Fatigue Damage Evaluation of Welded Joints Under Thermal Stresses at Elevated Temperatures

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1. INTRODUCTION

The use of welded joints at elevated temperatures is restricted as the result of too conservative rules for the creep-fatigue damage evaluation in the structural design codes. For instance in the ASME Code Case N-47 the allowable cycles are reduced to half in the fatigue damage evaluation of SUS304 welded joints. As the result, numerous forging parts are used in place of welded joints and manufacturing costs rise up. The development of the creep-fatigue damage evaluation method for welded joints is indispensable for their extensive use at elevated temperatures. A fatigue damage evaluation method was investigated for the welded joints of vessels under thermal stresses here.

Metallurgical discontinuities are dominant in the fatigue strength reductions at the welded joints of vessels whose surfaces could be finished, although local structural discontinuities are dominant at the welded joints of pipings. In the welded joints of SUS304 with TYPE 308 weld metal fatigue strength reductions are caused by strain concentrations at the weld metal as the result of the relative softening of the weld metal to the base metal under cyclic loadings.

A combination model of two elastic-fully-plastic materials was assumed and was applicable to the structures under thermal stresses where displacements were self-controlled. Metallurgical discontinuities were represented by the difference of the yield strength. This model was examined with the structural fatigue strength data from the circumferential welded joints subjected to sodium thermal transients.

Then an attempt was performed to evaluate the fatigue strength reduction at the longitudinal welded joint of a large FBR main vessel in the vicinity of the sodium surface. The flow of the investigation is shown in Fig. 1.

2. MATERIAL TEST DATA UNDER CYCLIC LOADING

The fatigue strength of SUS304 TIG welded joints are investigated (Hasebe et al, 1989). As an example fatigue strength data of the welded joints and the weld metals at 550°C are shown together with the average trend curve of the base metal in Fig. 2. Reductions of the strength are observed in the welded joints but not in the weld metals.

An example of the stress ranges of the base metal and the weld metal varying with the number of cycles is shown in Fig. 3. At the initial stage the weld metal is harder than the base metal but because of the cyclic softening of the one and the cyclic hardening of the other, the base metal becomes harder than the weld metal.

It is found from the material test data that fatigue strength reductions of SUS304 TIG welded joints result from the strain concentration at the weld metal part due to the relative softening of the weld metal to the base metal under cyclic loadings.

3. METALLURGICAL DISCONTINUITY MODEL

3.1 Assumption of the model

Welded joints are considered as a combination of the base metal, the weld metal and the heat affected zone. For simplicity a welded joint was assumed to be a combination of two materials with different inelastic properties where the effect of the heat affected zone was considered as the increase of the metallurgical discontinuities.

In the inelastic analyses for the fatigue damage evaluation, the elastic-fully-plastic model is generally used because conservative estimations of strain ranges are required. The authors established a combination model of two elastic-fully-plastic materials which was applicable to the structures under thermal stresses where displacements were self-controlled. In this model metallurgical discontinuities were described only with the difference of the yield strength.

3.2 Examination with the structural strength data

The most important parameter of the two elastic-fully-plastic materials model would be the yield stress ratio. The authors tried to determine the yield stress ratio with the structural fatigue strength data under thermal stresses which had been performed at OEC, PNC.

Those fatigue strength data were acquired at Sodium Piping Thermal Transient Test Loop (SPTT). Test specimens were composed of SUS304 pipes butt welded with the TIG welding. Fig. 4 shows the profile of the specimen, whose maximum diameter and thickness are 93mm and 13mm, respectively.

Thermal transient tests were performed with the alternative flow of hot and cold sodium. The hot sodium temperature was 550°C and the temperature differences were 200°C, 250°C and 300°C. The period of a cycle was 10min and the flow rate was 730 mm/sec. An example of the sodium temperature varying with the time is shown in Fig. 5.

Crack initiation cycles were acquired as the strength data both at the base metal part and at the welded joint. The crack initiation cycle was estimated from the striation spacings measured at 0.5mm pitch along the crack length.

3.3 Determination of the yield stress ratio

Strain ranges were estimated from the crack initiation cycles using the fatigue strength curve of the base metal because the fatigue strength of SUS 304 base metal was nearly equal to that of TYPE 308 weld metal. Then the ratio of the strain range at the welded joint to that at the base metal part was obtained from the same specimen.

On the other hand the relation between the yield stress ratio and the strain range ratio was obtained from the inelastic parameter analyses. In these analyses local structural discontinuities due to weld bead configurations were not considered because the strength reductions due to them were considered as the increase of metallurgical discontinuities.

Test results are plotted on the curve obtained from the FEM analyses in Fig. 6. Some of the data reveal no reductions of the strength and they are plotted as γ_y equals 1.0. The authors decided that γ_y was 0.8 because most of the data existed where γ_y was not less than 0.8. The value 0.8 was adopted as the yield stress ratio in the following analyses.

4. EVALUATION OF THE LONGITUDINAL WELDED JOINT OF A LARGE FBR MAIN VESSEL

4.1 Analysis method

A large FBR main vessel receives thermal transients of the coolant sodium and abrupt gradients in the axial temperature distribution occur in the vicinity of the sodium free surface. As the result, strain concentrations arise there and they are enhanced by metallurgical discontinuities at the longitudinal welded joint.

The general view of the structural model is shown in Fig. 7. Although the configuration was axisymmetric, 3-dimensional analyses were needed because of the metallurgical discontinuity at the welded joint. The reference conditions are listed in Table 1. The temperature dependency of material properties were not considered in the stress analysis for simplicity.

Temperature analyses were performed with the axisymmetric model until the temperature distribution became steady. The elastoplastic analyses were performed two cycles to obtain the closed loop of the stress strain hysteresis curve. These analyses were performed using the FINAS code.

4.2 Analysis results

The strain range was defined as the sum of the elastic strain component and the plastic strain component. The total strain range ε_t is expressed as the following equation.

$$\varepsilon_t = \sigma / E + \varepsilon_p \tag{1}$$

In the equation σ and ε_p mean Mises' type equivalent stress range and equivalent plastic strain range, respectively. E means Young's modulus.

Strain ranges were computed from the differences of strain ingredients between the two extreme points of the time which were determined to present the maximum value of the strain range. The strain range distributions along the axial direction are presented in Fig. 8. The maximum strain range along the axial direction is found to occur about 100 mm below the sodium surface.

The analysis where the yield stress of the base metal was reduced to half as against the reference condition was performed to grasp the behaviors more clearly. The strain concentration behaviors are shown in Fig. 9. The vertical axis means the equivalent strain increment normalized by twice the yield strain. The horizontal axis means the equivalent stress increment obtained from the elastic analysis normalized by twice the yield stress. The equivalent stress and strain increments were computed based on the difference from one of the extreme points. Strain increments begin to increase abruptly at the weld metal's yield. After the base metal's yield, the growth rate of the strain increment reduces outside but not inside because of the bending component of the circumferential strain.

4.3 Evaluation of strain concentration

Generally inelastic strain concentrations at the structural discontinuities present elastic follow-up type behaviors. The elastic follow-up parameter q is defined as the following equation.

$$q = \triangle \varepsilon_p / \{ (\triangle \sigma_{EL} - \triangle \sigma) / E \} \tag{2}$$

In the equation $\Delta\varepsilon_p$, $\Delta\sigma$ and $\Delta\sigma_{EL}$ mean the equivalent plastic strain increment, the equivalent stress increment and the equivalent stress increment in the elastic analysis, respectively.

The stress range in the elastic-fully-plastic model equals twice the yield stress. The yield stress at the welded joint becomes γ_y times the base metal yield stress σ_y . Assuming that behaviors at the welded joint are elastic follow-up type, the total equivalent strain increment $\Delta\varepsilon$ is described by with the following equation.

$$\Delta\varepsilon=\{1+(q-1)\cdot(1-\gamma_y\cdot 2\sigma_y/\Delta\sigma_{EL})\}\cdot\Delta\sigma_{EL}/E \qquad (3)$$

The behavior of the strain increment estimated with eq. (3) is expressed as a straight line in Fig. 9. This line has a slope q and originates from the point (γ_y, γ_y). The lines of q=3 are drawn as the chained line in the figure. It is found from the figure that the strain concentration at the welded joint could be evaluated using the elastic follow-up model and the maximum value of the elastic follow-up parameter q is 3.0.

5. CONCLUSION

Metallurgical discontinuities at the welded joints could be represented by the yield stress ratio of the combination model of two elastic-fully-plastic materials and its value was about 0.8. The longitudinal welded joint of a main vessel in the vicinity of the sodium surface was analysed with use of this result. Strain concentration behaviors at the welded joint could be evaluated using the elastic follow-up model and the maximum value of the elastic follow-up parameter was 3.0.

REFERENCES

Hasebe, S., et al. (1989). Creep and Fatigue Strength Evaluation of SUS304 Welded Joints. Proc. 27th Symposium on Strength of Materials at High Temperatures, JSMS

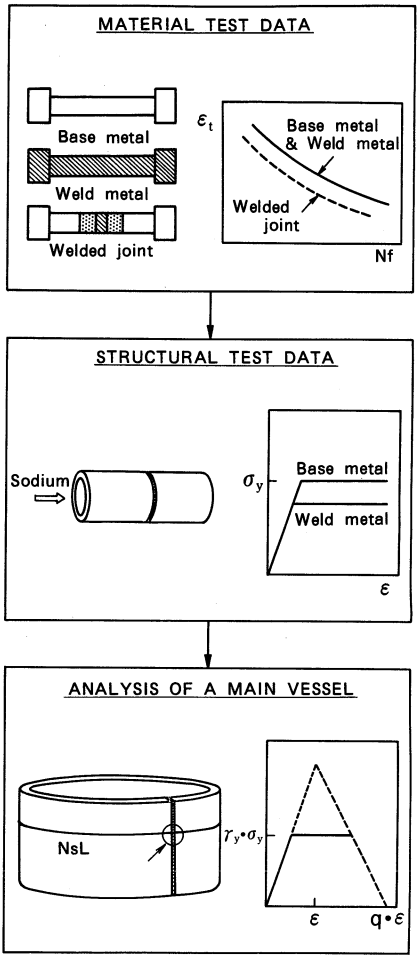

Fig. 1 Flow of investigation

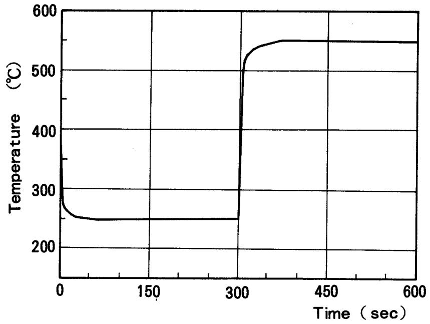

Fig. 5 An example of the sodium temperature history

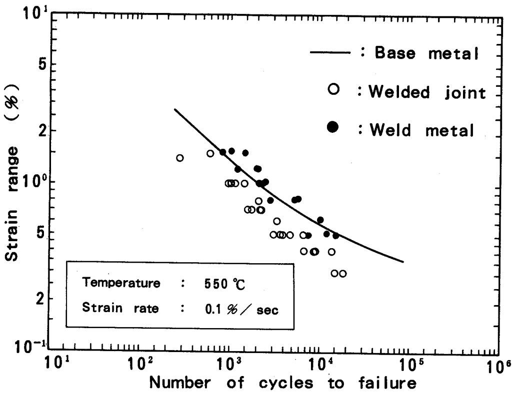

Fig. 2 Uniaxial fatigue strength data

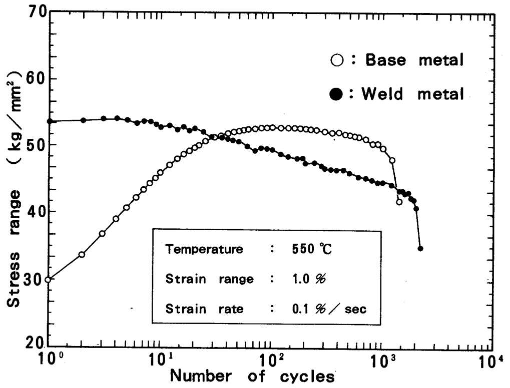

Fig. 3 Stress range history with number of cycles

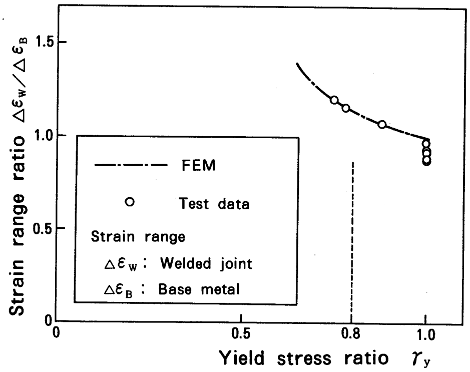

Fig. 6 Estimation of yield stress ratio γ_y

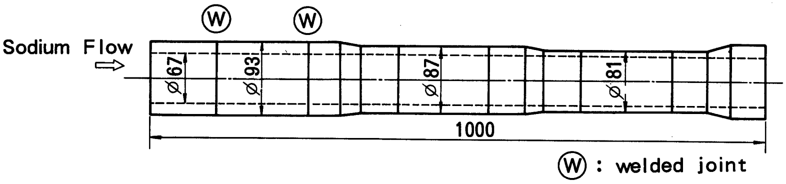

Fig. 4 Profile of circumferential welded joint specimen

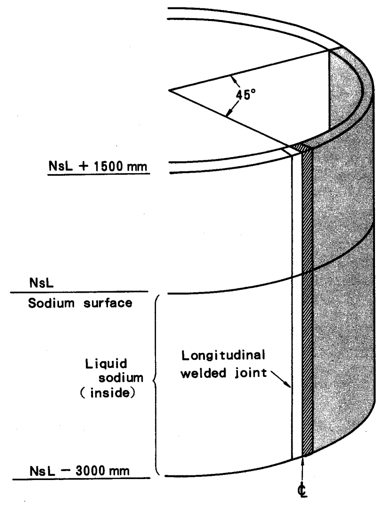

Fig. 7 General view of the main vessel model.

Table 1 Reference conditions

Dimensions	Diameter Thickness Height (Top) Height (Sodium surface) Width of welded joint	17 m 50 mm 4.5 m 3 m 10 mm
Loadings	Sodium temperature (Hot) Sodium temperature (Cold) Temperature up-down rate	510 ℃ 200 ℃ 20 ℃/hr
Boundary Conditions	Film coefficient, (Sodium) Film coefficient (Others) Top temperature Sodium surface Displacement	500 kcal/m² hr ℃ Insulated 50 ℃ Fixed Free
Material Properties	Base metal yield stress Yield stress ratio Young's modulus Poisson's ratio Expansion (Average)	16.1 kg/mm² 0.8 16100 kg/mm² 0.3 18.12 × 10⁻⁶ 1/℃

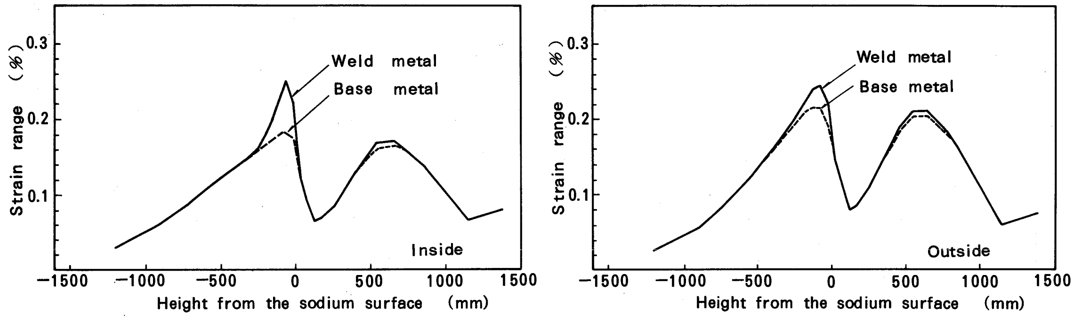

Fig. 8 Axial distribution of the strain range.

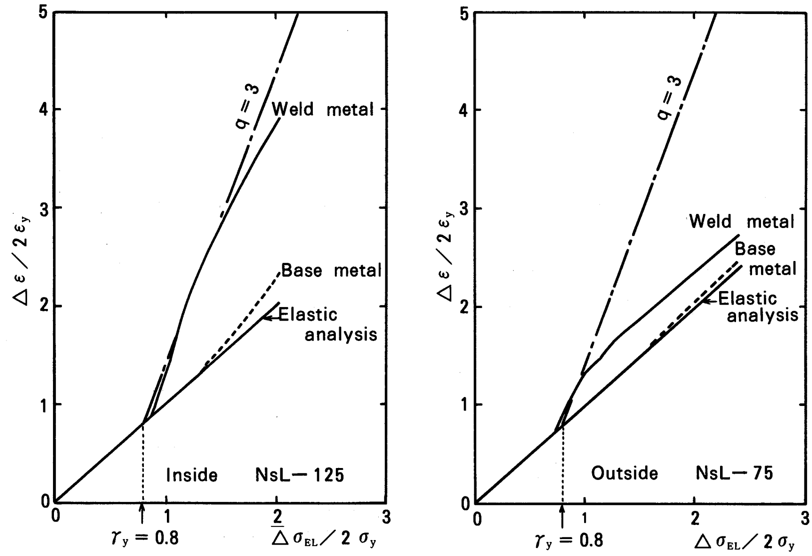

Fig. 9 Strain concentration behaviors (σ_y = 8.05kg/mm^2)