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Journal of Nuclear Materials 305 (2002) 21–28

journal of nuclear materials

www.elsevier.com/locate/jnucmat

The secondary stress analyses in the fuel pin cladding due to the swelling gradient across the wall thickness

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Received 19 November 2001; accepted 16 June 2002

Abstract

Irradiation deformation analyses of FBR fuel cladding were made by using the finite element method. In these analyses the history of the stress occurred in the cladding was evaluated paying attention to the secondary stress induced by the swelling difference across the wall thickness. It was revealed that the difference of the swelling incubation dose in the direction of the thickness and the irradiation creep deformation play an important role in the history of the secondary stress. The effect of the stress-enhanced swelling was also analyzed in this study.

PACS: 41.81.B; 61.25.H; 83.50.B

1. Introduction

In the highly irradiated FBR fuel cladding, the void swelling occurs due to the radiation damage by the fast neutron irradiation. Under the irradiation, the cladding has temperature gradients in the direction of the thickness because the heat must be conducted from fuel to coolant. Fig. 1 shows schematically such phenomenon. In general, the swelling has the temperature dependence and it causes the swelling difference across the thickness of the cladding. Fig. 2 shows microstructures of the fuel cladding of 20% cold worked P, Ti modified 316 stainless steel irradiated up to about 100 dpa in FFTF reactor [1]. These microstructures were taken at the same axial position near the center of the core but the positions in the direction of the thickness are different each other. The voids were observed and it is clear that their number densities are different among these positions through the wall thickness of the tube.

As shown in Fig. 1, such swelling difference induces the internal secondary stress gradient across the thickness of the cladding. Selan et al. reported that CW316Ti fuel claddings took similar behavior, and moreover that the secondary stress might have an effect on the swelling enhancement [2]. It is important form the view point of effect on the swelling enhancement [2]. It is important from the view point of studying the integrity of the fuel pin cladding to evaluate the secondary stress level caused by the swelling gradient and stress relief by irradiation creep as well as the stress effect on the swelling enhancement.

These analyses should lead to some evidence that the swelling of the cladding irradiated as a fuel pin is enhanced more than that irradiated as a tube specimen without fuel in stress-free condition, since swelling properties are unique only in the fuel pin with the temperature gradient in the direction of the cladding thickness [1,2].

In this study, the secondary stress and its effect on the swelling behavior are investigated based on the deformation analyses of the cold worked 316Ti fuel cladding highly irradiated in the Phenix reactor by means of the finite element method.

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PII: S0022-3115(02)00909-1

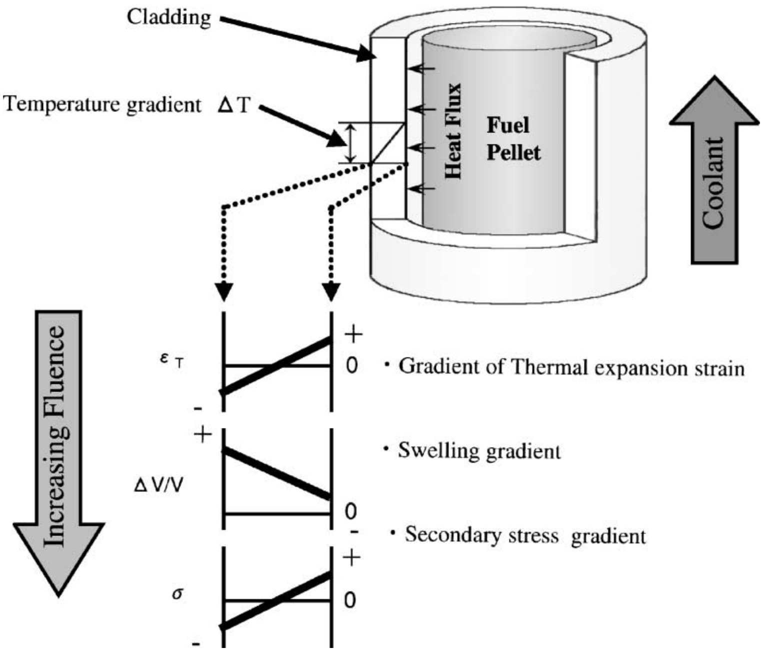


Fig. 1. Schematic of the gradients of swelling and the secondary stress in the wall thickness of the FBR fuel cladding during irradiation.

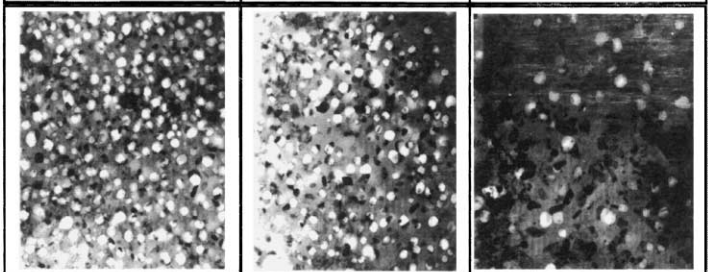
	Near-outer surface	Mid-wall	Near-inner surface
			
Average temperature during irradiation	484℃	502℃	521℃
Swelling	8.36vol.%	8.07vol.%	2.15vol.%

Fig. 2. Microstructure of 20% cold worked P, Ti modified 316 stainless steel irradiated up to 100 dpa in FFTF.

2. Method of the analyses

2.1. Analytical model of irradiation deformation of the fuel cladding

The fuel pin selected in the analyses is the one from the assembly irradiated in Phenix reactor. The maximum burn up and dose level of this subassembly are about 12 at.% and 110 dpa, respectively. The material of the fuel cladding used is 20% cold worked 316Ti stainless steel. After the irradiation, large diametral strain of 6–7% occurred due to the swelling in the fuel claddings. It is suspected that the swelling gradient is large in the direction of the thickness from the similar results reported by Selan et al. [2].

Fig. 3 shows the schematic of the one dimensional finite element method model in the direction of the wall thickness to analyze the stress of the cladding under the

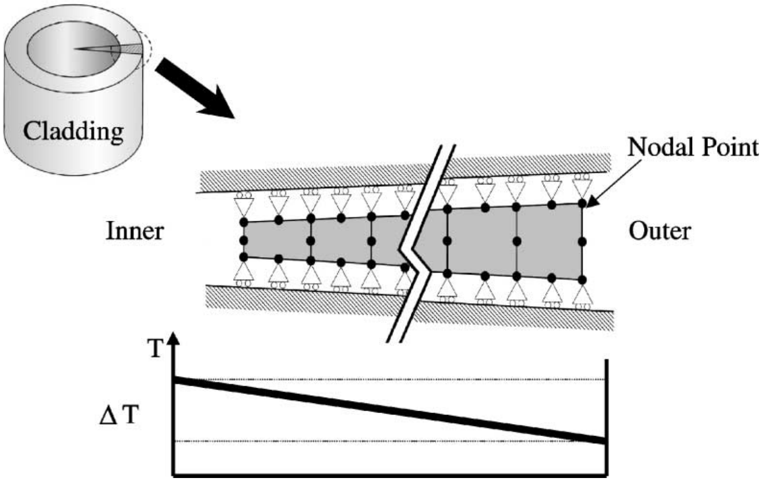


Fig. 3. Schematic of analysis model by finite element method.

irradiation. In this model 9-node generalized plain strain elements are used to consider that the axial strain is constant because both the axial ends of fuel cladding are connected by end plugs.

The wall thickness is divided into 50 meshes of elements so as to calculate the detailed distribution of the stress in the cladding during the irradiation. The temperature gradient is set across the wall, and the swelling gradient in the thickness is generated according to the temperature dependence of the cladding. The irradiation behaviors of the fuel cladding considered in this model are thermal expansion, swelling, increasing of fission gas pressure, stress relaxation due to the irradiation creep. The mechanical interaction between fuel and cladding (FCMI) is not considered in the analyses.

2.2. Swelling and irradiation creep properties

In the analyses the properties of swelling and irradiation creep of the fuel cladding play very important roles. Eq. (1) is a basic equation of the swelling

$$S = R_0(\phi_t - \tau_0), \tag{1}$$

where S is the volume swelling; ϕ_t, the fast neutron dose; R_0, the constant swelling rate; τ_0, the swelling incubation dose.

This equation means that the swelling increases with fast neutron dose ϕ_t at the constant rate of R_0 after the neutron dose ϕ_t exceeds the swelling incubation dose τ_0. R_0 and τ_0 are temperature dependent parameters. Fig. 4 shows the temperature dependence of R_0 and τ, which were used in this analysis [3]. Fig. 5 represents swelling characteristics at three equal dose levels as a function of

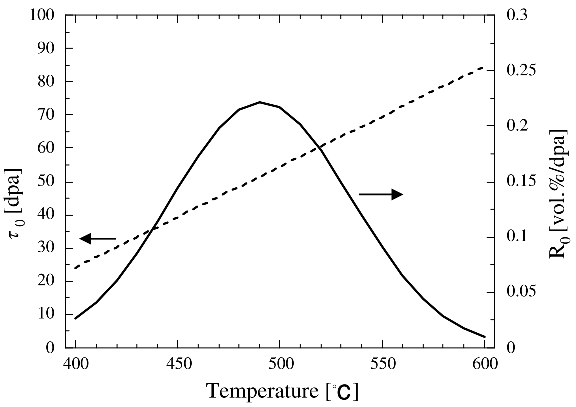


Fig. 4. Temperature dependence of R_0 and τ_0 in swelling property.

temperature, which can be derived using the temperature dependences of R_0 and τ_0.

The properties of the irradiation creep are indicated by the following equation:

$$\varepsilon_c = B_0\phi_t\sigma + DS\sigma, \tag{2}$$

where ε_c is the equivalent irradiation creep strain; σ, the equivalent stress; ϕ_t, the fast neutron dose; S, the volume swelling; B_0, D, the temperature and stress dependent parameters.

The irradiation creep strain is the sum of the creep component proportional to dose and that accelerated by the swelling. Fig. 6 shows the temperature dependence of B_0 and D, which take larger values with

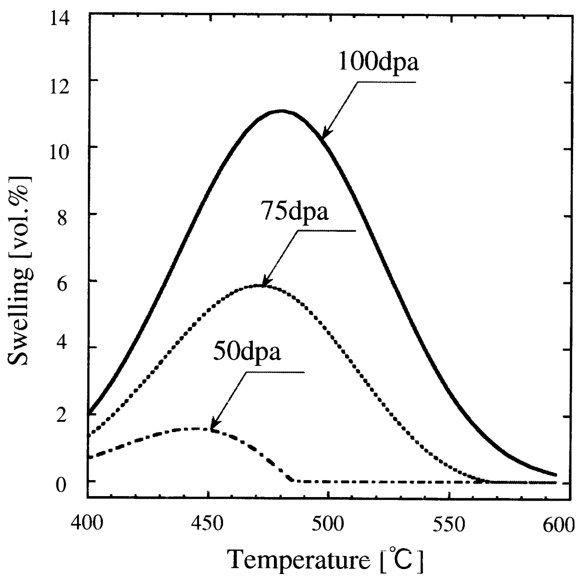


Fig. 5. Temperature dependence of the swelling.

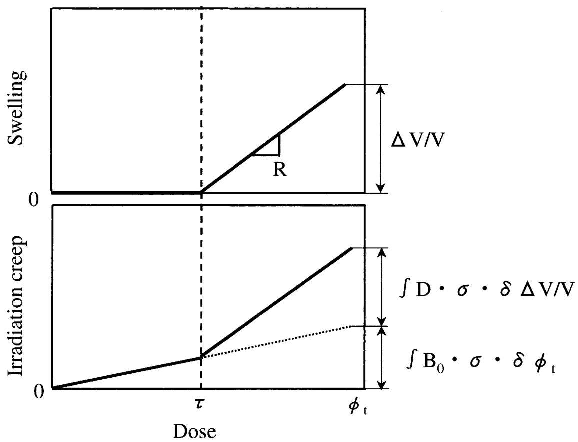


Fig. 7. Schematic of swelling and irradiation creep properties.

increasing temperature [3]. In particular, B_0 is characterized to be affected by the applied stress. Fig. 7 shows the schematic of the property of swelling and irradiation creep as a function of neutron dose. The swelling induces an enhancement of the irradiation creep and it plays an important role for analyzing the stress relaxation of the secondary stress, which will be described later.

2.3. Analysis conditions

The conditions in the analysis are summarized as follows.

(1) Geometry

The fuel cladding diameter and thickness are 6.55 and 0.45 mm, respectively, which are typical design geometries for Phenix driver fuel cladding.

(2) Irradiation conditions

Before start-up of the reactor the temperature of the cladding is 387 °C and constant across the wall thickness. After start-up cladding has linear temperature gradient between outer and inner surface whose tem-

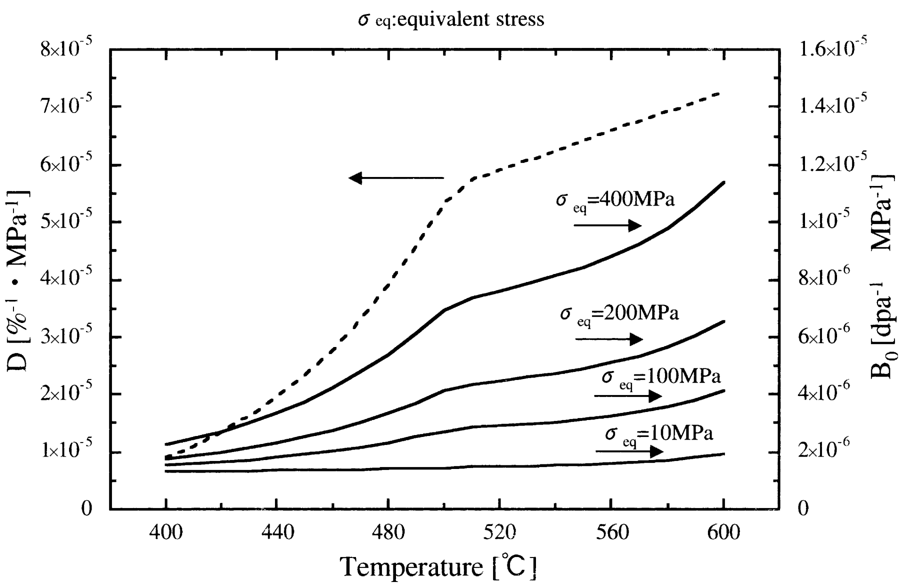


Fig. 6. Temperature dependence of the irradiation creep parameters B_0 and D.

peratures are 465 and 505 °C, respectively. This temperature gradient was assumed to be kept during the irradiation.

The neutron dose linearly increases with time up to 104 dpa at the end of the irradiation. These conditions correspond to those at the center of the core region of the fuel pin. The internal pressure of the fuel pin was assumed to be 0.23 MPa at the beginning of irradiation and linearly increase up to 10 MPa at the end of irradiation to simply consider the accumulation of the fission gas.

3. Results and discussion

3.1. Mechanism of the stress history

Fig. 8 shows the analytical results for the hoop stress histories at three regions, e.g., inner surface, mid-wall and outer surface, in the wall thickness of the cladding compared with swelling histories in relation to neutron dose. At the beginning of the irradiation tensile stress is induced at outer surface and compressive stress at inner surface due to the thermal expansion difference across the wall thickness. In the inner region of the cladding, the thermal expansion is larger and constrained by the outer region. As the result, the hoop stress in this region becomes compressive, whereas the outer region of the cladding is tensed by larger thermal expansion of the inner region and the stress becomes tensile. These stresses caused by the thermal expansion difference are relaxed by the irradiation creep deformation. The slightly gradual increase of the hoop stress over the irradiation period except the middle of the irradiation is the result of the simplified history of the internal pressure. The steady state stress at the outer region is slightly larger than that at inner region until the end of irradiation. This is attributed to the difference of the constant swelling rate R_0 of Eq. (1) at each location of the wall thickness. The significant changes of the stresses in the middle of the irradiation are associated with the onset of the swelling. These changes are due to secondary stress caused by the swelling difference across the wall thickness.

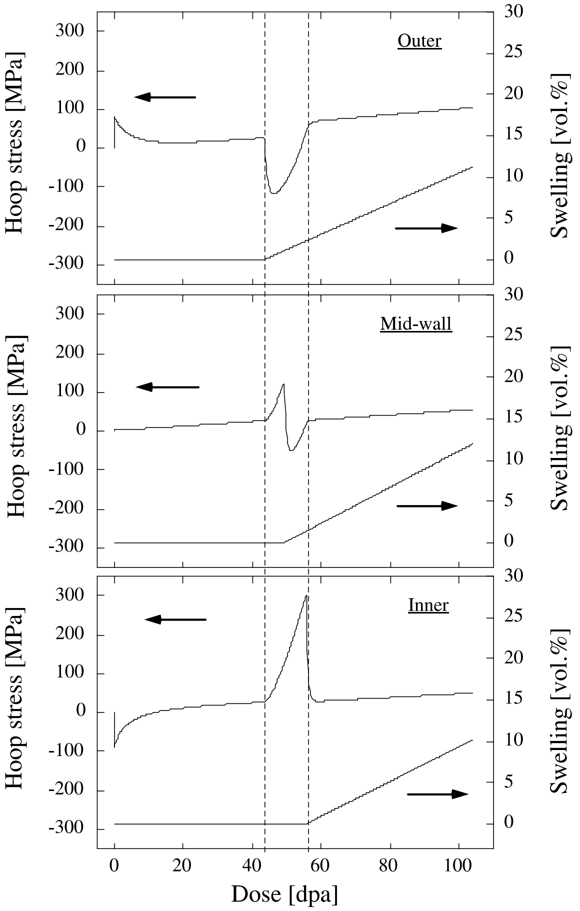


Fig. 8. Histories of hoop stress and swelling during irradiation.

From this figure, it is recognized that the secondary stress is caused by the difference of the incubation dose between inner and outer surfaces of the cladding. In the outer region the swelling occurs earlier than the inner region because the incubation dose is shorter. Therefore, the outer region is constrained from the inner region and the stress become compressive. Then this stress is relaxed by the irradiation creep accelerated by gradual increase of the swelling. Whereas the inner region becomes tensile because in the outer region swelling occurs earlier. The secondary stress in the inner region increases until onset of the swelling. After onset of the swelling, the secondary stress is relaxed due to the irradiation creep accelerated by the swelling. Therefore, there is a peak of about 300 MPa in the history of the secondary stress in the inner region of the cladding. However, this stress level is sufficiently lower than the reported tensile strength level of irradiated cold worked 316Ti [4].

It can be said from this analysis that the secondary stress occurs only during the period from onset of swelling at outer region to inner region, and this stress level induced by swelling difference across the wall thickness should not affect the fuel pin integrity, because the secondary stress is readily relaxed by the irradiation creep deformation. After onset of the swelling the irradiation creep is enhanced by the swelling interaction term in Eq. (2). Fig. 9 shows the irradiation creep rate of neutron dose proportional term, $B_0\sigma$, and swelling interaction one, $DS\sigma$, in Eq. (2) separately. The irradiation creep rate is accelerated to be about twice by interaction with the swelling. Fig. 10 shows the difference in stress

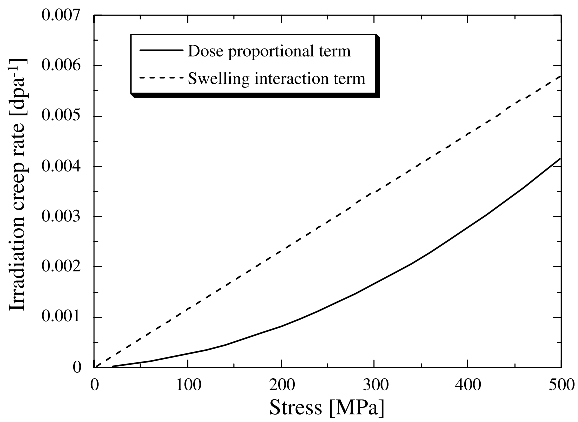


Fig. 9. Property of irradiation creep rate of individual term at 500 °C of Eq. (2).

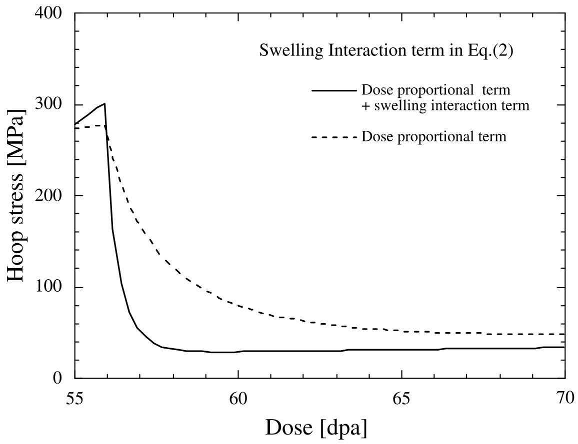


Fig. 10. History of stress relaxation at inner surface of the cladding.

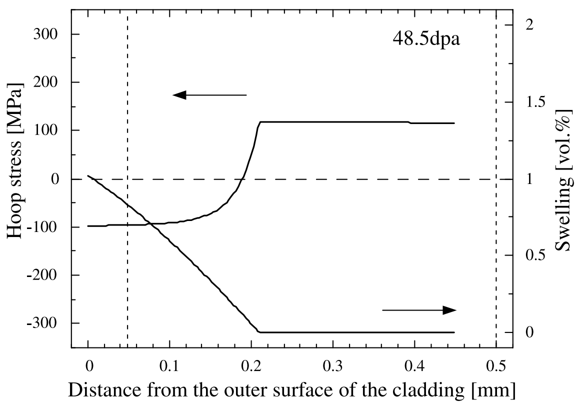


Fig. 11. Radial distributions of stress and swelling.

relaxation history at inner surface in two cases: the irradiation creep enhanced by the swelling and that of only dose proportional term. It is recognized that the stress is effectively relaxed by the creep deformation enhanced by the swelling.

Fig. 11 shows the analytical result for swelling and resulted stress distributions along the wall thickness at the intermediate neutron dose of 48.5 dpa, when the swelling takes place from the outer surface to the middle of the wall thickness. In the local position of the swelling region, the stress is compressive and in the non-swelled region, the stress is tensile. The stress distribution in the swelled region is almost constant due to the relaxation by the irradiation creep accelerated by the swelling. The steep change of the stress distribution at the boundary between no swelling and swelling regions in the wall thickness is attributed to the swelling property where the swelling takes place at the constant rate without curvature as shown in Fig. 7. In the actual fuel cladding, stress distribution along the wall thickness would be milder than the result of this analysis because swelling rate gradually increases up to constant rate with the neutron dose.

3.2. Effect of stress induced swelling

The histories of swelling and stress are analyzed in the condition that the swelling is enhanced by the secondary stress due to the swelling difference in the direction of thickness by using the finite element model used in the previous analysis. The stress effect on the swelling has been investigated and empirically formulated in the following simple equations [5]

$$R(\sigma) = R_0(1 + p\sigma), \tag{3}$$

$$\tau(\sigma) = \tau_0 - q\sigma, \tag{4}$$

where R_0 and τ_0 are constant swelling rate and incubation dose induced as given in swelling of Eq. (1), respectively. The p and q are parameters which relate the enhancement of the swelling rate and shortening of the incubation dose with respect of the applied stress σ, respectively. The effects of stresses due to thermal expansion difference and internal pressure are small and not considered in this analysis to evaluate the only effect of the secondary stress due to the swelling difference.

It has not been clarified what kind of stress affects effectively the swelling enhancement. However it is suspected that the direct interaction between stress and the efficiency of the void absorption of interstitials is not the major cause of the swelling enhancement. Because in this case the compressive stress would suppress the swelling. But experimental results indicated that both tensile and compressive stresses enhance the swelling [6]. Therefore it is considered that evolution of dislocation structure is promoted by any kind of stresses, and thus acceleration of radiation induced microstructure change enhances the swelling. Considering these phenomena, the swelling is considered to be always promoted by the stress. And for simplifying calculations, the equivalent Von Mises type stress is adopted in the present analysis as the applied stress.

By taking the equivalent stress in Eqs. (3) and (4), the incubation dose τ is shortened and the constant swelling rate R is accelerated by the secondary stress during the period that the swelling is initiated. As a parameter, the possible ranges of p and q are selected to 0.006–0.015 MPa^{-1} and 0.075 dpa^{-1} MPa^{-1}, respectively, which were obtained from Ref. [5,7,8]. The radiation induced deformation analysis was conducted considering the stress effect on the swelling with the swelling equation (1) where R_0 and τ_0 were substituted by those in Eqs. (3) and (4). The parameters p and q are set to be 0.015 and 0.075, respectively. Fig. 12 shows the histories of hoop stress and swelling at outer and inner surfaces compared with those with $p = q = 0$. At the outer surface the swelling occurred at the same dose in both cases, while at the inner surface, the swelling occurred much earlier due to the shortening of incubation dose. Therefore the difference of the incubation dose between inner and outer surfaces becomes little and the period of increasing secondary stress at the inner surface is shortened. The secondary stress is also relaxed immediately after the swelling occur due to the enhanced irradiation creep. Consequently, the peak level of secondary stress is not so large as the case of the stress-free swelling, and the enhancement of the swelling due to the secondary stress is not significant. It can be suggested that the swelling of the fuel cladding is enhanced by the secondary stress, but the difference of the swelling in the wall thickness would not be so large, because duration of the stress loading is shortened by decreasing a difference of incubation dose between inner and outer region of the cladding due to the stress effect.

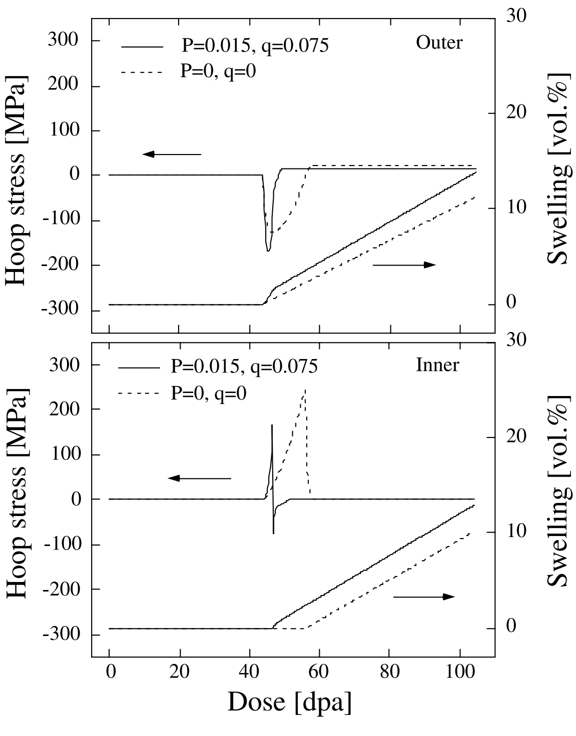


Fig. 12. Histories of hoop stress and swelling during irradiation.

4. Conclusions

The analyses of secondary stress of the fuel cladding due to the swelling gradient in the direction of thickness were made by the radiation induced deformation model using the finite element method. The following results were obtained.

(1) The secondary stress is caused mainly by the gradient of the swelling incubation dose. The secondary stress dose not become significant at the end of irradiation due to the relaxation of the stress by the irradiation creep deformation enhanced by the swelling.
(2) The effect of the stress-enhanced swelling on the secondary stress was analyzed. The result shows that the secondary stress becomes rather smaller than that of non-stress induced swelling though the swelling becomes larger because the difference of incubation period at inner and outer surfaces is shortened and induced stress is readily relaxed by the enhanced irradiation creep. It is suggested that the secondary stress due to the swelling difference dose not significantly affect the integrity of the fuel pin cladding.

Acknowledgements

The authors would like to thank Jacques Truffert of Cadarache in CEA for providing material property equations of CW 316Ti. The authors also would like to thank M. Ito of Nuclear Engineering System Inc. for his assistance in conducting the finite element analysis of this study.

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