Transactions of the **13th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 13), Escola de Engenharia - Universidade Federal do Rio Grande do Sul,
Porto Alegre, Brazil, August 13-18, 1995

Influence of constitutive model in prediction of thermal ratchetting deformation

Takahashi, Y.,
Central Research Institute of Electric Power Industry, Komae, Tokyo, Japan
Tanimoto, K.
Mitsubishi Heavy Industries Ltd., Takasago, Hyogo, Japan

ABSTRACT: To investigate the effects of inelastic constitutive model in prediction of thermal ratchetting, inelastic analyses were conducted for thermal ratchet test models of low-carbon type 316 stainless steel. It was found that extended Ohno-Wang model gave better estimation of ratchetting behavior than the two-surface type plasticity model.

1. INTRODUCTION

Preventing large deformation is one of the important subjects in the design of components used in the conditions involving inelastic deformation. Various components of liquid-metal cooled fast breeder reactor (LMFBR) plants were subjected to cyclic thermal stresses due to variation of a coolant temperature accompanying plant operation and the possibility of thermal ratchetting should be carefully examined.

A simple ratchetting estimation method which was derived from the analysis of a tube subjected to constant inner pressure and through-wall temperature cycles by Bree (1967) was principally employed in the past design rules (e.g. American Society for Mechanical Engineers 1993). However, applicability of this method to different structural conditions is questionable. Relating with the design of large vessels with sodium free surface in LMFBR plants, it has become a well-known fact that the vessel with axial thermal gradients can ratchet even without any primary loads such as axial force or internal pressure (e.g. Karadeniz et al 1987). From the viewpoint of material characterization, assumption of elastic-perfectly plastic material behavior made in these studies is especially unrealistic for the structural materials concerned.

Therefore, development of a reliable assessment procedure using inelastic analysis is desiable. A proper constitutive model should be chosen because available results of the study for material ratchetting indicated thatinelastic constitutive law gives large influence on ratchetting behavior (Ohno, Wang 1993ab).

In this study, influences of inelastic constitutive law in prediction of thermal ratchetting were studied by inelastic analyses of thermal ratchet tests for large cylinder models. A two-surface type plasticity model and an extension of Ohno-Wang model were applied and influence of material strength level was also studied.

2. CONSTITUTIVE MODELS

A material dealt with in this study is a class of low-carbon type 316 stainless steel specifically developed for application to LMFBR plants and designated 316FR (Fast Reactor) steel. Nitrogen was added to compensate the reduction of strength due to low-carbonization. Because viscous effects were found small in the temperature and time scale concerned (maximum temperature less than 600° C), only time-independent elastic-plastic models were considered. Two types of plastic constitutive models which differ mainly in kinematic hardening law were applied. Their outlines are given in this section.

2.1 Two-surface model

One of the present authors developed a plastic constitutive model for type 304 stainless steel (Takahashi 1991). This model is categorized into two-surface models and it was demonstrated by comparisons with the results of strain-controlled low-cycle fatigue tests that stress-strain responce under monotonic and cyclic loading conditions can be expressed with good accuracy. In this model, cyclic hardening is expressed by expansion of an outer surface (bounding surface) rather than that of an inner surface (yield surface). To represent the dependency of saturated stress level on strain range, the size of the bounding surface is developed with a hardening index surface defined in a plastic strain space.

Moreover, temperature-dependency of the instantaneous resistance to plastic deformation as well as temperature history-dependency of cyclic hardening is taken into account. Stress-strain hysteresis in a particular cycle is decided by a nonlinear kinematic hardening law whose direction and rate were determined from the positions and sizes of the both surfaces. More details of this model is given in (Takahashi 1991). A few constants were modified to fit the test data of 316FR steel.

2.2 Model with Ohno-Wang kinematic hardening law

Ohno and Wang (1993a,b) proposed a new nonlinear kinematic hardening law to overcome a shortcoming shared by various classical nonlinear kinematic hardening models observed in especially in the predictions of ratchet deformation. The present authors extended this model by incorporating cyclic hardening effect. The outline of the model is given in what follows.

(1) Yield surface

Yield surface is given as a hyper-sphere in the deviatoric stress space as in the most engineering plastic constitutive model.

$$F=\frac{3}{2}(s_{ij}-\alpha_{ij})(s_{ij}-\alpha_{ij})-\kappa^2=0 \tag{1}$$

where s_{ij} is deviatoric stress tensor、 α_{ij}、 κ are the internal state variables representing the center and the size of the yield surface, respectively. As in the former model, κ is assumed to be dependent only on the current temperature as

$$\kappa = Af(T_{abs}) \tag{2}$$

where A is a constant and $f(T_{abs})$ is a function of the absolute temperature, T_{abs}, which was determined from the temperature-dependency of monotonic stress-strain relations.

(2) Kinematic hardening rule

Nonlinear kinematic hardening rule proposed by Ohno and Wang is expressed as

$$\alpha_{ij} = \sum_{k=1}^{n} \alpha_{ij}^{(k)} \tag{3}$$

$$\Delta\alpha_{ij}^{(k)}=\zeta^{(k)}\left\{\frac{2}{3}r^{(k)}\Delta\varepsilon_{ij}^{p}-\left(\frac{\overline{\alpha^{(k)}}}{r^{(k)}}\right)^{m}\frac{\left\langle\Delta\varepsilon_{ij}^{p}\alpha_{ij}^{(k)}\right\rangle}{\overline{\alpha^{(k)}}}\alpha_{ij}^{(k)}\right\} \tag{4}$$

where $\Delta\varepsilon_{ij}^{p}$ is the plastic strain increment, $\zeta^{(k)}$ and $r^{(k)}$ were constants. $\overline{\alpha^{(k)}}$ is the intensity of each kinematic hardening parameter defined as

$$\overline{\alpha^{(k)}} = \sqrt{\frac{3}{2}\alpha_{ij}^{(k)}\alpha_{ij}^{(k)}} \tag{5}$$

m is a parameter which represents the nonlinearity of dynamic recovery term and the power-law function reduces to the Heaviside function with the limit of $m=\infty$. Moreover, $< >$ represents Macauley's parenthesis which acts as $<x>=x$ when $x \geq 0$ and $<x>=0$ when $x<0$.

In our model, instead of assuming constant $r^{(k)}$, the following equation was assumed for introducing temperature dependency and cyclic hardening into the original Ohno-Wang model.

$$r^{(k)} = f(T_{abs})g^{(k)}(R_H) \tag{6}$$

Here R_H is a hardening parameter determined in a similar way as in the two-surface model and $g^{(k)}(R_H)$ is a function monotonically increasing with R_H. A correction term was added to take into account of the effect of variation of $r^{(k)}$ as

$$\Delta\alpha_{ij}^{(k)}=\zeta^{(k)}\left(\frac{2}{3}r^{(k)}\Delta\varepsilon_{ij}^{p}-\left(\frac{\overline{\alpha^{(k)}}}{r^{(k)}}\right)^{m}\frac{\left\langle\Delta\varepsilon_{ij}^{p}\alpha_{ij}^{(k)}\right\rangle}{\overline{\alpha^{(k)}}}\alpha_{ij}^{(k)}\right)+\frac{\Delta r^{(k)}}{r^{(k)}}\alpha_{ij}^{(k)} \tag{7}$$

where $\Delta r^{(k)}$ is an increment of $r^{(k)}$ generated by variation of R_H and the temperature.

In this way, cyclic hardening and temperature-dependency were introduced into the original model. Each constant and function was determined from the stress-strain diagrams in the low-cycle fatigue tests. As for m, which has a role to control ratchetting strain, both finite and infinite values were used to assess its effect. Examples of comparison between test data and simulations for stabilized hysteresis loops are shown in Figure 1.

3. ANALYSIS OF THERMAL RATCHET TEST

3.1 Outline of tests

Overview of a test appratus is shown in Figure 2. Test models are thin-walled hollow cylinders with an inner diameter of 996 mm, wall thickness of 4.4 mm and height of 1000 mm. Two tests with different thermal conditions were analyzed in this study. Radius to thickness ratio is about the same as the value of a main reactor vessel in the basic design for the Japanese Demonstration LMFBR plant.

Axial temperature distribution was given to these models using flowing water within the model and a high-frequency induction heating coil set outside around the circumstance of the model. It is possible to move the coil and the water level, independently. As some axial distance was taken between the positions of the water level and the coil during the tests, temperature distribution was considered to be mainly of axial direction rather than radial direction. One cycle was about an order of 1 hour. A constant uniform tensile stress of 29.4MPa was given by a servo-hydraulic loading system throughout the tests.

Different temperature cycles were given for the two test models denoted model A and model B hereafter. For model A, only the coil was moved up and down for a distance of 90 mm with the water level constant. On the other hand, both the coil and water level were moved for 250 mm keeping their distance for model B. Variations of axial temperature distribution measured by thermo-couples welded on the outer surface are shown in Figure 3.

Geometry of the test model was occasionally measured, after cooling the model to the room temperature and unloading, by a automatic geometry measurement system composed of a laser light /TV camera unit and a turntable.

3.2 Comparison between predictions and test results

Gradual decrease of the diameter was observed due to hot-front type movement of the temperature. Comparison of the maximum radial contraction is shown in Figure 4. It can be easily seen in these figures that the both constitutive models gave very similar results for the first cycle but the two-surface model started to predict excessive deformation after a few cycles and the extended Ohno-Wang model yielded favorable agreement with the test results.

The following observations can be additionally made from the parametric study using the extended Ohno-Wang model for the test model A.

(a) Influence of m is rather small for m larger than 5.
(b) Effect of isotropic hardening (cyclic hardening) is very small.
(c) Yield stress level gives important influence.
(d) Effect of axial load is also large.

Hoop stress - hoop strain loci at the center of thickness of the largest ratchetting strain section predicted by the analyses with and without axial load are compared in Figure 5. It can be seen that effective yield stress was reduced by superposition of axial tensile stress and this brought about larger ratchetting strain. Moreover, strain loci shown in Figure 6 indicates that much larger axial strain was predicted in the case with axial stress by an assumption of the normality rule.

4. CONCLUSION

Effect of inelastic constitutive model was studied through the inelastic analysis for large thermal ratchet test models subjected to the cyclic movement of axial temperature distribution. It was found that the extended Ohno-Wang model gave better agreement with the test results than the two-surface type model. Effects of various parameters were also investigated.

REFERENCES

American Society for Mechanical Engineers, 1993, *Boiler and Pressure Vessel Code, Code Case N-47.*

Bree, J. 1967. Elastic-Plastic Behavior of Thin Tubes Subjected to Internal Pressure and Intermittent High Heat Fluxes With Application to Fast Nuclear-Reactor Fuel Elements. *J. Strain Analysis.* 2:226-238.

Karadeniz, S, Ponter, A.R.S & Carter, K.F. 1987. The Plastic Ratcheting of Thin Cylindrical Shells Subjected to Axisymmetric Thermal and Mechanical Loading. *J. Pressure Vessel Technology.* 109:387-393.

Ohno, N. & Wang, J.-D. 1993a. Kinematic Hardening Rules with Critical State of Dynamic Recovery, Part I: Formulation and Basic Features for Ratchetting Behavior. *Int. J. Plasticity.* 9:375-390.

Ohno, N. & Wang, J.-D. 1993b. Kinematic Hardening Rules with Critical State of Dynamic Recovery, Part II: Application to Experiments of Ratchetting Behavior. *Int. J. Plasticity.* 9:391-403.

Takahashi, Y. 1991, Modeling of Temperature- and Temperature History-Dependence of Cyclic Deformation Behavior of Type 304 Stainless Steel. *Trans. 11th Int. Conf Structural Mechanics in Reactor Technology.* vol. L:151-156.

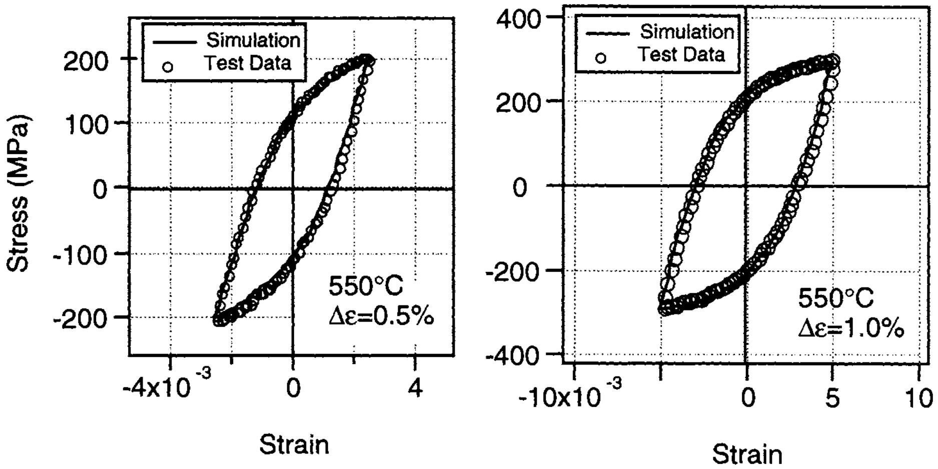


Figure 1 Simulation of Cyclic Deformation Behavior by Extended Ohno-Wang Model

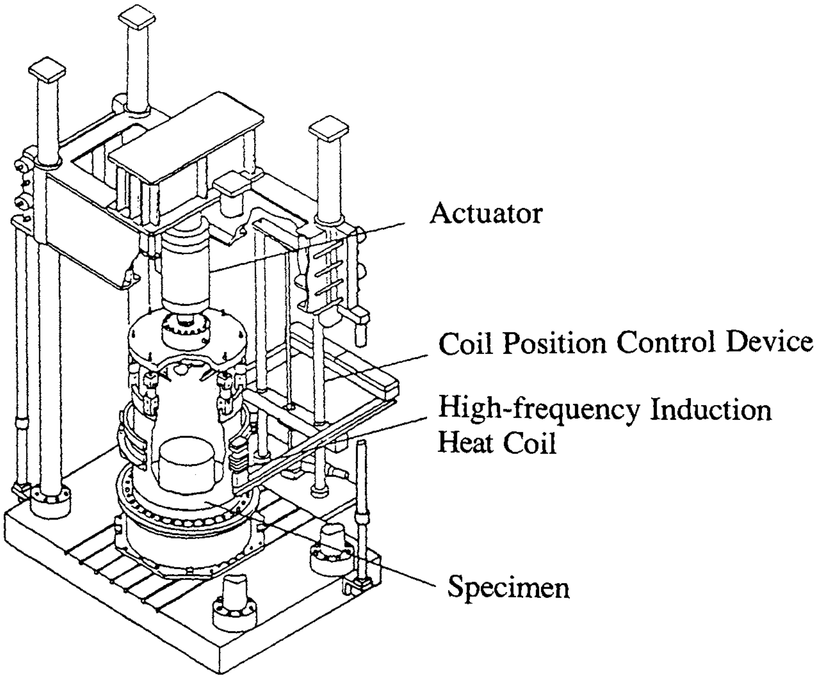
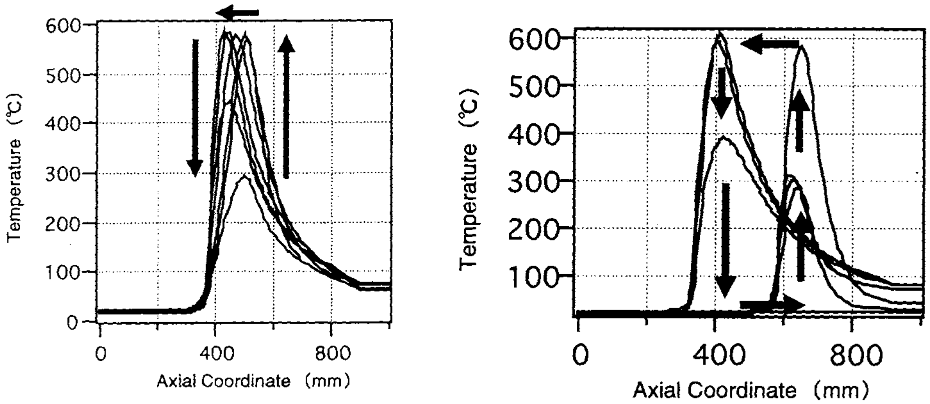


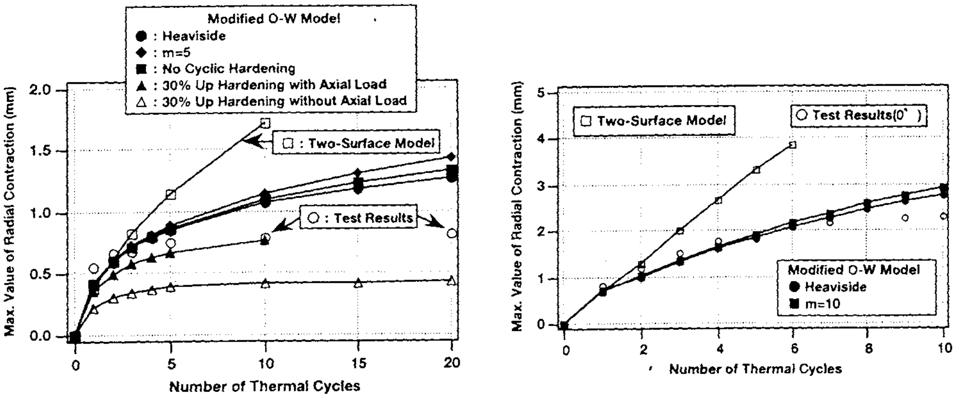
Figure 2 Overview of Thermal Ratchet Test Facility



(a) Model A

(b) Model B

Figure 3 Variation of Axial Temperature Distribution



(a) Model A

(b) Model B

Figure 4 Variation of Residual Deformation with Thermal Cycle

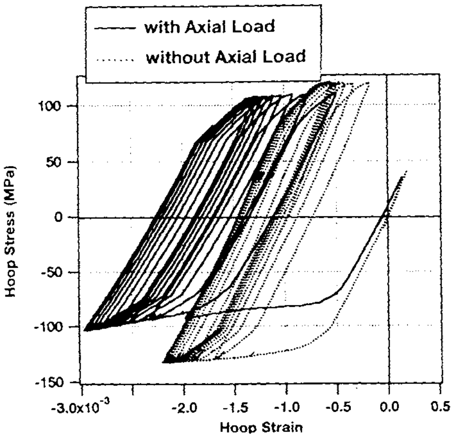


Figure 5 Hoop Stress - Strain Relation

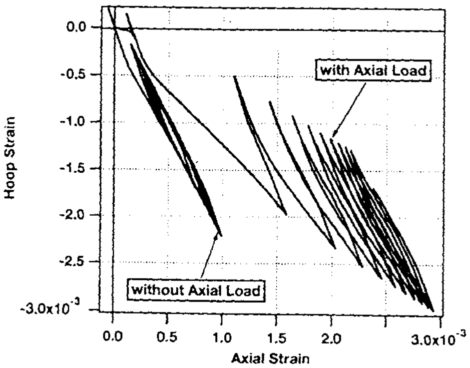


Figure 6 Hoop Strain - Axial Strain Loci