# Simulation for Thermal Ratchetting of SUS304 Cylindrical Shell

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ABSTRACT

This paper presents a study on thermal ratcheting of SUS304 cylinder,which was subjected to an axially moving thermal gradient in order to verify the ratcheting mechanism. An elastic-plastic analysis is conducted using an axisymmetric finite element method and analytical results were compared with the measured deformation data. Then,the plastic deformation increases during each cycle of the thermal transient. It is shown that detailed finite element analyses could qualitatively simulate thermal ratchet behavior.

## 1. INTRODUCTION

Incremental plastic deformation due to cyclic thermal loading is an important consideration in the structural design which operated at elevated temperature,for example fast breeder reactors and advanced high temperature plants. For the design of liquid metal fast breeder reactors,thermal transients in the primary liquid sodium circuit cannot be avoided during operation . However the circuit is not pressurized so that components are subject to high levels of thermal loading only. Karadeniz,et al. discussed the relationship between material properties and structural ratcheting for thin cylindrical shell subjected to severe thermal loading. Ohshima,et al. examined the structural integrity for equipment in the main vessel of a fast breeder reactor. The test cylinders were subject to cyclic thermal transient by heating to 550℃,and then submersing in liquid sodium at lower temperature. Ratcheting due to thermal stress caused the residual deformation in the cylinders. In this paper,an elastic-plastic thermal stress analysis in a simple structure of a cylindrical shell,is presented using a finite element method. As a result, thermal stress is induced by axially moving temperature from 550℃ to 350℃ along the length of a tube,and then the plastic deformation increases during each cycle of the thermal transient. It is shown that the thermal ratcheting is a dominant factor of such cyclic thermal loading and causes unacceptable change in radial displacement. These results are compared with the experimental results.

## 2. ANALYTICAL PROCEDURES

## 2.1 Heat conduction equation

Thermal stress are obtained during small intervals of time,each interval corresponding to a particular change in temperature.Computation begins with determination of the temperature distribution in the cylinder at the current stage of thermal transient. The transient heat conduction for an axisymmetric body is governed by the equation using density($\rho$), specific heat(C), temperature(T),time(t),thermal conductivity(K),and heat generating rate(Q), respectively. A discretization in the full space-time domain can be derived from the relation of $T[r,z,t]=[N(r,z)]\{\Phi(t)\}$ and Crank-Nicholson differential equation. The final equation described with the heat conductivity matrix([K]),the heat capacity matrix([C]),the heat flux vector({F}) and the heat transfer coefficient($\alpha_c$).

## 2.2 Stress analysis

The elastic-plastic thermal stresses are analyzed by a finite element method proposed by Inoue and Tanaka. According to Mises' yield condition considering strain history,yield function which consisted with the deviatoric stress,the equivalent stress and the equivalent plastic strain is used. The following Ramberg-Osgood stress-strain relation is employed.

$$E\varepsilon_t=\sigma_t[1+K(\sigma_t/\sigma_1)^{q-1}]$$

where $\sigma_t$, $\varepsilon_t$ and E are uniaxial stress,uniaxial strain, and Young's modulus. K and q are the material constants. $\sigma_1$ is the temperature-dependent yield stress obtained from a least square fit of experimental results as follows.

$$\sigma_1=242-0.73T+1.78X10^{-3}T^2-1.60X10^{-6}T^3 \text{ (MPa)}$$

## 2.3 Analytical model

Figure 1 shows the cylinder with the finite element mesh. The parabolic isoparametric element with four nodes and 2X2 Gauss points is used. The total number of elements and nodes are 332 and 420,respectively. The comparatively fine mesh are chosen at the bottom of the cylinder where the rapid temperature variation is undergone. The cylinder is subject to thermal cycle repeatedly below length of 250mm. It will be assumed that the temperature lies below the creep range so that inelastic deformation caused by the plastic properties of the material. The program takes as input temperature distributions at a sequence of times during the cycle and at a sequence of points along the cylinder.

The cylinder has an initial temperature of 550℃. Then at t=0,the bottom of the cylinder touches the liquid sodium and is submerged in the liquid with the rate of 40mm/min. As soon as the cylinder reaches the depth of 250mm,it is lifted with the rate of 80mm/min. After the whole cylinder reaches in the Ar gas atmosphere,it is heated at 550℃ during 1 minute.This kind of heating and cooling cycle is repeated,and ratcheting deformation is computed.

## 2.4 Material and thermal properties

Some material and thermal properties of 304 stainless steel are assumed to be temperature independent parameter,because the effect of temperature on these properties seems to be negligible compared with that on yield stress. The values of these properties are defined in table 1.

## 3. RESULTS AND DISCUSSION

### 3.1 Temperature distribution

Figure 2 show the temperature contour diagram at t=375sec, when liquid sodium reaches the level of 250mm from the bottom. The lines between 360℃ and 490℃ represents the temperature at each increment of 10℃. The lower parts of the cylinder submerged in liquid sodium have a uniform temperature distribution. But the vicinity of cooling front at the level of 250mm,the larger temperature gradient is obtained. At the upper parts of the cylinder remained in Ar gas, the middle of the wall has a little lower temperature due to cooling from the lower parts of the cylinder. Figure 3 shows the temperature distribution along the axial direction at t=375sec.Time delay of temperature gradient traveling in the middle wall is shown.

### 3.2 Deformation due to thermal ratcheting

Figure 4 shows the deformations of the cylinder when liquid sodium reaches the level of 250mm from the bottom and when the cylinder is lifted completely from liquid sodium for 1 and 5 cycle. When the cylinder is submerged in the liquid, it is contracted and when the cylinder is lifted to high ambient temperature,it is expanded.Affected by the deformation of the lower parts of the cylinder,its upper parts shows the behavior of contraction and expansion.Suffered by the larger temperature gradient,the cylinder is distorted complicatedly at the level of 250mm from the bottom.

Figure 5 shows the experimental results measured after thermal transient tests. Each line shows the residual deformation after 10th cycle thermal loading at the $\Delta T$=100,150,200℃ respectively. In this 'cold front' condition,the expansion of the radius increased drastically over $\Delta T$=200℃.

Figure 6 shows the prediction of the ratcheting deformation at the bottom of cylinder by FEM results. Measured data was also plotted in same figure. Current analysis underestimates ratchet deformation about 20 percent. Geometric variation and material constitutive equations for cyclic loading are remaining concerns in the analytical model.

### 3.3 Stress distribution

Figure 7 show the distribution of the hoop stress along the length of the cylinder at t=375sec. The stress reversal is observed at the level of 250mm where the cold front reaches. Stresses have the extreme value of tension in the lower parts and on the contrary,in the upper parts they have the extreme value of compression.It is examined that hoop membrane stress concern with this type of thermal ratchet by analysis.

## 4 CONCLUSIONS

In this paper,thermal ratcheting of the cylinder caused by axially moving temperature gradient is analyzed using a finite element method. The results obtained from numerical calculation and compared with the experimental results show the following conclusion:

(1)Thermal stresses are induced by the thermal gradient traveling.

(2)The cylinder is contracted in radial direction when it submerges in liquid sodium,while lifting from the liquid it is expanded.

(3)With increasing of number of heating and cooling cycle ,the expansion of tube increases. Then finally the larger distortion due to thermal ratcheting remains permanently.

(4)When the cylinder was applied by the 'cold front' type traveling thermal cycle, the residual deformation could be qualitatively simulated by detailed finite element analyses.

It is necessary to examine the following fundamental contributions to confirm of the thermal ratchet prediction.

- The shape of thermal gradient effect
- The length of traveling thermal gradient effect
- The structural discontinuity effect
- Creep and Relaxation effect

## REFERENCES


Karadeniz,S.,Ponter,A.R.S,and Carter,K.F. (1987). The plastic ratchetting of Thin Cylindrical Shells subjected to Axisymmetric Thermal and Mechanical Loadings. ASME Journal of Pressure Vessel Technology, Vol.109,pp.387-393

Tanaka,N.,Ohshima,I.,Hirayama,H,et.al.(1989).Structural Integrity of DFBR Internal Structure under Severe Thermal Loading. ASME PVP. Conference, PVP-Vol.163,pp.39-46

Inoue,T.,and Tanaka,K.(1975).An Elastic-Plastic Stress Analysis of Quenching when Considering a Transformation,International Journal of Mechanical Science,Vol.17,pp.361-367

Ishikawa,H., and Hata,K.(1980) Thermo elasto-plastic Creep Stress Analysis for a Thick-Walled Tube,International Journal of Solids and Structures, Vol.16,pp.291-299


Table 1. Parameters for analysis

| Parameter | Value | Unit |
|---|---|---|
| heat generation rate(k) | 21 | W/m℃ |
| specific heat(C) | 500 | Wsec/Kg℃ |
| density($\rho$) | $7.9\times10^3$ | $Kg/m^3$ |
| Young's Modulus(E) | 163.3 | GPa |
| Poisson ratio($\nu$) | 0.34 | |
| Coefficient of thermal expansion($\alpha$) | $1.79\times10^{-5}$ | 1/℃ |
| Thermal conductivity($\alpha_C$) | 3000 | $W/m^2$℃ |
| Material constants in Ramberg-Osgood(K) | 3/7 | |
| (q) | 19 | |

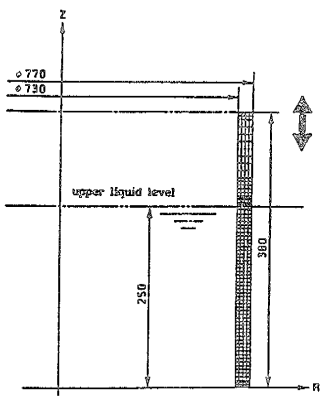


Fig.1 Finite element model

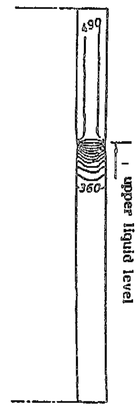


Fig.2 Temperature distribution after 375sec

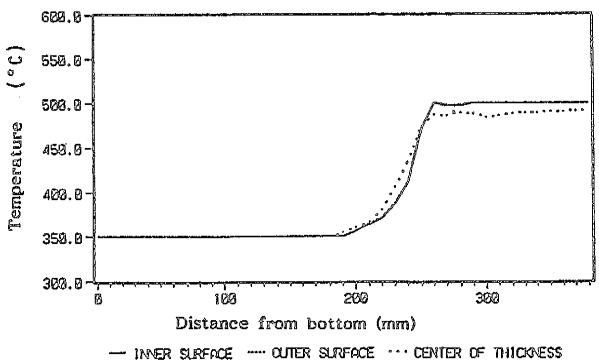


Fig.3 Temperature distribution along the axial direction after 375sec

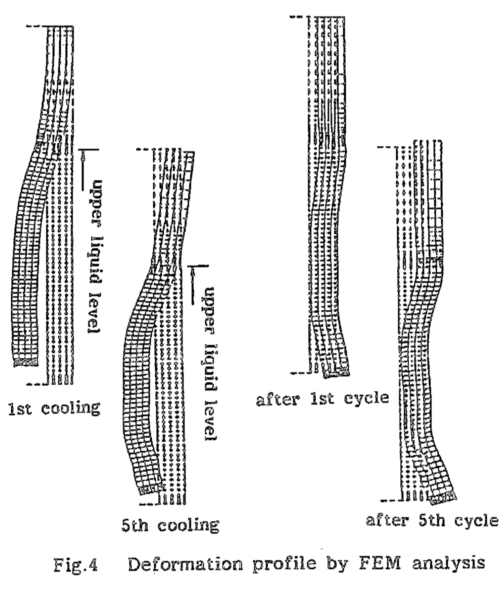


Fig.4 Deformation profile by FEM analysis

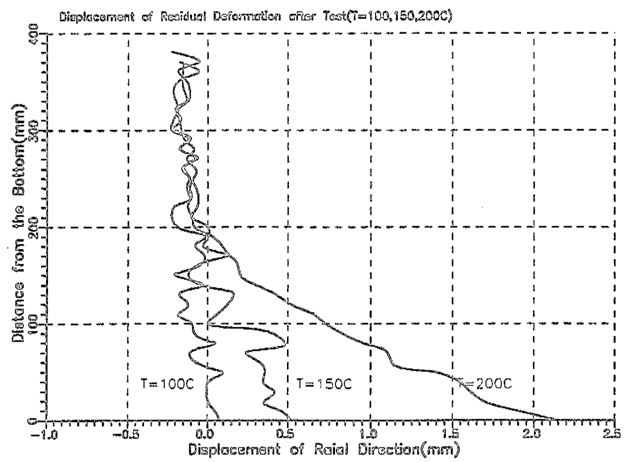


Fig.5 Deformation profile by previous experiment

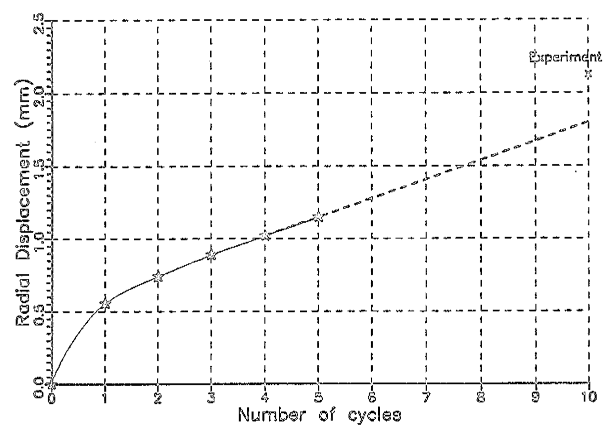


Fig.6 Comparison with the experimental results

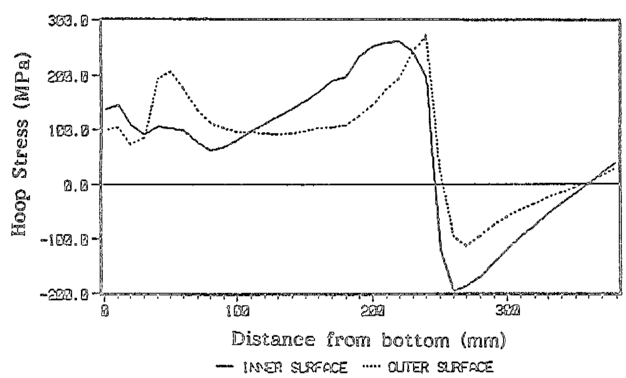


Fig.7 Hoop stress distribution after 375sec