Creep Characteristics in Thick Welded Joints and Their Improvements (Report II)[†]

— Applicability of a Simple Model for Creep Analysis of Thick Welded Joints —

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Abstract

Reliable predictions of the creep behavior of thick welded joints are very important to secure the safety of elevated temperature vessels like nuclear reactors. Creep behavior is very complex, thus it is difficult to perform the experiment and conduct the theoretical analysis.

A simple accurate model for theoretical analysis was developed in the first report. The simple model is constructed of seven one-dimensional finite elements which can analyze not only one-dimensional stress creep behavior but also the three-dimensional situation. The simple model is verified by comparing the analyzed results with the experimental ones in this report. The model is easy to treat, and needs only a little labor and computation time to predict the creep curve and the local strain for a thick welded joint.

KEY WORDS : (Creep Test) (Thick Welded Joint) (Theoretical Analysis) (Simple Mathematical Model) (One-Dimensional FEM) (Three-Dimensional Creep Behavior) (Stress-Relief Annealing)

1. Introduction

Reliable predictions of the creep behavior of thick welded joints are very important to secure the safety of elevated temperature vessels like nuclear reactors. The thick welded joint experiences a complex thermal history. Its material properties including creep are very complicated and are significantly different, depending on the location. So the creep behavior of a thick welded joint is very complex.

In this study, for the thick welded joint of a nuclear reactor, etc., the creep behavior to rupture, which is important as one of the limit capacities of the joint, is analyzed by theoretical calculation and by experiment. Based on the results, the desirable material properties and welding methods are investigated to improve the creep capacities (the creep strain rate, the life time, etc.) of the joint, considering the control of the metal structure. In the first report[1], to achieve these aims rationally and efficiently, a simple mathematical model based on FEM was developed, capable of simulating accurately the creep behavior of the

thick welded joint. The structure and the theory of the simple model were explained. In this report, the simple model is verified by comparing the analyzed results with the experimental ones. The applicability and the degree of multi-axial stress state of the model are investigated. In relations with them, the effect of stress-relief annealing is discussed.

2. A Simple Mathematical Model for Creep Analysis of A Thick Welded Joint

2.1 Thick welded joint for analysis

The thick joint produced by multi-layer butt welding and the extracted test specimen, for this study, are shown in **Fig. 1**[2]. The materials of the base plate and the weld metal are SUS304HP and Y308 respectively. The narrow gap of 50 mm thickness was welded by submerged arc welding using 24 passes and 13 layers. The specimen with a 10 mm width was cut out from the joint. The load acts on the specimen in the direction (X-direction) of the perpendicular to the weld line.
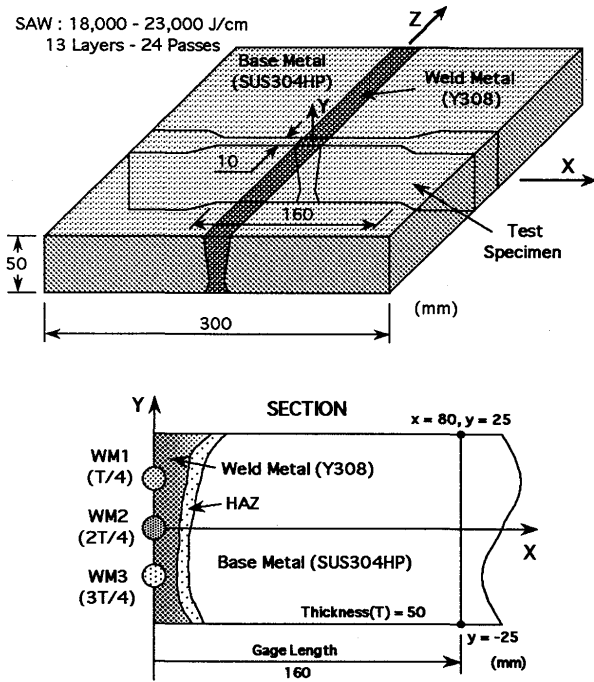
Fig. 1 Thick welded joint and its creep test specimen

Fig. 2 Creep curves of weld metals and base metal

2.2 Structure of a simple model

The creep properties of the weld metal and the base metal were determined in previous experiments[2]. The creep behaviors are significantly different, depending upon the location. Figure 2 shows the creep curves of the weld metals (WM1: a quarter of thickness inside from the top surface, WM2: half of thickness inside, WM3: three quarters of thickness inside, see Fig. 1) and the base metal, under the condition of 550 °C and 235 MPa of initial loading stress.

A simple model is constructed with seven one-dimensional elastic-plastic creep elements[3] to simulate the creep behavior of the above thick welded joint, as shown in Fig. 3. Elements EWM1 - EWM3 correspond to the weld metal. Elements EBM1 - EBM4 correspond to the base metal. The heat-affected zone (HAZ) is divided into two regions of the weld metal and the base metal, because the elastic-plastic creep properties of the HAZ are between those of the weld metal and of the base metal, and the width of the HAZ is very small. So the region of the HAZ is separated in half, and they are included in the weld metal elements and the base metal elements. Each element has elastic-plastic creep properties depending on the temperature and the stress. For example, they have the properties shown in Fig. 2 at 550 °C and 235 MPa, depending on location. The details of the temperature and the stress dependencies of the properties at each location are shown in Ref. 2.
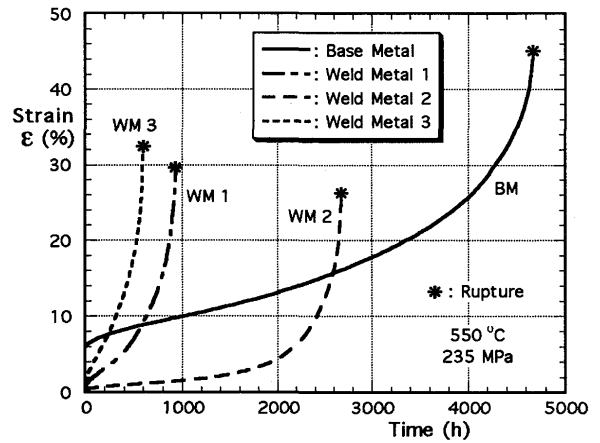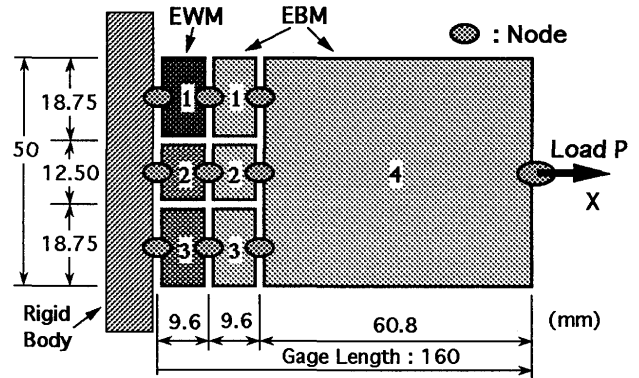

Fig. 3 A simple mathematical model for creep analysis of a thick welded joint

The creep property is the same in the base plate. Nevertheless the base plate is separated into four elements EBM1 - EBM4. The reason is as follows. The joint is a continuous solid body. The creep property of the weld metal is significantly different, depending on the location. The interaction of the creep behaviors occurs in the joint, especially near the weld metal. The role of the base plate for the interaction is realized in one-dimensional analysis, by being divided into four elements, such as shown in Fig. 3. The elements EBM1 - EBM3 have the almost same length as the EWM1 - EWM3. Their nodes at the outer sides are connected to the element EBM4, and have the same displacement. The interaction among the EWM1 - EWM3 can be carried out through elements EBM1 - EBM4.

2.3 Sizes of elements

Here the sizes of each element will be decided. The dividing line is drawn at the mean location of the region of the HAZ, perpendicular to the surface. The region between the Y axis (x=0) and this line is further divided into three parts by separating at the two means (WM1-WM2,

WM2-WM3) of the three positions where the creep property was investigated in the experiments. The three parts are named the weld metal elements EWM1 - EWM3. The depths (the dimensions of the Y-direction) of the base plate elements EBM1 - EBM3 are assumed to be the same as the elements EWM1 - EWM3 described above. It may be appropriate that the length (the dimension of the X-direction) of the elements EBM1 - EBM3 is about the length of the elements EWM1 - EWM3 from a consideration of the material mechanics, so they are assumed to have the same length as the elements EWM1 - EWM3. The model which has these sizes is called the basic model. The length of the elements EBM1 - EBM3 will be discussed again in the analysis for the verification of the model in the section 5.

3. Theory of the Simple Model

The model described in the previous section is a simple model constructed of seven one-dimensional elastic-plastic creep elements, and can be used easily. In the actual thick welded joint, complex three-dimensional welding residual stresses exist in the initial state, and the creep behavior may be different from the one-dimensional stress state. So a new theory was developed, which can incorporate the effect of the three-dimensional stress state, when using the one-dimensional element. This theory is expressed for displacement, strain, and stress in only one direction, which are important and given special attention, but the effect of the existence of components in the other directions is included in the equations, with an assumption. The main equations were shown in the first report[1].

4. Procedures of Analysis

4.1 Consideration of change of sectional area due to loading

The magnitude of the tensile load acting on the specimen is constant, but the magnitude of the stress in the specimen increases with the decrease of the sectional area due to the elongation of the specimen. The increase of the stress is very small in each increment, but the creep strain rate changes, depending on the magnitude of the stress, very sensitively. The analysis has to consider these behaviors, in the one-dimensional element, precisely. In the incremental method, the change of the sectional area, the new magnitude of the stress for the new sectional area, and the creep strain rate for the new stress have to be calculated accurately in each increment, satisfying the equilibrium condition between the load and the stresses of the elements.

4.2 Creep hardening rule and creep strain rate

The creep properties of the joint are significantly different, depending upon the location, as shown in Fig. 2. They can be expressed with Garofalo's constitutive equation,

as follows.

$$\varepsilon^c = \varepsilon_t \left(1 - \exp\left(-\gamma \cdot \tau\right)\right) + {}^r\varepsilon_m \cdot \tau \tag{1}$$

where

$$\varepsilon^c = \text{creep strain}$$

$$\varepsilon_t = c_1 \cdot \sigma + c_2 \tag{2}$$

$$\gamma = c_3 \cdot \exp\left(c_4 \cdot \sigma\right) \tag{3}$$

$${}^r\varepsilon_m = c_5 \cdot \sigma^n \tag{4}$$

$$\sigma = \text{stress}$$

$c_1, c_2, c_3, c_4, c_5, n$ = constants for each creep curve, which are shown in the reference2

$$\tau = \text{time}$$

The creep strain rate is obtained by differentiating Eq. (1) by time.

$${}^r\varepsilon^c = \varepsilon_t \cdot \gamma \cdot \exp\left(-\gamma \cdot \tau\right) + {}^r\varepsilon_m \tag{5}$$

Equations (1) and (5) are the function of the stress σ. The creep strain ε^c and the creep strain rate ${}^r\varepsilon^c$ have different values for different stresses, even if the time τ is the same. In this study, the value of stress changes with the production of creep strain (refer to section 4.1). To determine the creep strain rate at the time, the strain hardening rule[4] is applied here.

The strain hardening rule is an assumption that the creep strain rate depends on the magnitude of stress and the quantity of developed creep strain. The creep strain rate ${}^r\varepsilon_i^c$ at the time τ_i is obtained as the creep strain rate ${}^r\varepsilon^c$ at the location of the creep strain ε_i^c at the time τ_i, on the creep curve for the stress σ_i at the time τ_i. The time for the creep strain ε_i^c on the creep curve for the stress σ_i is generally different from the real time τ_i, because the stress changes every moment. Accordingly, the creep strain rate ${}^r\varepsilon_i^c$ can not be obtained by substituting τ_i into τ in Eq. (5).

The creep strain rate ${}^r\varepsilon_i^c$ is calculated with the following procedure.

① τ is calculated by substituting σ_i and ε_i^c into Eq. (1), and by applying the Newton method. The derived τ is denoted as τ_{ic} and is usually not equal to real time τ_i.

② ${}^r\varepsilon_i^c$ can be calculated by substituting τ_{ic} and σ_i into Eq. (5).

Each time increment is made short enough to assume that the creep strain rate does not change in each time increment. Then, the creep strain increment $d\varepsilon_i^c$ is obtained by multiplying ${}^r\varepsilon_i^c$ by the time increment $d\tau_i$.

4.3 Introduction of welding residual stresses

The creep test specimen shown in Fig. 1 has a thickness of 10 mm, which is thin. But most welding residual stresses of in-plane directions remain in the specimen. The remaining welding residual stresses may affect the creep behavior

of the specimen. So the welding residual stresses are introduced into the analysis using the simple model, as follows. The effect of the welding residual stresses for the creep behavior is examined.

4.3.1 Introduction in uni-axial stress state

In the analysis as assumed to be one-dimensional stress state, which uses one-dimensional stress element (Eqs. (1)-(6), (38), (39) in the first report), the welding residual stress in the direction of loading (X-direction) is investigated as follows. This stress component is largest among the welding residual stresses remaining in the specimen, and directly affects the creep strain rate.

The initial stresses correspond to the welding residual stresses are given in the elements of the model before the loading in the creep test. **Figure 4** shows the initial stress distribution assumed in the model, which is based on the author's studies[5]. In the figure, the broken line SM-1-WR near "Initial" is the initial stress distribution in the elements EWM1-EWM3. The stress distribution satisfies the equilibrium condition in the section. The elements EBM1-EBM3 have the same stress distribution from the structure of the model. The load for the creep test is imposed on the model under this condition.
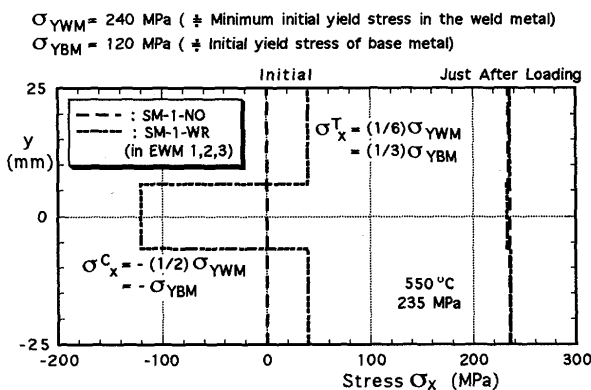

σ_{YWM}= 240 MPa ($\doteqdot$ Minimum initial yield stress in the weld metal)
σ_{YBM} = 120 MPa ($\doteqdot$ Initial yield stress of base metal)

Fig. 4 Welding residual stress σ_x in the simple model and that just after full loading

4.3.2 Introduction in multi-axial stress state

In the specimen, there are the other residual stress components which are comparatively smaller than the above X-directional component. The joint is in the multi-axial stress state. Then, the effect of the stress state for the creep behavior is examined, using the initial stresses of Fig. 4 and the theory (equations) for multi-axial stress state shown in the first report. Actually the multi-axial stress coefficients m^{el}_x, m^{EQ}_x and m^{de}_x included in the theory are different, depending on the location, and they change by the loading and with time. It is assumed in this study that the coefficients m^{el}_x, m^{EQ}_x and m^{de}_x are constant for every elements and every time.

5. Analytical Results by Simple Model and Discussions

The creep analysis (one-dimensional FEM analysis) using the simple model was conducted for the specimen of the thick butt welded joint shown in Fig. 1, under the creep test condition of the temperature of 550 °C and the initial loading stress of 235 MPa. The simulated result was compared with the experimental result, to verify the accuracy and the usefulness of the model.

The creep behavior of the thick welded joint which was analyzed in the above condition is complex as follows. The magnitude of load is large because the test is an accelerated test. So the plastic deformation is largely produced in the elements of the base plate by loading. During the creep test, unloading occurs in some elements in some for a while as the creep strain rates are different in each element. At last all elements largely deform plastically, and the model ruptures.

5.1 Effect of welding residual stresses

5.1.1 In case of uni-axial stress state

The creep analyses were performed for two conditions, using uni-axial stress elements. One was the case which considers no initial stresses. Another was the case which considers the welding residual stresses of Fig. 4. The result of the former is shown as SM-1-NO in **Fig. 5**. The latter is shown as SM-1-WR. These creep curves are almost same. The reason is that the stresses in the elements just after the loading are almost same, independent on the initial stresses before the loading, as shown in Fig. 4, because the magnitude of loading is large. These creep strain rates are about one and half times the experimental result[2].
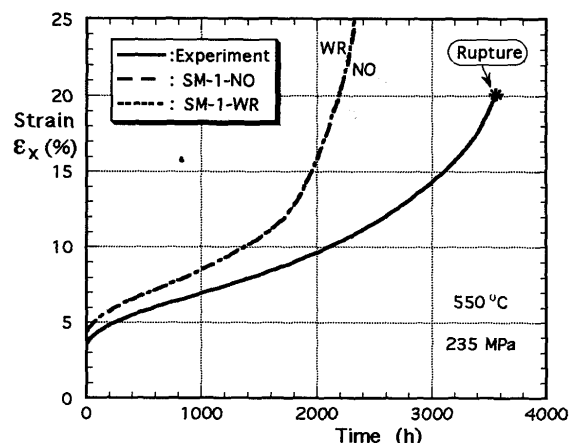

Fig. 5 Effect of welding residual stress on creep behavior (uni-axial stress state)

5.1.2 In case of multi-axial stress state (Degree of multi-axial stress state of the joint)

Next the creep analyses were conducted in the multi-axial stress state. The stress component in the direction of thickness, σ_y, which is the second large component, is considered in addition to the component in the direction of loading, σ_x. By increasing the ratio of σ_y to σ_x, the effect for the creep behavior was investigated. The multi-axial stress coefficients m^{el}_x, m^{EQ}_x and m^{de}_x can be calculated with Eqs. (14)-(16) in the first report, and they are used in the analyses. **Figure 6** shows the results for the changes of the coefficient m^{EQ}_x which is the ratio of the equivalent stress to the axial stress (σ^{EQ}/σ_x). While the ratio σ_y/σ_x changes from 0.00 to 0.255, the ratio σ^{EQ}/σ_x changes from 1.00 to 0.90. From Fig. 6, it is known that the rate of creep deformation is greatly affected by the magnitude of the equivalent stress, and the rate becomes very slower if the equivalent stress becomes a little smaller due to multi-axial stress state.
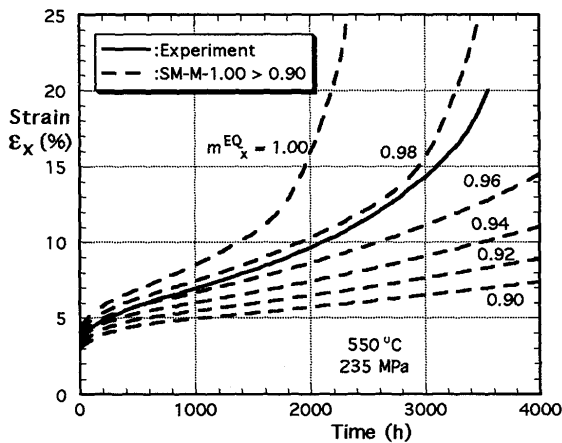

Fig. 6 Effect of welding residual stress on creep behavior (multi-axial stress state)

Then, changing the ratio σ_y/σ_x finely, the creep curve which corresponds with the experimental result was obtained. As shown in **Fig. 7**, when the ratio σ_y/σ_x is 0.05 (m^{EQ}_x is 0.976), the creep curve corresponds with the experimental result very well during all the stages from the initial to the rupture. This result indicates that the simple model has the ability to accurately simulate the creep behavior of a thick welded joint, and that the degree of multi-axial stress state of the joint is about $m^{EQ}_x = 0.976$ on average, in the joint.

Figure 8 shows the distribution of load-axial strain in the elements (EWM1 - EWM3) of the weld metal at 1200 hours, in the case of $m^{EQ}_x = 0.976$. The experimental result is the distribution at the middle cross section (x=0). The above analyzed result is the average in the weld metal. Both results correspond well, though the comparison is not on the same basic.
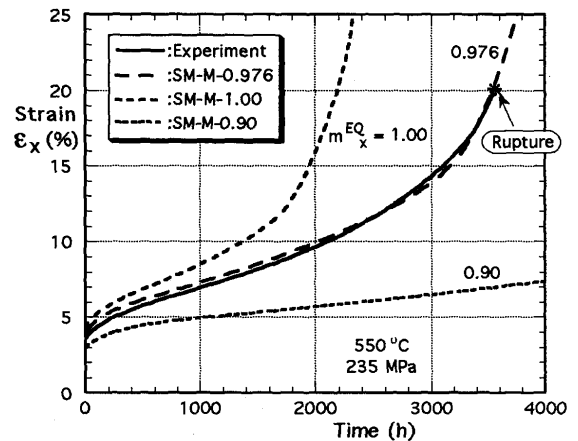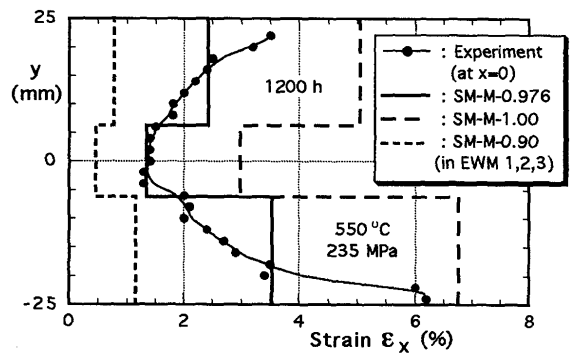

Fig. 7 Comparison of creep curves

Fig. 8 Comparison of strains in the weld metal (after 1200 hours)

5.2 Length of elements of base plate

In section 2.3, the length of the elements EBM1 - EBM3 was tentatively assumed to be the same as the elements EWM1 - EWM3, and the model was called the basic model. The length of the elements EBM1 - EBM3 is discussed again here. The multi-axial stress coefficient m^{EQ}_x is assumed to be 0.976 ($\sigma_y = 0.05 \, \sigma_x$) mentioned in section 5.1. The analyses were conducted for two different lengths of the elements EBM1 - EBM3 from the base model. One is the case of a half length of the base model, and the other is the case of twice. The length of element EBM4 changes to hold the gage length constant.

The creep curves are shown in **Fig. 9**. The distributions of load-axial strain in the elements of the weld metal are shown in **Fig. 10**. HM-M-0.976 represents the result for the case of a half length, and DM-M-0.976 represents that for twice length. In Fig. 9, both the creep curves almost coincide with the basic model until about 2500 hours. After that, three creep curves are different each other, but not significantly. The distributions of load-axial strain have the same tendency as shown in Fig. 10.
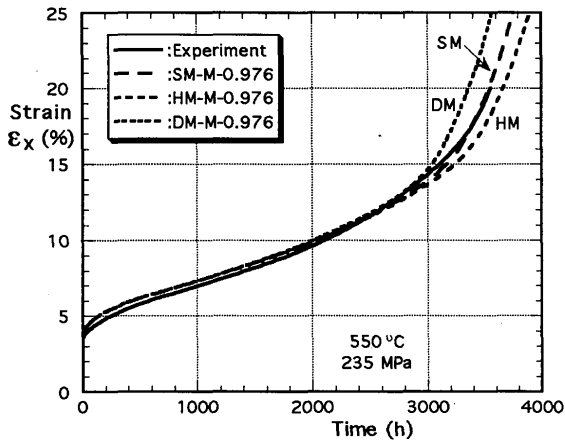
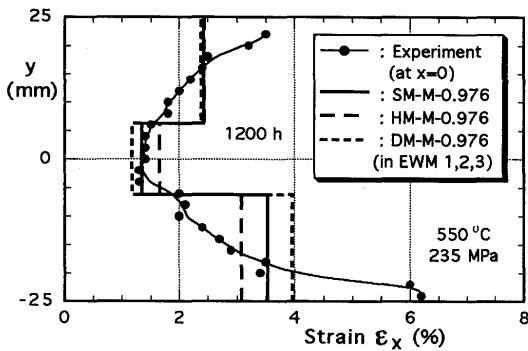**Fig. 9**   Effect of element size on creep curve

Fig. 10   Effect of element size on local strain
(after 1200 hours)

From the above results, the length of the elements EBM1 - EBM3 appears to have little effect on the behavior of the model provided that the length is not changed substantially. The best length may be near the basic model, between the basic model and the half length model, judged from the correspondence with the experimental result. But the effect of changing the length into this best may be very small, so there is no necessity to change the length. The length of the elements EBM1 - EBM3 of the basic model is used as the one of the simple model.

5.3 Effect of stress-relief annealing

In section 5.1, the applicability and the degree of multi-axial stress state of the model were investigated by changing the stress state. The results indicate the following important information. When the stress-relief annealing for the thick welded joints is included in the fabrication process, the treatment may adversely affect the creep strength of the joint. The reason will be explained in detail.

When the joint is loaded in one direction after almost all the welding residual stresses are reduced with stress-relief annealing, the stress state of the joint almost approaches the

one-dimensional state. The creep rate of the joint becomes faster than the joint without the stress-relief annealing, like the case of SM-1-NO in Fig. 5. On the other hand, when the equivalent stress is smaller than the loading stress, due to the welding residual stress, the creep rate of the joint becomes slower, and the creep life of the joint becomes longer than the one without the welding residual stresses.

Accordingly, judging from the analyzed results using the simple model, it is estimated that welding residual stresses do not reduce the creep capacity of the joint, and that they may reduce the creep strain rate and make the creep life longer. This conclusion relies on the assumption that the creep properties of the joint, including the elongation at the rupture, do not change due to the stress-relief annealing. That is, they remains as welded, which are used in this analysis. It is desirable to investigate by experiment the effect of the welding residual stresses, and the creep properties after stress-relief annealing.

6. Conclusion

In this study, for thick welded joints of nuclear reactors, etc., the creep behavior to rupture, which is important as one of the limit capacities of the joint, is analyzed by theoretical calculation and by experiment. Based on the results, desirable material properties and welding methods are investigated to improve the creep capacities (the creep strain rate, the life time, etc.) of the joint.

To accomplish these purposes rationally and efficiently, in the first report, a simple mathematical model based on FEM had been developed. The simple model was constructed of seven one-dimensional elastic-plastic creep elements. In the actual thick welded joint, complex three-dimensional welding residual stresses exist in the initial state, and the creep behavior may be different from the one-dimensional stress state. So a new theory has been developed. The theory is expressed for displacement, strain, and stress in only one direction, but the effect of the existence of components in the other directions is included in the equations, with an assumption. Then the model can analyze creep behavior in the three-dimensional stress state, using the one-dimensional element with the multi-axial stress coefficients.

The model is easy to treat, and needs only a little labor and computation time with a normal personal computer to predict the creep curve and the local strain of a thick welded joint. In this second report, the simple model was verified by comparing the analyzed results with the experimental ones. The creep curve of a thick welded joint obtained by the model corresponds well with the experimental one, over the whole range of the creep curve. For the local strains in the weld metal of the joint, the similar correspondence was observed.

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In the discussing about the applicability and the degree of multi-axial stress state of the model, the following important indication was gained for the effect of the stress-relief annealing for thick welded joints. In the creep test, the welding residual stress components, other than the loading direction, have larger effects than the loading directional component. If the stress components make the equivalent stress smaller than the stress of the loading direction, the creep strain rate becomes slower than in the case where only the stress of loading direction exists. The stress-relief annealing takes out the welding residual stresses. So the treatment may make the creep strain rate faster, then it may adversely affect the creep strength of the joint.

As a simple model has been completed, it becomes possible to test easily the calculations under various conditions with a personal computer, to improve of the creep property of thick welded joint.

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