A study on plastic strain accumulation caused by traveling of temperature distribution synchronizing with temperature rise

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Abstract

The prevention of excessive deformation by thermal ratcheting is important in the design of high-temperature components of fast breeder reactors (FBR). This includes evaluation methods for a new type of thermal ratcheting caused by an axial traveling of temperature distribution, which corresponds to moving-up of liquid sodium surface in startup phase. Long range traveling of the axial temperature distribution brings flat plastic deformation profile in wide range. Therefore, at the center of this range, residual stress that brings shakedown behavior does not accumulate. As a result, repeating of this temperature traveling brings continuous accumulation of the plastic strain, even if there is no primary stress. In contrast, in the case with short range traveling, residual stress is caused by constraint against elastic part, and finally it results in shakedown. Because of this mechanism, we supposed that limit for the shakedown behavior depends on distance from the elastic part (i.e. half length of region with plastic deformation). In this paper, we examined characteristics of the accumulation of the plastic strain caused by realistic heat transients, namely, traveling of temperature distribution synchronizing with temperature rise. This examination was based on finite element analyses using elastic-perfectly plastic material. As a result, we confirmed that the shakedown limit depends not on the traveling range of the temperature distribution but the plastic deformation range, which was predicted by the elastic analysis. In the actual application, we can control the plastic deformation range by changing rate of the moving-up of liquid sodium surface.

Key words : Ratcheting, Plastic strain, Thermal stress, Traveling temperature distribution, Finite element analyses

1. Introduction

In designing fast reactors that use sodium as the coolant, an elevated temperature design standard that focuses on the thermal stress is required. The prevention of excessive plastic deformation due to ratcheting is one important consideration for the elevated temperature design. The most well-known ratcheting mechanism is the Bree-type ratcheting (Bree, 1967) which occurs under the combination of primary stress (such as internal pressure) and cyclic thermal stress.

The continuous accumulation of plastic strain may also be caused by axial movement of the temperature-distribution along the cylindrical structure, such as that during the thermal transient of the startup process for the reactor vessel. This ratcheting can occur under thermal stress alone, and primary stress is not required for strain accumulation. Wada et al. (1989, 1993) proposed the evaluation method for the plastic strain increment due to the temperature distribution traveling long ranges. Igari et al. (1990) studied the ratcheting mechanism experimentally, and confirmed the conservative nature of the method proposed by Wada et al.

The ratcheting strain depends on the traveling range of the temperature distribution, that is, accumulation of the ratcheting strain derived from short range traveling of the temperature distribution saturates at early stage. Igari et al. (2000) proposed the mechanism-based evaluation method to evaluate the thermal ratcheting due to the temperature distribution traveling not only long range but also short range. In the “hot-spot model” used in their formulation, the

range in which the plastic strain accumulates is equivalent to the traveling range of the temperature distribution.

We proposed a screening method of thermal ratcheting strain due to the short range traveling in the previous paper (Okajima et al., 2014). In the previous paper, we focused not on the traveling range of the temperature distribution but an axial length of the plastic deformation area. Based on a set of elasto-plastic finite element analyses, we validated applicability of the proposed method to the lamp-shape temperature distribution simulating that nearby the liquid sodium surface. In this validation, the shape of the temperature distribution was assumed as constant in the traveling phase.

In actual process of the FBR startup, without any conscious control, the increasing of the coolant level is synchronizing with the increasing of the coolant temperature. This synchronizing transient brings smaller plastic deformation area than the transient used in the usual papers (Igari et al., 2000)(Okajima et al., 2014).

In this paper, we studied characteristics of the accumulation of the plastic strain caused by traveling of temperature distribution synchronizing with temperature rise. This study was based on finite element analyses using elastic-perfectly plastic material.

2. Prevention method for thermal ratcheting strain caused by the traveling temperature distribution

2.1 Mechanism of the thermal ratcheting

At start-up phase of fast reactors that use sodium as the coolant, large change of the coolant temperature occurs. Due to high heat transfer coefficient between the liquid sodium and the vessel wall, a sharp axial temperature gradient is generated on the vessel wall near the liquid sodium surface. Meanwhile, the temperature change of the coolant brings thermal expansion of the coolant that result in increasing of coolant level. Increasing the liquid sodium level causes the temperature distribution to move along the vessel wall.

Fig.1 The traveling temperature model of the reactor vessel near the liquid sodium surface

Figure 1 shows the traveling temperature model of the reactor vessel near the liquid sodium surface at the start-up phase. In a short time step, the temperature distribution on the vessel wall changes only in the narrow range near the liquid surface. In this narrow range, since there is constraint against the section of wall where the temperature has not changed, almost all of the thermal expansion from the temperature change is exchanged into the elastic and plastic compressive strain in the circumferential direction. Meanwhile, in surrounding region, tensile strain is caused by the thermal expansion in the narrow range with temperature change. Because of difference of rigidity, the compressive strain caused in the range with the temperature change is larger than the tensile strain caused in the surrounding region.

With a long range traveling temperature distribution, a large plastic deformation region is generated. In the center of the plastic region, spatially uniform plastic strain accumulates, and there is no residual stress after the temperature distribution has moved. In this case, because the residual stress that brings shakedown behavior does not accumulate, the plastic strain accumulates each cycle. Therefore, the lack of residual stress accumulation is the main mechanism of ratcheting due to the long traveling temperature distribution.

When the traveling range of the temperature distribution is short, constraint against the elastic part causes residual stress to accumulate (even occurs in the middle of the traveling range), as shown in Fig. 2. The magnitude of the residual stress depends on the distance from the elastic part (i.e. the traveling range of the temperature distribution). The residual stress decreases the ratcheting strain increment in the following cycles. With the sufficient constraint against the elastic part, the residual stress increases with transient cycles, until finally shakedown occurs.

Fig.2 Comparison of residual stress distributions for different traveling ranges

2.2 Mechanism-based evaluation method (Igari et al., 2000)

Igari et al. (2000) formulated the residual stress based on the Timoshenko's shell theory (Timoshenko and Krieger, 1959), using hot-spot model consisting of very short region on the cylinder with hot temperature and the residual cold part. This hot-spot-shape temperature distribution causes compressive plastic strain in very short region and compressive thermal membrane stress in the residual part.

In the case when this temperature distribution moves on axial direction, plastic deformation is caused in an entire part passed through by the temperature distribution. When the residual stress in part that is not passed through the temperature distribution reaches the yield strength, part with the plastic deformation expands and the constraint against elastic part is reduced. Because of this reason, Igari et al. explained that shakedown occurs when yielding does not occur at start and end point of the temperature distribution movement.

2.3 Screening criteria proposed in the previous study (Okajima et al., 2014)

In the previous paper (Okajima et al., 2014), we proposed a screening method of thermal ratcheting strain for practical components design. The proposed method initially determines whether plastic deformation occurs at all points through the wall thickness. If all points of certain cross-section are in the plastic state, the proposed method determines whether the plastic strain saturates based on axial length of the plastic deformation area, l_p . To prevent the continuous accumulation of the plastic strain, we required to satisfy Eq.(1) in the previous paper. Equation (1) was validated by a set of finite element analyses using elastic perfectly plastic material.

$$\beta l_p \leq 0.93 \quad (1)$$

where β is Timoshenko's shell parameter (Timoshenko and Krieger, 1959), which can be obtained by Eq.(2).

$$\beta = \frac{\sqrt[4]{3(1-\nu^2)}}{\sqrt{r \cdot t}} \quad (2)$$

where r and t are inner radius and thickness of the cylinder. ν is Poisson's ratio of the cylinder material.

3. Analytical study

3.1 Conditions and procedures

3.1.1 Heat transfer analysis

To study feature of the plastic strain accumulation, we carried out a series of finite element analyses for the model

with traveling of temperature distribution synchronizing with temperature rise. The analyses series consist of 2 types of analyses: heat-transfer analyses and structure analyses. Conditions used in these analyses are shown in this section. The FEM code and element used in these analyses were FINAS (Iwata et al., 1982) Ver.21 and the 8-node axisymmetric solid element, respectively.

At first, we carried out heat transfer analysis to obtain temperature response against the heat transient that imitates transient in startup and shutdown processes. Figure 3 shows the heat transients used in the case whose increase rate of the coolant level are 20 mm/hour and 25mm/hour, as the example of the heat transient. In other cases, we used similar heat transient corresponding to the level increase rate. At the end of the startup and shutdown transient (that is 100 and 200 hour in Fig. 3 a)), we carried out steady heat conduction analyses.

Figure 4 shows comparison of assumed heat transient between this paper and the conventional studies (Igari et al., 2000)(Okajima et al., 2014). Because the traveling of the coolant level is results of the change of the coolant temperature, without any conscious control, the increasing of the coolant level is synchronizing with the increasing of the coolant temperature as shown as Fig.4 (a). In this paper, we assumed this type of heat transients.

In spite of the above mechanism, simplified heat transients are used in the conventional studies (Igari et al., 2000)(Okajima et al., 2014). These simplified transients are characterized by increasing of the coolant level after increasing of the coolant temperature, as shown as Fig.4 (b). In these simplified transient models, maximum thermal stress is caused on the entire traveling range of the coolant surface that results in larger plastic strain. That is to say, the conventional studies have been used the heat transient with the conservative assumption.

a) Increase rate of the coolant level is 20 mm/hour

b) Increase rate of the coolant level is 25 mm/hour

Fig. 3 Sample of heat transient used in the analyses

Fig. 4 Comparison of assumed heat transient between this paper and conventional study

3.1.2 Structural analysis

After the heat transfer analysis, we carried out structural analyses. In these analyses, we used the temperature distribution evaluated by the heat transfer analysis as input data.

In the structural analyses, we carried out elastic analyses to obtain the axial length of the plastic deformation area, l_p , at first. We predicted l_p as the length of the area in which Eq. (3) is satisfied, that is, as the length of the area in which the membrane stress intensity exceed yield stress.

$$\langle P_m + Q_m \rangle_{\max} > S_{yh} \quad (3)$$

where P_m and Q_m are Primary and Secondary membrane stress. $\langle \rangle_{\max}$ denotes maximum value of stress intensity. S_{yh} is yield stress associated with the higher wall averaged temperature for the stress extremes defining the secondary stress range.

After the elastic analysis, we carried out inelastic finite element analysis assuming elastic-perfectly plastic material, which is often assumed in the design evaluation process. To simulate elastic-perfectly plastic material, we defined strain-hardening coefficient as one-thousandth of the Young modulus.

3.1.3 Conditions of the finite element analysis

Figure 5 shows boundary conditions used in the heat-transfer and the structural analyses. Table 1 shows physical properties used in these analyses. We defined properties as the value for 316FR stainless steel on 550°C.

Fig. 5 Boundary conditions used in the analyses

Table 2 shows the cases evaluated in this study. In all cases, lengths of the increasing of the coolant level are same value, 1200 mm. Meanwhile, in order to study the cases with various value of the length of plastic deformation area, we varied increase rates of the coolant level and temperature. We used 20, 25, and 30mm/hour as the increase rate of the level. In addition, we planned to investigate 3 types of effects: effect of temperature dependency of the yield stress, effect of primary stress due to weight load and internal pressure, and thickness ratio of the reactor vessel.

Table 1 Properties used in the analyses (JNC, 2005)

Thermal conductivity of the vessel [W/(m · K)]	23.0
Specific heat [J/(kg · K)]	5.72×10^2
Density [kg/m ³]	7.97×10^3
Young Modulus, E [MPa]	154000
Poisson Ratio, ν	0.306
Thermal Expansion Coefficient, α [mm/mm]	20.64×10^{-6}

Table 2 Evaluated cases in the validation

	Increase rate		Yield stress	Primary stress	Radius [mm]	Thickness [mm]
	Level [mm/h]	Temperature [K/h]				
L-20	20	5.83	Constant (105MPa)	0	5350	60
L-25	25	7.29				
L-30	30	8.75				
CL-20	20	5.83	Depend on temperature			
CL-25	25	7.29				
CL-30	30	8.75				
PL-20	20	5.83	Constant (105MPa)	Internal Preessure 0.15MPa Axial tensile 18.95MPa	5350	60
PL-25	25	7.29				
PL-30	30	8.75				
PCL-20	20	5.83	Depend on temperature			
PCL-25	25	7.29				
PCL-30	30	8.75				
TL-20	20	5.83	Constant (105MPa)	0	2675	120
TL-25	25	7.29				
TL-30	30	8.75				
TCL-20	20	5.83	Depend on temperature			
TCL-25	25	7.29				
TCL-30	30	8.75				

3.2 Results

3.2.1 Heat transfer analyses

Figure 6 shows the analyzed temperature distributions on the vessel wall when the increasing of the coolant level finishes in cases L-20, L-25, and L-30, which are defined in Table 2. As shown in Table 2, numerical values in the case name indicate the increase rate of the coolant level. Larger increasing rate of the coolant level brings sharper temperature gradient nearby the coolant surface, which brings larger thermal stress on circumferential direction.

Fig. 6 Comparison of the analyzed temperature distributions

3.2.2 Elastic analyses

Figure 7 shows maximum and minimum value of the circumferential stress in the transient cycle, which is evaluated by the elastic analyses. Larger increasing rate of the coolant level brings larger thermal stress on circumferential direction. In case L-30, whose increase rate is large, thermal stress reaches yield stress earlier than case L-20. Therefore, case L-30 has larger l_p than case L-20. Because of this mechanism, although there is limitation, we can control l_p by changing increase rate of the coolant temperature and level.

Fig. 7 Comparison of the evaluated thermal stress

Table 3 shows results of the elastic structure analyses. In Table 3, $\langle P_m + Q_m \rangle_R$ denotes range of stress intensity, and β is Timoshenko's shell parameter that is obtained by Eq.(2). In the case with consideration of the temperature dependency, the yield stress at intermediate points in the traveling range become larger. As the result, length of the plastic deformation area, l_p , become smaller. The value of l_p in the case CL-25 was nearly equal to maximum value that satisfy Eq.(1).

Table 3 Results of the elastic analyses

	$\langle P_m + Q_m \rangle_{\max}$ [MPa]	$\langle P_m + Q_m \rangle_R$ [MPa]	Yield stress	l_p [mm]	β_{lp} [-]
L-20	129	184	Constant (105MPa)	300	0.69
L-25	143	209		685	1.56
L-30	157	234		800	1.84
CL-20	129	184	Depend on temperature	250	0.58
CL-25	143	209		425	0.97
CL-30	157	234		575	1.29
PL-20	126	184	Constant (105MPa)	265	0.59
PL-25	140	209		635	1.44
PL-30	154	234		775	1.78
PCL-20	126	184	Depend on temperature	225	0.51
PCL-25	140	209		410	0.92
PCL-30	154	234		495	1.18
TL-20	131	187	Constant (105MPa)	421	0.95
TL-25	146	213		648	1.47
TL-30	160	236		753	1.71
TCL-20	131	187	Depend on temperature	340	0.77
TCL-25	146	213		446	1.01
TCL-30	160	236		543	1.23

3.2.3 Inelastic analyses

Figure 8 shows axial distributions of the accumulated plastic strain on the circumferential direction evaluated by the analyses with elastic-perfectly plastic material. In the case L-20, whose increase rate is small, the accumulation of the circumferential plastic strain was quickly saturated. On the other hand, in the case L-30, whose increase rate is large, the circumferential plastic strain accumulated continuously.

Fig. 8 Accumulation of the circumferential plastic strain

Table 4 shows the results of the inelastic finite element analyses. In the Table 4, values of the accumulated plastic strain at the end of the 1st and 10th cycles of the heat transient are shown.

In order to study whether the plastic strain accumulates even after 2nd cycle, we focused on the ratio of plastic strain at 10th cycle to that at 1st cycle. In the case when this ratio is larger than 1, the plastic strain accumulates even after 2nd cycle. Figure 9 shows relation between this ratio of the circumferential plastic strain and βl_p . β is Timoshenko's shell parameter that is obtained by Eq.(2). l_p is the axial length of the plastic deformation area that is obtained in 3.1.2.

As shown in Fig.9, regardless of the existence of the primary stress, the temperature dependency of the yield stress, and the radius/thickness ratio of the reactor vessel, the ratio of circumferential plastic strain depends on βl_p . Therefore, we proved βl_p to be dominant parameter for the saturation of the plastic strain accumulation. In the cases when βl_p is smaller than about 1.3, significant circumferential plastic strain did not increase after 2nd cycle. Therefore, we confirmed that the proposed criteria in the previous paper (Okajima et al., 2014), which require that βl_p is smaller than 0.93 as shown in Eq.(1), prevents continuous accumulation of the plastic strain with reasonable margin, even in the case with the synchronizing increase of coolant temperature and level.

In spite of ratcheting mechanism shown in section 2, which brings circumferential plastic strain, axial plastic strain was accumulated continuously in cases PL-25 and PL-30. As shown in Table 3, $\langle P_m + Q_m \rangle_R$ was nearly equal to shakedown range ($105 \times 2 = 210 \text{ MPa}$) in case PL-25, and it exceeded shakedown range in case PL-30. Therefore, we thought that the accumulation of the axial plastic strain in cases PL-25 and PL-30 was derived from excessive thermal stress range. The proposed method in the previous paper (Okajima et al., 2014) assumed the membrane stress range below the shakedown range.

Table 4 Results of the inelastic analyses

	l_p [mm]	βl_p [-]	Accumulated Plastic Strain (Spatial Maximum, 10^{-4} mm/mm)			
			Circumferential		Axial	
			1 st	10 th	1 st	10 th
L-20	300	0.69	-3.9	-3.7	1.9	2.7
L-25	685	1.56	-5.0	-6.1	2.4	3.8
L-30	800	1.84	-6.2	-11.3	2.9	5.4
CL-20	250	0.58	-3.9	-3.6	2.0	2.5
CL-25	425	0.97	-5.1	-4.8	2.6	3.0
CL-30	575	1.29	-6.3	-7.0	3.2	4.0
PL-20	265	0.59	-3.5	-3.0	3.5	6.1
PL-25	635	1.44	-4.6	-5.0	4.1	11.2
PL-30	775	1.78	-5.8	-9.8	4.7	21.5
PCL-20	225	0.51	-3.7	-3.4	3.7	4.9
PCL-25	410	0.92	-4.8	-4.2	4.3	6.1
PCL-30	495	1.18	-6.0	-6.0	5.0	8.3
TL-20	421	0.95	-4.5	-4.5	1.9	2.4
TL-25	648	1.47	-5.6	-7.4	2.4	3.5
TL-30	753	1.71	-6.7	-12.0	3.0	4.5
TCL-20	340	0.77	-4.4	-3.9	1.9	2.0
TCL-25	446	1.01	-5.7	-5.7	2.5	2.9
TCL-30	543	1.23	-7.0	-8.0	3.2	4.0

Fig. 9 Relation between ratio of the accumulated plastic strain and the length of the plastic deformation area

4. Conclusions

In this paper, we studied characteristics of the accumulation of the plastic strain caused by traveling of temperature distribution synchronizing with temperature rise. This study was based on finite element analyses using elastic-perfectly plastic material.

As a result, we confirmed that the saturation of the plastic strain accumulation depends not on the traveling range

of the temperature distribution but the plastic deformation range, which was predicted by the elastic analysis. Additionally, in the cases when βl_p is smaller than about 1.3, significant circumferential plastic strain did not increase after 2nd cycle. Therefore, we confirmed that the proposed criteria in the previous paper (Okajima et al., 2014), which is formulated as Eq.(1), prevents continuous accumulation of the plastic strain with reasonable margin. In the actual application, we can control the plastic deformation range by increasing rate of the liquid level.

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