Proposal of a Strain Concentration Model of Welded Joints for Creep-Fatigue Evaluation of Welded Structures*

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As the main causes of strength reduction in welded joints subjected to cyclic thermal transients, attention was given to (1) metallurgical discontinuity in which different deformation responses of base metal and weld metal can result in nonuniform stress and strain across the weldment, (2) peak strain concentration at penetration beads of unfinished welded joints, and (3) degradation of weld metal due to precipitation of dissolved metal. In order to evaluate the first two factors, an elastic follow-up model was applied. Thermal transient strength test results verified that the elastic follow-up model ensures adequate life in elevated-temperature component weldments. The proposed method was proven to be adequate in Type 304 SS, and to have safety margin in FBR grade Type 316 SS.

Key Words: Welded Joint, Structural Analysis, Creep-fatigue, Elastic Follow-Up, Metallurgical Discontinuity, Strain Concentration

1. Introduction

Generally fatigue and creep-fatigue strength of welded joints are lower for the base metal. Therefore, in the conventional structural design, the fixed coefficients which conservatively envelope the test data was widely used for evaluating the strength reduction^{(1),(2)}. On the other hand, a demand of economical efficiency and improvement of reliability of the recent structural design would require precious evaluation methods considering the strength degradation mechanism of welded joints⁽³⁾.

From such requirement, authors studied the creep-fatigue evaluation method of welded joints from such viewpoints of (1) metallurgical discontinuity among weld metal and base metal, (2) peak strain concentration due to penetration beads of the weld

metal, and (3) degradation of weld metal itself (Fig. 1).

The strength of TYPE 304 SS/Type 308 SS welded joints test piece broached transversely from bead was lower than one with TYPE 304 SS base metal and Type 308 SS weld metal, when the displacement control type fatigue test is carried out at 550°C⁽⁴⁾.

From this result, metallurgical characteristics discontinuity between weld metal and base metal is considered as a factor of the strength reduction of the welded joints. Then, the yield stress of the weld metal was small compared with the base metal in most part

Fig. 1 Main factors of fatigue strength reduction of welded joints

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in the life, when the hysteresis of stress range under the displacement control type fatigue test was observed⁽⁴⁾.

In addition, creep-fatigue strength of welded joints was predicted in the equivalent accuracy to base metal, when they evaluated the strain of the weld metal by considering the sharing proportion of the strain of soft weld metal and stiff base metal, and put this together with linear damage rule⁽⁵⁾. From these results, the factor in which creep-fatigue strength of the TYPE 304 SS welded joints lowers for the base metal seems to be the strain concentration to the soft region which originates from the difference in base metal and weld metal of the yield stress (the cyclic stress-strain relation), namely metallurgical discontinuity. In actual welded joints in the structures, finish of the joint surface are sometimes insufficient or not made, and there exist many cases that geometric peak strain concentration at penetration beads, etc. become origins of the crack initiation. In such case, it is necessary to consider the strain concentration in addition to metallurgical discontinuity. Furthermore, the followings are mentioned as a strength degradation factor except for the superscription: mesoscopic strain concentration in the welding pass boundary surface, residual stress in the bond part, minute strain concentration by the precipitation of the additive rare metal under high-temperature service, and lowering of the ductility, etc.. In the current, a strength reduction factor on the basis of the test data seems to be the validness for the factor on such degradation of weld metal, since it is complicated and there are many unclear points.

In this study, authors propose a strain concentration model considering the mechanism of welded joints in the structure, focusing on factor (1) and factor (2) which were mechanical factors, and applied it to the creep-fatigue evaluation of the welded structures.

2. Model of the Strain Concentration due to Metallurgical Discontinuity

2.1 Strain concentration evaluation by an elastic follow-up model

In low rigid portions of structures, the creep-fatigue strength reduction occurs, by strain concentration and by the lowering of the stress relaxation ratio with elastic-follow-up mechanism, when plasticity or creep deformation occurs in the material. Elevated temperature structural design codes of Liquid Metal Fast Reactors can predict actual strain range ε_t from elastic analysis results such as stress range $\Delta\sigma_e$ and strain range ε_e by using elastic follow-up parameter q (the definition is described in Fig. 2) which shows the

Fig. 2 Strain evaluation method based on elastic follow-up model

structure proper strain redistribution characteristics and yield stress σ_y according to the following equation⁽⁶⁾.

$$\varepsilon_t = \left\{ 1 + (q-1) \left(1 - \frac{2\sigma_y}{\Delta\sigma_e} \right) \right\} \varepsilon_e \quad (1)$$

2.2 Consideration of the yield stress reduction in the weld metal

The reduction of yield stress causes the stress range decrease and increase of the strain range in weld metal under cyclic loadings. Tanigawa et al. introduced coefficient γ_y which shows the yield stress ratio of weld metal and base metal like the Fig.2 broken line for Eq.(1) from the viewpoint of the behavior of such weld metal⁽⁴⁾. 0.8 is proposed as a concrete γ_y value on welded joints by the combination of TYPE 304 SS base metal and Type 308 SS weld metal.

$$\varepsilon_t = \left\{ 1 + (f_w q - 1) \left(1 - \gamma_y \frac{2\sigma_y}{\Delta\sigma_e} \right) \right\} \varepsilon_e, \quad (2)$$

$\gamma_y = 0.8$

2.3 Strain concentration model considering metallurgical discontinuity

Strain concentration according to the general structural discontinuity and effect of metallurgical discontinuity are overlapped, when there was welded joints in actual structures. Literature⁽⁴⁾ evaluates both effects by multiplying " q " which describes the former and design factor " $f_w = 1.5$ " which show latter together. In this study, authors propose a mechanical model of the strain concentration for welded joints, where metallurgical discontinuity and convolution mechanism of the general structural discontinuity are evaluated with an elastic follow-up model⁽⁷⁾. For the model which combined the different elastic-plastic material like Fig. 3(A), the following equation is established, when assuming Ramberg-Osgood type equation, which can conveniently express stress-strain relationship without hurting the essence of

Fig. 3 Elastic follow-up model considering metallurgical discontinuity

stress-strain redistribution by elastic follow-up.

$$l_1 \varepsilon_1 + l_2 \varepsilon_2 = \delta \quad (3)$$

$$\varepsilon_1 = \sigma_1 / E_1 + A_1 \sigma_1^n \quad (4)$$

$$\varepsilon_2 = \sigma_2 / E_2 + A_2 \sigma_2^n \quad (5)$$

When substituting Eq.(4) and Eq.(5) into Eq.(3) by consideration of equilibrium of force: $\sigma_1 = \sigma_2$.

$$\frac{\sigma_1}{E_1} = - \left[\frac{1 + (A_2/A_1)(l_2/l_1)}{1 + (l_2/l_1)(E_1/E_2)} \right] A_1 \sigma_1^n + \frac{\delta}{l_1 + l_2(E_1/E_2)} \quad (6)$$

When substituting Eq.(6) for Eq.(2)

$$\varepsilon_1 = - \left[\frac{1 + (A_2/A_1)(l_2/l_1)}{1 + (l_2/l_1)(E_1/E_2)} - 1 \right] A_1 \sigma_1^n + \frac{\delta}{l_1 + l_2(E_1/E_2)} \quad (7)$$

Assuming $A_1 = A_2 = 0$, elastic solution for ε_1 is obtained as ε_{1e} .

$$\varepsilon_{1e} = \frac{\delta}{l_1 + l_2(E_1/E_2)} \quad (8)$$

From Eq.(6), Eq.(7), and Eq.(8), elastic follow-up parameter q_w for metallurgical discontinuity is calculated as Fig. 4 and it shows that q_w depends on material properties and width of weld metal⁽⁹⁾.

$$q_w = \frac{\varepsilon_1 - \sigma_1/E_1}{\varepsilon_{1e} - \sigma_1/E_1} = \frac{1 + (l_2/l_1)(E_1/E_2)}{1 + (A_2/A_1)(l_2/l_1)} \quad (9)$$

In addition, it is possible to evaluate welded joints in some structural discontinuous, by the model in which metallurgical discontinuity is overlapped like Fig. 3(B) to elastic follow-up system (can be supposed to describe at elastic follow-up parameter q). Its convolution behavior can be described by a serial elastic follow-up model⁽⁹⁾ which authors propose, and it becomes next way.

$$\varepsilon_t = \{1 + (q_w \cdot q - 1) \left(1 - \gamma_y \frac{2\sigma_y}{\Delta\sigma_e}\right)\} \varepsilon_e \quad (10)$$

Where q : elastic follow-up parameter except for the welding, q_w : elastic follow-up parameter for metallurgical discontinuity, γ_y : weld metal yield stress divided by base metal yield stress, σ_y : base metal

Fig. 4 Elastic follow-up parameter q_w of circumferential welded joints of cylinders due to bending stress

Fig. 5 Predicted strain concentration factors considering metallurgical discontinuity

yield stress, $\Delta\sigma_e$: stress range by the elastic analysis.

2.4 Verification of strain concentration model for metallurgical discontinuity

In the case of circumferential welded joints of cylinders due to the temperature gradient in plate thickness, which is typical thermal loading, the accuracy of metallurgical discontinuity strain concentration model was verified by comparing Eq.(10) with the inelastic analysis result by FEM. The relationship between elastic follow-up parameter q_w for TYPE 304 SS welded joints and weld metal width normalized by plate thickness (t/W) is shown in Fig. 4. Strain concentration factor $K_e (= \varepsilon_t / \varepsilon_e)$ predicted by Eq.(10) with elastic follow-up parameter q in Fig. 4 were compared with inelastic F.E. calculated results on various dimensionless stress intensity ($S_n / 2\sigma_y$) as Fig. 5. It is proven that strain concentration factors for each joint width evaluated by Eq.(10) are appropriate.

3. Strain Concentration Model for Metallurgical Discontinuity and Peak Strain Concentration

3.1 Consideration of both metallurgical discontinuity and peak strain concentration

At unfinished welded joints in actual structures, peak strain concentration occurs by (1) penetration beads, (2) counter bore processing, and (3) shrinkage of the weld line, etc. In order to examine the effect of these peak strain concentration, elastic stress concentration factor of welded joints in the structural test models for TTS of Oarai Engineering Center was examined. The TTS can enforce thermal transient stresses to about 2 m height structural models, until the creep-fatigue cracks are generated, by repeatedly pouring the liquid metal sodium of high temperature and low temperature. The following are shown in Fig. 6: Thermal transient test result and elastic stress concentration factors of weld zone in the reactor vessel type model⁽¹⁰⁾. Still, stress concentration factors were calculated from the ratio between nominal stress and peak stress which removed the thermal peak stress from the surface stress by the linearization technique.

From these investigations, it was proven that unfinished welded joints have elastic stress concentration factors approximately within $K=1.0\sim 2.5$, and averagely have the concentration factor of about $K=1.3$. And, it seems to be reducing the strength in unfinished welded joints by the convolution of (1) metallurgical discontinuity and (2) peak strain concentration, since the origin of the crack is observed in the stress concentration zone like Fig. 6⁽¹¹⁾. Here, (2) peak strain concentration is the very local behavior at the plate surface, while elastic follow-up phenomena between (1) metallurgical discontinuity and nearby structure is gross deformation behavior which reaches the whole plate thickness.

Fig. 6 Stress concentration factors at welded joints in a vessel model

From this fact, authors propose convolution evaluation model of metallurgical discontinuity and peak strain concentration for welded joints like Fig. 7, by applying the parallel elastic follow-up model which can evaluate the convolution of gross deformation (Ke'_G and local strain concentration (KKe'_L) of the general structural discontinuities by both multiplication⁽⁹⁾.

Strain concentration factor which estimates peak strain ϵ_t of the weld zone from nominal strain ϵ_e by the elastic analysis becomes a following equation, when elastic follow-up parameter of the local field behavior is made to be q_K and Eq.(10) describe the gross behavior.

$$\begin{aligned}\epsilon_t &= KKe'_L Ke'_G \epsilon_e \\ Ke'_L &= \left\{ 1 + (q_K - 1) \left(1 - \gamma_y \frac{2\sigma_y}{K\Delta\sigma_e} \right) \right\} \\ Ke'_G &= \left\{ 1 + (q_w - 1) \left(1 - \gamma_y \frac{2\sigma_y}{\Delta\sigma_e} \right) \right\}\end{aligned}\quad (11)$$

Strength reduction factors for welded joints predicted by Eq.(11) are shown in Fig. 7. As elastic follow-up parameter for peak strain concentration here, authors give the following equation for elastic follow-up parameter q_K in giving elastic stress concentration factor K , since both of analogy⁽⁹⁾ from Neuber's rule and estimation from the J integral⁽¹²⁾.

$$q_K = K^{\frac{n-1}{n+1}} \quad (12)$$

3.2 Comparison among the proposed method and F. E. analysis

In order to confirm validity of Eq.(11), peak strain concentration factors were estimated on unfinished welded joints of various joint width J_i which takes up the metallurgical discontinuity and stress concentration factor K . In making J_i ($i=1, 2$,

Fig. 7 Elastic follow-up model considering metallurgical and geometrical discontinuities

Fig. 8 Welded joint model with metallurgical and geometrical discontinuities

Fig. 9 Predicted strain concentration factors considering metallurgical and structural discontinuity

3) to be a parameter, prediction by Eq.(11) was compared with the inelastic analysis by FEM. With changing joint width changes, it is possible to make the relative position in weld metal and base metal boundary for peak strain concentration to be a parameter. On stress concentration factor K , the shape as $K = 1.0 \sim 3.0$ was chosen. Strain concentration factors $K_\epsilon (= \epsilon_i / \epsilon_e, \text{ stress intensity } S_n = 2.5 \times 2\sigma_y)$ were compared with predictive value by the FEM analysis as shown in Fig. 9. It is observed that the FEM analytical results also increase on strain concentration factor, as stress concentration factors increase from 1 to 3. And, on weld metal and base metal boundary location, strain concentration factor becomes a maximum in case of J_1 , and it decreases in the order J_2 and J_3 . Eq.(11) was able to be verified to be appropriate as a design evaluation method, because predictive value is the degree in which stress concentration factor surpasses the value of J_1 a little in the range from 1 to 3.

4. Welded Structure Strength Evaluation Method and Verification by Thermal Transient Test

4.1 Creep-fatigue strength evaluation procedure of welded structures

In this study, authors propose creep-fatigue strength evaluation procedure of welded joints in the structures like Fig. 10, using strength reduction evaluation equation (11) based on strain concentration model with a Linear damage rule. It is strain concentration evaluation parts proposed in this study that the hatching division in the figure.

An unique point of this procedure is that strain range is estimated from imaginary stress range $\Delta\sigma_e$ and strain range ϵ_e calculated by the elastic analysis, based on strain concentration factor considering metallurgical discontinuity and peak strain concentration in actual welded joints.

Here, metallurgical discontinuity between base

Fig. 10 Creep-fatigue evaluation procedure of welded joints

metal and weld metal is not clear in creep than in plasticity⁽⁵⁾, however, this procedure assumes conservatively identical. And, the convolution with reduction factor K_{ϵ_0} considering the degradation of weld metal⁽¹³⁾ is taken into account. In addition, it considers the form of the residual stress by thermal transient stress⁽¹⁴⁾ in the prediction of initial stress of relaxation.

Values in Fig. 10 is the followings, ϵ_e : strain range, N_f : allowable number of cycles in proportion to strain rate, N : load number of cycles, i : suffix which shows the point of time in which thermal transient stress becomes a maximum, $t_R(\sigma)$: creep rupture time of this temperature for stress σ , q_{EFF} : elastic follow-up parameter for the stress relaxation evaluation considering the convolution of q_k , q and q_w ⁽⁸⁾, D_f : fatigue damage factor, D_c : creep damage factor, D : Creep-fatigue damage factor.

4.2 The applicability of proposed creep-fatigue strength evaluation method

Firstly applicability of proposed creep-fatigue strength evaluation is verified on finished welded joints in which there is no peak strain concentration. For this purpose, thermal transient strength test have been conducted on a welded vessel model under cyclic thermal transient stresses⁽¹⁵⁾. The test model is vessel type which incorporated welded joints in here, as

Fig. 11 Welded vessel model for thermal transient strength test

Fig. 12 Observed creep-fatigue cracks on the vessel model

shown in Fig. 11, and it has inner vessel in the inside. Outside container and half of the structure of inner vessel are TYPE 304 SS on the material, and they are 316 FR low carbon nitrogen for Liquid Metal Fast Reactors the remainder half. Thermal transient stress was given by repeatedly pouring 1 055 cycles sodium of 600°C and 250°C from the upper nozzle of the test specimen in annulus space between inner vessel and outside container. And, the creep damage would be applied by holding time for 2 hours in 600°C condition. Initiated cracks on the surface of the inner vessel observed by the liquid flow detection test (PT) after the test is shown in Fig. 12. In the 316 FR division of inner vessel, microcracks were found only at a part of welded joints, while many cracks were observed to both of welded joints and base metal in the SUS 304 parts. And, the cracks at welded joints were observed to be deeper than that of the nearby

Fig. 13 Evaluated creep-fatigue damage of finished welded joints on the vessel model (SUS304)

Fig. 14 Evaluated creep-fatigue damage of finished welded joints on the vessel model (SUS316FR)

base metal. In the evaluation flow of Fig. 10, $q=5/3$ is adopted because the main loading is a temperature distribution in plate thickness⁽¹⁶⁾. And, though 316 FR welded joints have been designed so that the difference of base metal and weld metal may decrease, the evaluation flow of Fig. 10 uses the identical yield stress reduction factor for 316 FR welded joints with TYPE 304 SS ones, since there is no existing γ_y and q_w which describes metallurgical discontinuity of 316 FR in the current. On finished welded joints of the welded vessel model, the result of plotting the relationship between creep-fatigue predicting damage by the evaluation method of Fig. 10 and crack data of the TYPE 304 SS part got in the experiment is shown in Fig. 13. And, the result of the 316 FR part is similarly shown in Fig. 14. Both figures have also shown crack initiation regions which are the outside of the continuous lines. These results showed that the crack initiation prediction position in TYPE 304 SS agreed with actual crack initiation region and that it carries out the appropriate evaluation. In 316 FR, both of welded joints and base metal had the position which had predicted the crack initiation per the crack unoccurrence

Fig. 15 Evaluated creep-fatigue damage of unfinished welded joints on the vessel model

division, and it was proven that the margin of safety is included for the evaluation method. This reason seems to be that 316 FR has designed so that the difference of base metal and yield stress of the weld metal may become smaller than TYPE 304 SS^{(17),(18)}.

Next, unfinished welded joints shown in Fig. 6 was evaluated in order to examine the applicability of the flow of Fig. 12 to the welded structure in which peak strain concentration is overlapped in metallurgical discontinuity. In Fig. 15, the horizontal axis is a distance along the surface of the photograph of unfinished welded joints shown in the figure. The vertical line serves as two meaning, and one is crack depth (CRACK). There is respectively cracks of the depth of 27 mm and 16 mm in peak strain concentration position in the horizontal axis position of 67 mm and 85 mm, and the microcracks of about 1 mm are distributed in the peripheral part. Another meaning of the vertical line is the creep-fatigue damage value. Creep-fatigue damage (BASE) estimated by the evaluation method for the base metal is about 1.3.

Its value corresponds to cracks of the depth of 1 mm in the case of past thermal transient test data⁽¹⁶⁾, therefore, the microcracks of about 1 mm distributed in the peripheral part can be explained by the proposed method.

In addition, the damage value becomes 2.8, when evaluation of welded joints only considering metallurgical discontinuity is done (MET), and these values may not deal with the cracks over 10 mm observed at 2 places, since it is correspondent to the crack initiation of about several mm from the experience in a past. When considering peak strain concentration in addition to metallurgical discontinuity (MET+GEO), damage value of two deep cracks exceeds 6, and its values are correspondent to deep cracks. From above results, it was confirmed that the creep-fatigue strength of the unfinished welded joint was predictable by considering both peak strain concentration and

metallurgical with the flow of Fig. 10.

5. Conclusions

In order to evaluate the strain concentration caused from metallurgical discontinuity of base metal and weld metal which is one of the main factors of the creep-fatigue strength reduction, authors have proposed a strain concentration model based on a elastic follow-up model, which is used in elevated temperature structural design code for Liquid Metal Fast Reactors.

For unfinished welded joints, the strain concentration model considering peak strain concentration in addition to metallurgical discontinuity was newly proposed in this study, since peak strain concentration such as penetration beads become the main strength degradation factor. The prediction accuracy of the strain concentration model was verified by the comparison with the elasto-plastic analysis results by FEM. Furthermore, a creep-fatigue strength evaluation method of welded structures based on the strain concentration model was proposed, and its applicability was comparatively confirmed using short term thermal transient test data. Still, degradation of weld metal may become strength reduction factor in the high temperature and long time conditions⁽¹³⁾. The proposal will be also carried out on the evaluation method on this factor in future.

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