comparison of total strength evaluation methods of base metal and welded joints against actual loading conditions..

1. Introduction

In order to take strength reduction of welded joints into account for elevated temperature structural design, design codes are required to provide rational evaluation methods for welded joints.

CEA and JNC have developed design evaluation procedures for considering strength reduction of weldments[1]. Under the framework of CEA/JNC cooperation in fast reactor technology, inter-comparison of both procedures is planned through application to the same benchmark problems. For benchmark, CEA and JNC have submitted two complementary problems. One of benchmarks, which was provided by CEA, is fatigue and creep-fatigue evaluation of welded plates due to reverse bending at 550℃[2]. Another problem proposed by JNC is creep-fatigue evaluation of a welded vessel due to cyclic thermal transient loading. The objective of the later problem is comparison of creep-fatigue evaluation methods of base metals and welded joints on actual components due to cyclic thermal transients. This report describes benchmark problem on a welded vessel and compares benchmark analysis results by CEA and JNC procedures without artificial design margins.

2. Benchmark problem on a welded vessel

A thermal transient strength test was conducted on a welded structure model by using a sodium test facility TTS. The test model is a vessel type structure, which has an outer container and an inner vessel as Fig.1[3]. 1055 cycles of thermal transients were applied by alternate flow of hot (600℃) and cold sodium (250℃) which passed though the annulus space between the outside container and the inner vessel. During each cycle, creep damage was accumulated by 2 hours holding time in 600℃. As for materials, the outside container and half of the structure of the inner vessel are made of SUS304 (Japanese Type304SS), and the remainder half is made of 316FR (Japanese low carbon and medium nitrogen stainless steel for use in FBRs). Circumferential and longitudial welded joints are incorporated in both SUS304 and 316FR portions. A photograph of the vessel model and observed cracks after cyclic thermal transients are as in Fig.2. The dimensions of the outside container of the vessel model is 2210mm high and 980mm in diameter with 25 mm thickness wall, and the inner vessel is 456mm inner diameter with 20 mm thickness wall. The inner vessel has a restraint plate with 25mm wall thickness to make stress gradient on the inner vessel.

After 1055 cycles thermal transients, cracks were inspected on the surface of the inner vessel by the liquid flaw detection test (PT). In the 316FR division of inner vessel, few small cracks were found only at welded joints, while many cracks were observed at both base metals and welded joints in the 304SS parts. Here, the cracks at welded joints were observed to be deeper than that of the nearby base metal. During thermal cycles, thermocouples monitored both sodium and structural temperatures. By utilizing these measurements, temperature and stress distribution were evaluatred by finite element analysis as in Fig.3. Fig.4 shows Mises stress range and Tresca stress range from linearized stress components Sn (stress intensity) on the surface of inner vessel (Evaluation area in Fig.3).

In order to define a scope of the problem as the comparison of creep-fatigue evaluation procedures and to eliminate influences from differences of materials and structural analysis results, this benchmark program provides common material properties[4] and structural analysis results[5] as in Fig.5. Furthermore, this benchmark program restricts the evaluation area into the outer surface of the inner vessel as indicated in Fig.3. Materials to be evaluated are SUS304 base metal, flash grained welded joint of SUS304, 316FR base metal, and flash grained welded joint of 316FR. All of these material portions have the same geometry and are subjected to the same loading. Such structural analysis results were provided from thermal elastic analysis based on measured temperature data, that Mises stress range on the surface, Tresca stress range from linearized stress components Sn (stress intensity), and a stress classification table.

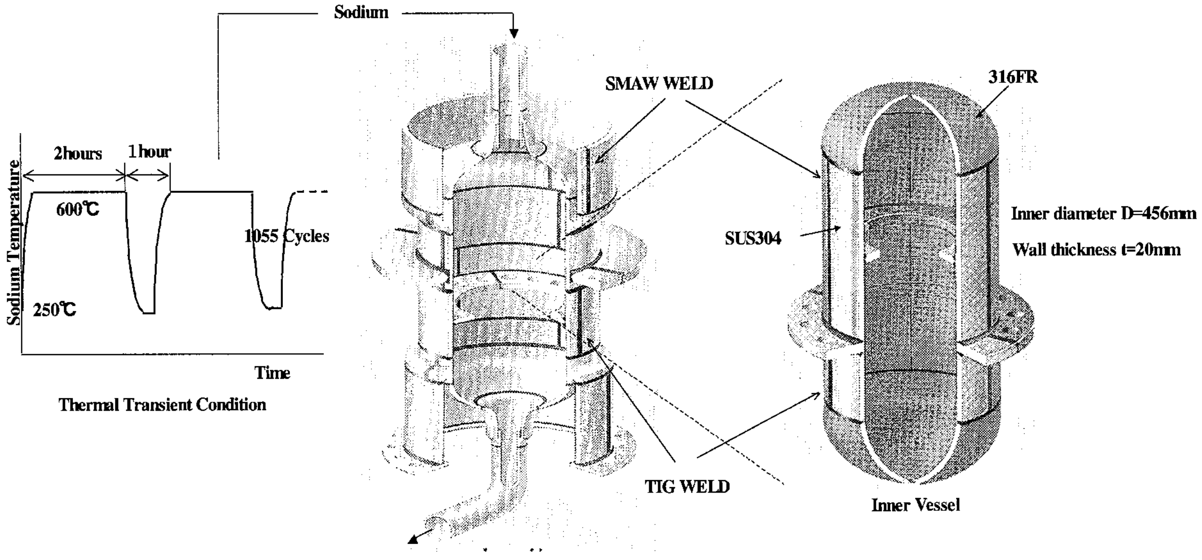


Fig.1 Welded joints in the welded vessel model

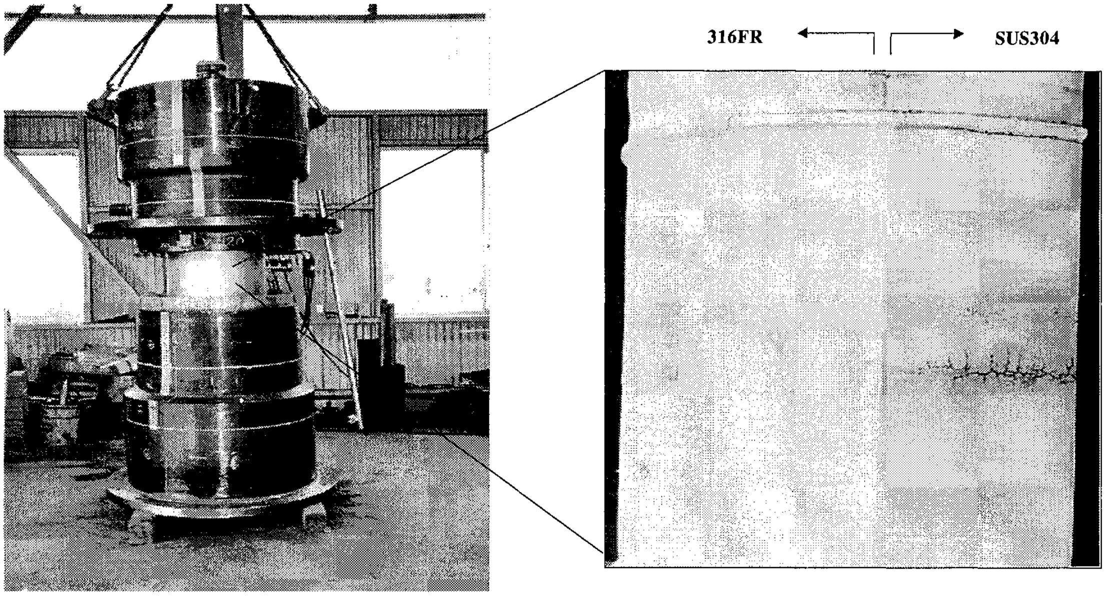


Fig.2 Welded joints in the welded vessel model

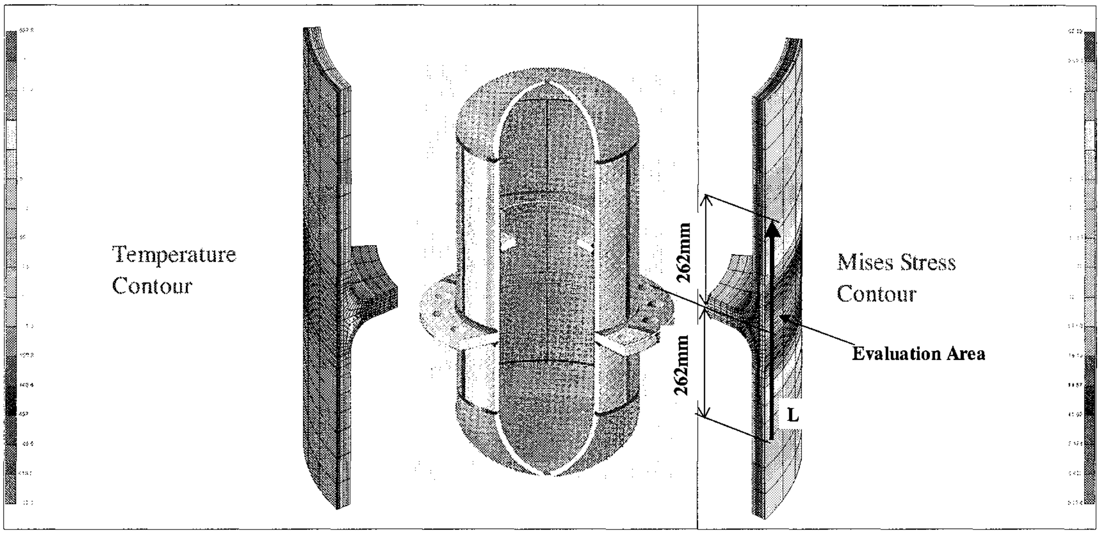


Fig.3 Thermal and thermal elastic analysis results

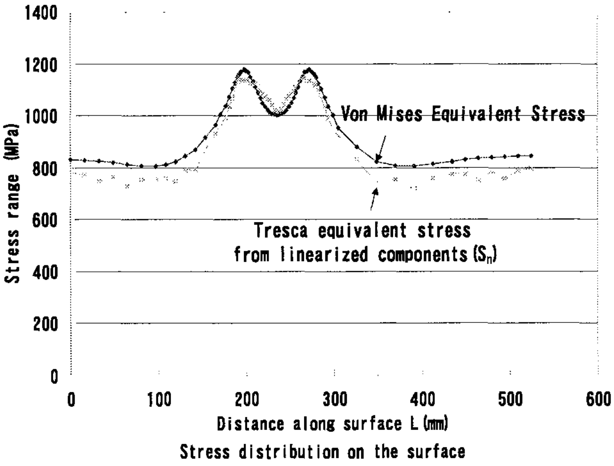


Fig.4 Thermal stress distribution along surface of inner vessel

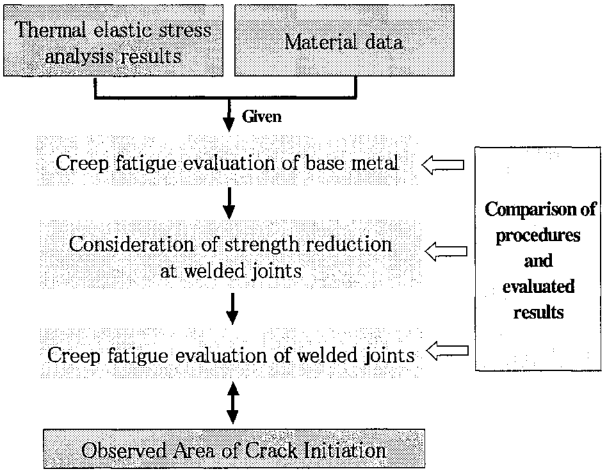


Fig.5 Scope of benchmark problem

3. Strength evaluation of base metal

3.1 Fatigue strength

Calculated total strain ranges and fatigue damage factors were compared as in Fig.6 and Fig.7.

In spite that strain ranges of CEA are larger than those of JNC, fatigue damage is approximately the same. The reason is that JNC evaluates fatigue damage factors based on lower strain rate than one of CEA.

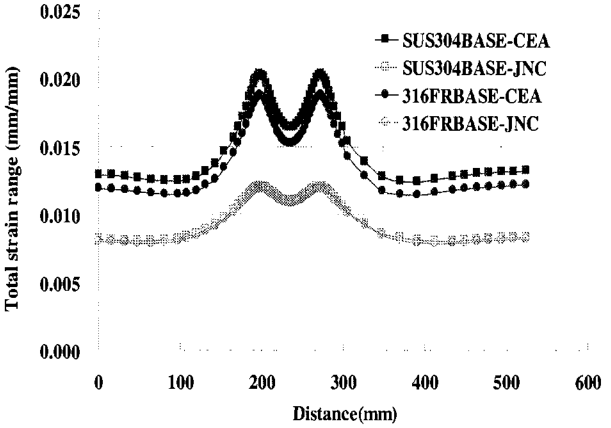


Fig.6 Comparison of total strain range

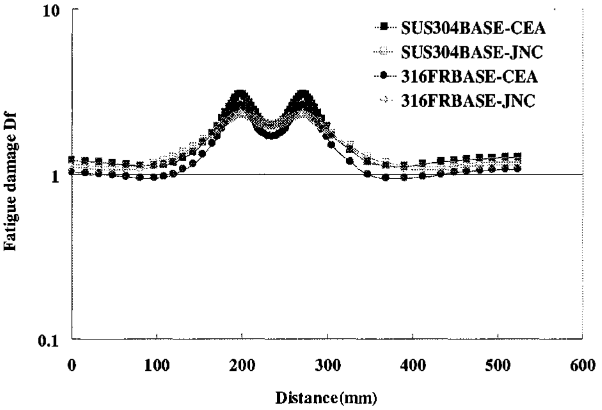


Fig.7 Comparison of fatigue damage

3.2 Creep strength

Initial stress of relaxation and creep damage factors were compared as in Fig.8 and Fig.9.

The CEA procedure evaluates higher initial stress and larger fatigue damage factor than JNC one.

Estimated creep fatigue damages were also compared with distribution of initiated cracks on the surface of the inner vessel as in Fig.10 and Fig.11. Both CEA and JNC procedures for 316FR are conservative because there are no cracks on the 316FR part.

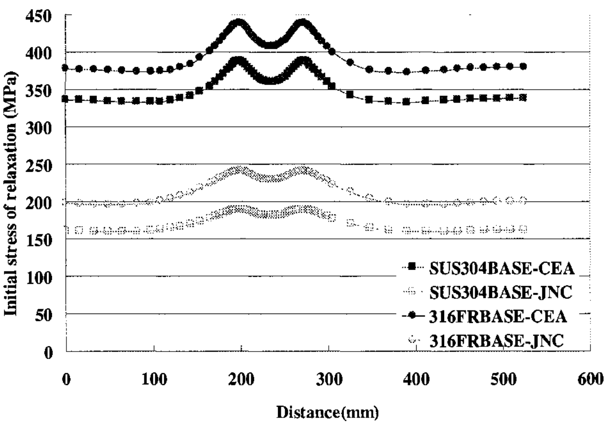


Fig.8 Comparison of initial stress

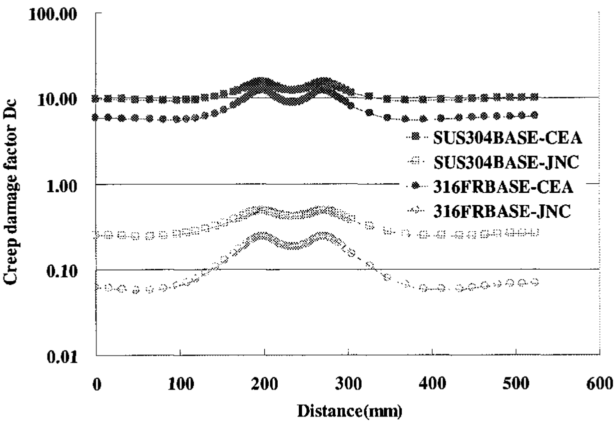


Fig.9 Comparison of creep damage factors

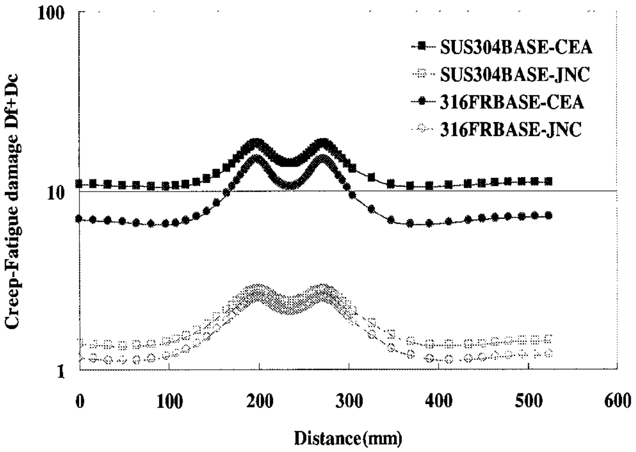


Fig.10 Comparison of creep-fatigue damage factors

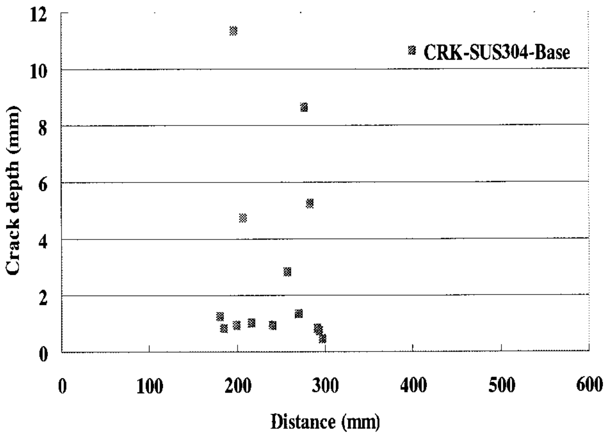


Fig.11 Distribution of crack depth at base metal

4. Strength evaluation of welded joints

4.1 Fatigue strength

Fatigue strength reduction factors, fatigue damage ratio of welded joints to base metal $(Df)_{weld}/(Df)_{base}$, and fatigue damage factor of welded joints $(Df)_{weld}$ were compared as in Fig.12, Fig.13 and Fig.14. Fatigue strength reduction factor of JNC is larger than CEA one, however, fatigue damage factors for welded joints are approximately the same.

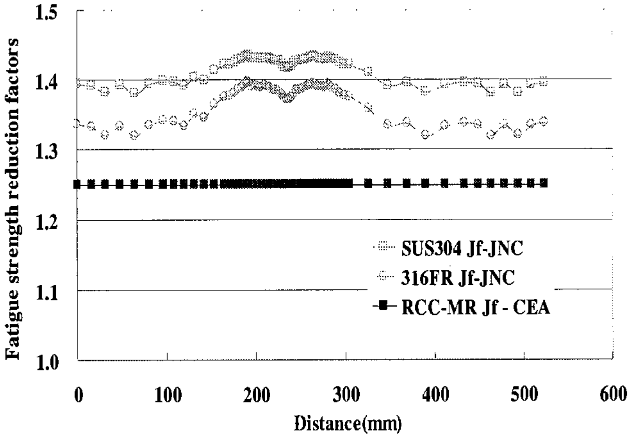


Fig.12 Comparison of fatigue strength reduction factors

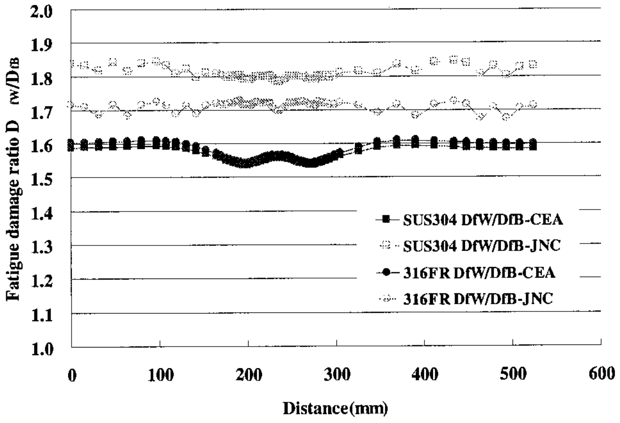


Fig.13 Comparison of fatigue damage ratio of welded joints to base metal

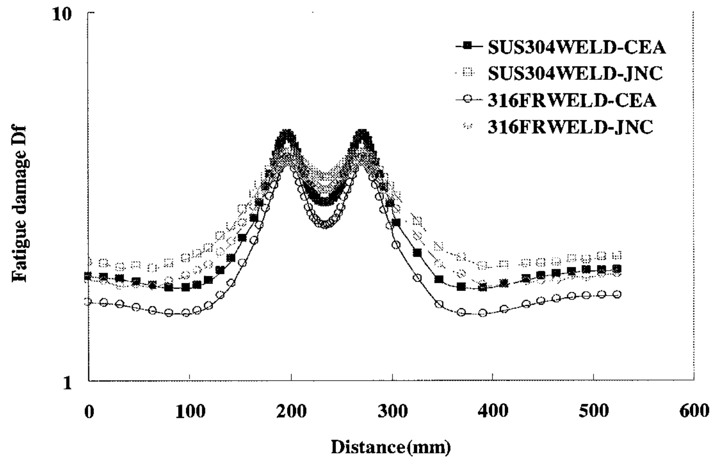
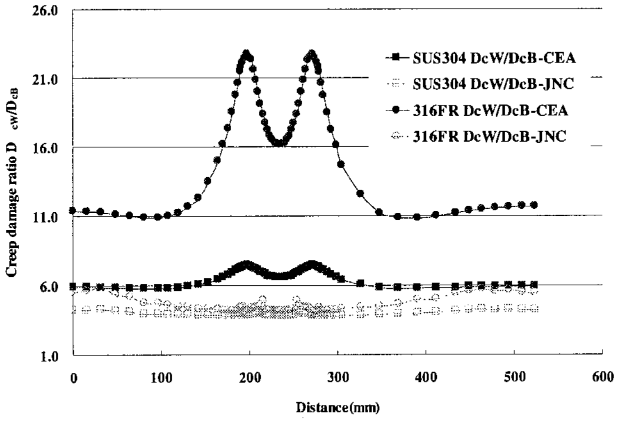


Fig.14 Comparison of fatigue damage factors

4.2 Creep strength

Since direct comparison of both methods for considering creep strength reduction is difficult, creep damage ratio of welded joints to base metal and creep damage factors were compared as in Fig.15 and Fig.16. Estimated creep fatigue damages were also compared with distribution of initiated cracks on the surface of the inner vessel as in Fig.17 and Fig.18. CEA creep strength reduction factor of welded joints to base metal is approximately equivalent to one of JNC for SUS304 and is larger than one of JNC for 316FR.



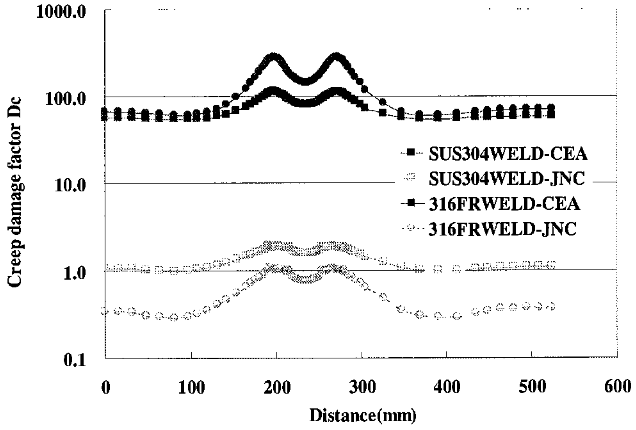


Fig.15 Comparison of creep damage ratio of welded joints to base metal

Fig.16 Comparison of creep damage factors

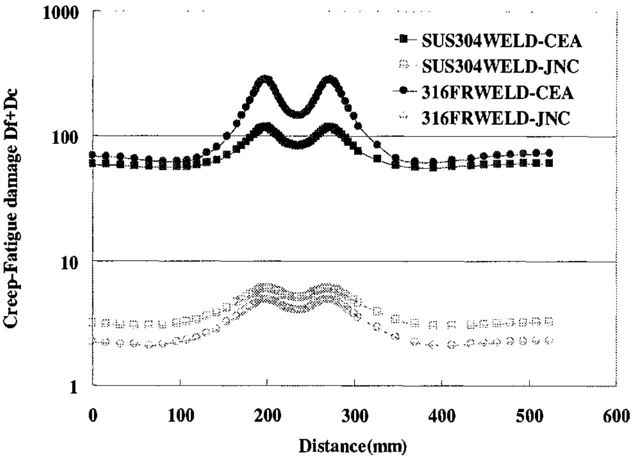


Fig.17 Comparison of creep-fatigue damage factors

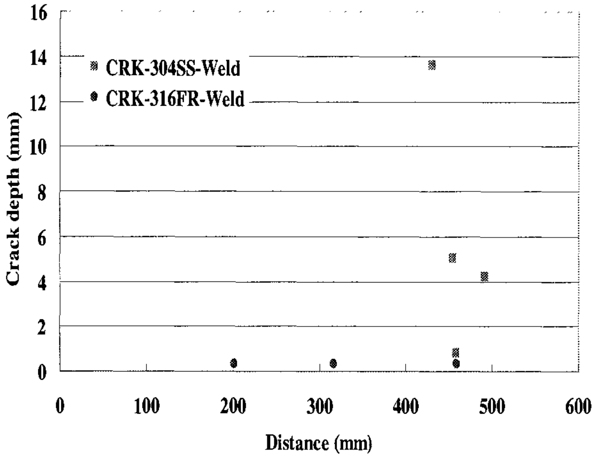


Fig.18 Distribution of crack depth at welded joints

5. Conclusions

(1) Strength evaluation of base metal

- CEA strain range was larger than JNC one due to difference of strain concentration evaluation methods. However fatigue damage factor was approximately the same between CEA and JNC, since JNC takes strain rate effects into consideration.
- CEA creep damage factor was larger than JNC one since difference of initial stress evaluation methods and elastic follow-up parameters.
- Both CEA and JNC predictions of creep-fatigue damage were conservative for 316FR. Among CEA and JNC, the former evaluated larger damage factors from difference of the creep damage evaluation method.

(2) Strength evaluation of welded joints

- CEA fatigue strength reduction factor of welded joints to base metal was a little bit smaller than one of JNC that is estimated from strain concentration factor. Both CEA and JNC predicted approximately the same fatigue damage factors.
- CEA creep strength reduction factor of welded joints was approximately equivalent to JNC 's one for SUS304 and was larger than JNC's one for 316FR. One of reasons is that yield strength difference between base and weld metals is less than γ_y=0.9 in the most of strain range of this test. Another reason is that aR=10 is adjusted factor to the weakest heat. These reasons are common with uni-axial material tests and SOUFFLE test, however, evaluation results of TTS test are considered to be more conservative than other tests. It is possible that qw caused by thermal stress is less than one of mechanical stress, even if value of is the same.
- In order to distinguish the effects of base metal approaches from those of weldments, the strength reduction factor of weldments to base metal is suitable for inter comparison. In spite of the difference in approaches, evaluated results of strength reduction factors were similar between CEA and JNC.

Acknowledgement

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