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A CONSTITUTIVE EQUATION OF CREEP, SWELLING AND DAMAGE UNDER NEUTRON IRRADIATION APPLICABLE TO MULTIAXIAL AND VARIABLE STATES OF STRESS

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Abstract—A constitutive equation of creep, swelling and damage under neutron irradiation applicable to general conditions of stress, including stress change in direction as well as in magnitude, is developed. The creep related to irradiation is divided into irradiation-induced creep and irradiation-affected thermal creep. The irradiation-induced creep is formulated by taking account of the stress-induced preferential absorption (SIPA) mechanism and climb-controlled glide (CCG) mechanism and by postulating an isotropic tensor function of stress of order zero and order one which is also a function of neutron flux and neutron fluence. The irradiation-affected thermal creep, on the other hand, is modeled by extending the creep-hardening surface model of variable stress creep to include the effects of neutron irradiation and damage. The validity and utility of the proposed constitutive equation are discussed by applying it to the creep of type 316 stainless steel at 650°C subjected to some stress histories including reversed loading and non-proportional loading under different irradiation conditions.

1. INTRODUCTION

Irradiation with high energy neutrons usually induces significant effects on the mechanical behavior of structural materials by creating interstitial atoms, vacancies, dislocation loops and other microstructural changes in the materials. Thus creep and creep damage under neutron irradiation are among the most crucial phenomena in nuclear structure components operating at elevated temperature under intensive flux of high energy fission or fusion particles. The authors (Murakami *et al.*, 1991; Murakami and Mizuno, 1991) recently developed a constitutive equation of creep, swelling and damage of polycrystalline metals in order to facilitate rational and accurate analyses of these components by incorporating it into computer algorithms.

By taking account of the physical mechanisms of creep under neutron irradiation and ordinary thermal creep, the constitutive equation was formulated by dividing the creep into irradiation-induced creep and irradiation-affected thermal creep. The irradiation-affected thermal creep, in particular, was formulated by extending the creep damage theory of Kachanov–Rabotnov to include the effects of neutron irradiation. However, because of the classical time-hardening and strain-hardening theory postulated in the equation, the applicability of the constitutive equation of irradiation-affected thermal creep was limited to a rather insignificant change of stress state.

In the first wall of fusion reactors, for example, the direction and the magnitude of stress are subject to salient change with burn cycles of plasma (Harries and Zolti, 1986). This change in the stress induces significant transient increase of creep rates, and has a large influence on the initiation and the growth of creep cracks in the materials. Thus, the constitutive equations of creep under irradiation are required to describe this transient increase of creep rate brought about by the salient change of stress.

The present paper is concerned with the elaboration of a constitutive equation of creep, swelling and damage to conform to a significant change in magnitude and direction of stresses. The creep-hardening surface model of non-steady creep proposed by the authors (Murakami and Ohno, 1982) is extended to include the effects of irradiation and material damage to give a constitutive equation of irradiation-affected thermal creep.

2. ELABORATION OF CONSTITUTIVE EQUATION OF CREEP, SWELLING AND DAMAGE UNDER IRRADIATION

In order to facilitate the discussion of this paper, we will first make a brief review of the previous works on a constitutive equation of creep under irradiation and that of unirradiated creep under variable states of stress. Then, we will discuss the elaboration of the constitutive equation of irradiation-affected thermal creep by extending the creep-hardening surface model of non-steady creep to include the effects of irradiation and material damage.

2.1. *Constitutive equation of creep under irradiation and that of unirradiated creep under variable states of stress*

2.1.1. *Irradiation-induced creep.* In the previous papers (Murakami *et al.*, 1991; Murakami and Mizuno, 1991) a constitutive equation of creep, swelling and damage under irradiation was formulated by dividing the total creep strain under irradiation, ε_{ij}^{C}, into irradiation-affected thermal creep, ε_{ij}^{ITC}, and irradiation-induced creep, ε_{ij}^{IIC}: the former is thermal creep affected by irradiation while the latter occurs only under irradiation even under the condition of vanishing stress.

In contrast to the irradiation-affected thermal creep, the stress-dependence of the irradiation-induced creep is small and the anisotropy of material properties caused by the irradiation may be insignificant (Ehrlich, 1981). Then, by taking account of the stress-induced preferential absorption (SIPA) mechanism and the climb-controlled glide (CCG) mechanism (Ehrlich, 1981; Gittus, 1978) for irradiation-induced creep, the present authors described the irradiation-induced creep rate $\dot{\varepsilon}_{ij}^{IIC}$ by an isotropic tensor function of stress σ_{ij} of order zero and order one as follows (Murakami *et al.*, 1991; Murakami and Mizuno, 1991):

$$\dot{\varepsilon}_{ij}^{IIC} = \eta\delta_{ij} + \xi\sigma_{kk}\delta_{ij} + \zeta\sigma_{ij}, \tag{1}$$

where δ_{ij} denotes the Kronecker delta, while η, ξ and ζ are material functions of neutron flux ϕ and neutron fluence $\Phi = \int \phi \, \mathrm{d}t$.

Since the irradiation-induced creep $\dot{\varepsilon}_{ij}^{IIC}$ represents dimensional change of material under irradiation, the volumetric part of ε_{ij}^{IIC} can be identified with the swelling S. Its deviatoric part, on the other hand, can be interpreted as the irradiation creep. By dividing eqn (1) into isotropic and deviatoric parts and rearranging the coefficients of eqn (1), we finally have the constitutive equation of irradiation-induced creep as follows (Murakami and Mizuno, 1991):

$$\dot{\varepsilon}_{ij}^{IIC} = \tfrac{1}{3}\dot{S}\delta_{ij} + \tfrac{3}{2}P\phi\sigma_{Dij}, \tag{2a}$$

$$\dot{S} = C\langle 1 + Q\sigma_{kk}\rangle\phi\left[1 - \frac{e^{R(\chi-\Phi)}}{1+e^{R(\chi-\Phi)}}\right], \quad \langle x\rangle = \begin{cases} 0, & x < 0, \\ x, & x \geqslant 0 \end{cases}, \tag{2b}$$

where P, C, Q, χ and R are material constants, and σ_{Dij} represents the deviatoric parts of σ_{ij}. The symbol $\langle \ \rangle$ denotes Macauley brackets.

2.1.2. *Creep hardening surface model under unirradiated and undamaged condition.* Thermal creep of polycrystalline metals under unirradiated conditions, on the other hand, shows salient dependence on stress or strain history. In the case of the classical strain-hardening theory, in particular, the thermal creep rate $\dot{\varepsilon}_{ij}^{TC}$ is expressed as a function of stress and the history of creep strain ε_{ij}^{TC} as follows (Kraus, 1980; Boyle and Spence, 1983; Ohno, 1990):

$$\dot{\varepsilon}_{ij}^{TC} = \frac{3}{2} f(\sigma_{EQ}; q) \frac{\sigma_{Dij}}{\sigma_{EQ}}, \qquad \dot{q} = (\tfrac{2}{3}\dot{\varepsilon}_{ij}^{TC}\dot{\varepsilon}_{ij}^{TC})^{1/2}, \tag{3a, b}$$

where σ_{EQ} and σ_{Dij} denote equivalent stress and deviatoric stress, respectively. The symbol q in eqn (3a), furthermore, is a creep-hardening variable (i.e. an internal state variable) representing the state of creep-hardening of the material.

The conventional theory represented by eqns (3a,b), however, cannot describe the transient increase of creep rate which is observed after stress reversals or change in stress direction (Murakami and Ohno, 1982), because the creep-hardening variable q cannot adequately describe the recovery of material hardening after the stress change.

In order to overcome this difficulty, Murakami and Ohno introduced a hyper-sphere (creep-hardening surface) in a creep strain space as follows (Murakami and Ohno, 1982):

$$g = \tfrac{2}{3}(\varepsilon_{ij}^{TC} - \alpha_{ij})(\varepsilon_{ij}^{TC} - \alpha_{ij}) - \rho^2 \leqslant 0, \tag{4a}$$

where α_{ij} and ρ denote center and radius of the hyper-sphere, respectively. The evolution equations of these variables are given as follows:

$$\dot{\alpha}_{ij} = \begin{cases} (1-\lambda_0)\dot{\varepsilon}_{kl}^{TC} n_{kl} n_{ij}, & g = 0 \ \text{ and } \ (\partial g/\partial \varepsilon_{ij}^{TC})\dot{\varepsilon}_{ij}^{TC} > 0 \\ 0, & g < 0 \ \text{ or } \ (\partial g/\partial \varepsilon_{ij}^{TC})\dot{\varepsilon}_{ij}^{TC} \leqslant 0 \end{cases}, \tag{4b}$$

$$\dot{\rho} = \begin{cases} \sqrt{(2/3)}\lambda_0 \dot{\varepsilon}_{ij}^{TC} n_{ij}, & g = 0 \ \text{ and } \ (\partial g/\partial \varepsilon_{ij}^{TC})\dot{\varepsilon}_{ij}^{TC} > 0 \\ 0, & g < 0 \ \text{ or } \ (\partial g/\partial \varepsilon_{ij}^{TC})\dot{\varepsilon}_{ij}^{TC} \leqslant 0 \end{cases}, \tag{4c}$$

$$n_{ij} = \frac{\varepsilon_{ij}^{TC} - \alpha_{ij}}{[(\varepsilon_{kl}^{TC} - \alpha_{kl})(\varepsilon_{kl}^{TC} - \alpha_{kl})]^{1/2}}, \tag{4d}$$

where λ_0 is a material constant specifying the rate of developing of ρ. Thus, the creep-hardening variable q representing the state of creep hardening under a given deformation history was specified by the use of α_{ij} and ρ in eqn (4) as follows:

$$q = \frac{1}{2\lambda_0}\left[\rho + (\varepsilon_{ij}^{TC} - \alpha_{ij})\frac{\sigma_{Dij}}{\sigma_{EQ}}\right]. \tag{5}$$

In the case of uniaxial reversed loading, the above creep-hardening surface model, i.e. eqn (3a) combined with eqn (5), with $\lambda = 1/2$ lead to the ORNL (Oak Ridge National Laboratory) modified strain-hardening model (Kraus, 1980), which is one of the most popular creep constitutive equations employed in the current analyses of engineering structures. However, the complexity in algorithm and the discontinuity (or non-uniqueness) in the numerical results observed in the ORNL model for more general non-proportional loading path have been excluded in the creep-hardening surface model of eqns (3a), (4) and (5) (Murakami and Ohno, 1982).

2.2. *Extension of creep-hardening surface model to irradiation-affected thermal creep*

The glide of dislocations is usually restrained by the piling up of dislocations to various obstacles. Some restrained dislocations start to glide again by overcoming the obstacles due to climb of dislocations. The balance between glide and restraint of dislocations will determine the creep rate. Besides the transgranular glide of dislocations, the sliding of grain boundaries produces cavities on the grain boundaries and the damage of material proceeds.

The effects of neutron irradiation on thermal creep are expressed both by neutron flux ϕ and by neutron fluence $\Phi = \int \phi \, dt$. Creep deformation is enhanced and creep damage is suppressed with neutron flux ϕ which is related to the production rate of interstitial atoms. On the other hand, creep deformation is suppressed and creep damage is enhanced with neutron fluence Φ which may represent the internal structure formed by previous neutron irradiation.

If we employ the Bailey–Norton† creep equation of constant uniaxial stress

$$\varepsilon^{TC} = A\sigma^n t^m, \tag{6a}$$

and postulate the strain-hardening hypothesis, we have the following equation of multiaxial creep (Murakami and Ohno, 1982):

$$\dot{\varepsilon}_{ij}^{TC} = \tfrac{3}{2} m A^{1/m} \sigma_{EQ}^{n/m} q^{(m-1)/m} \frac{\sigma_{Dij}}{\sigma_{EQ}} = \tfrac{3}{2} f(\sigma_{EQ}, q) \frac{\sigma_{Dij}}{\sigma_{EQ}}, \tag{6b}$$

where A, n and m denote material constants.

In view of the concept of continuum damage mechanics, the damage state of material under creep can be expressed by a damage variable D. If we employ the creep damage theory of Kachanov–Rabotnov, eqn (6b) can be further extended to incorporate the effects of creep damage as follows:

$$\dot{\varepsilon}_{ij}^{TC} = \tfrac{3}{2} m A^{1/m} q^{(m-1)/m} \left(\frac{\sigma_{EQ}}{1-D}\right)^{(n-m)/m} \frac{\sigma_{Dij}}{1-D}, \qquad \dot{D} = B\left(\frac{\sigma^{(1)}}{1-D}\right)^k, \tag{7a, b}$$

where $\sigma^{(1)}$ denotes the largest principal stress, and B and k are material constants. According to the creep-hardening surface model discussed in Section 2.1, the hardening parameter in eqn (7a) can be deduced from eqns (4a)–(5).

Though the rates of creep and creep damage are accelerated or decelerated by irradiation, the essential mechanisms of irradiation-affected thermal creep may be unchanged from those of the creep and damage under unirradiated condition. Then, a simple way to incorporate the effects of irradiation on thermal creep and creep damage may be provided by replacing the coefficients of the constitutive and the evolution equations (4), (5) and (7) under unirradiated condition with the corresponding material functions of ϕ and Φ. Thus, the constitutive equation of irradiation-affected thermal creep and the related evolution equation of creep damage can be provided from eqns (4), (5) and (7) as follows:

$$\dot{\varepsilon}_{ij}^{ITC} = \tfrac{3}{2} m(\phi,\Phi) A(\phi,\Phi)^{1/m(\phi,\Phi)} q^{[m(\phi,\Phi)-1]/m(\phi,\Phi)} \left(\frac{\sigma_{EQ}}{1-D}\right)^{[n(\phi,\Phi)-m(\phi,\Phi)]/m(\phi,\Phi)} \frac{\sigma_{Dij}}{1-D}, \tag{8a}$$

$$q = \frac{1}{2\lambda(\phi,\Phi)}\left[\rho + (\varepsilon_{ij}^{ITC} - \alpha_{ij})\frac{\sigma_{Dij}}{\sigma_{EQ}}\right], \tag{8b}$$

$$\dot{\alpha}_{ij} = \begin{cases} [1-\lambda(\phi,\Phi)]\dot{\varepsilon}_{kl}^{ITC} n_{kl} n_{ij}, & g = 0 \text{ and } (\partial g/\partial \varepsilon_{ij}^{ITC})\dot{\varepsilon}_{ij}^{ITC} > 0 \\ 0, & g < 0 \text{ or } (\partial g/\partial \varepsilon_{ij}^{ITC})\dot{\varepsilon}_{ij}^{ITC} \leqslant 0 \end{cases}, \tag{8c}$$

$$\dot{\rho} = \begin{cases} \sqrt{(2/3)}\lambda(\phi,\Phi)\dot{\varepsilon}_{ij}^{ITC} n_{ij}, & g = 0 \text{ and } (\partial g/\partial \varepsilon_{ij}^{ITC})\dot{\varepsilon}_{ij}^{ITC} > 0 \\ 0, & g < 0 \text{ or } (\partial g/\partial \varepsilon_{ij}^{ITC})\dot{\varepsilon}_{ij}^{ITC} \leqslant 0 \end{cases}, \tag{8d}$$

$$n_{ij} = \frac{\varepsilon_{ij}^{ITC} - \alpha_{ij}}{[(\varepsilon_{kl}^{ITC} - \alpha_{kl})(\varepsilon_{kl}^{ITC} - \alpha_{kl})]^{1/2}}, \qquad \dot{D} = B(\phi,\Phi)\left(\frac{\sigma^{(1)}}{1-D}\right)^{k(\phi,\Phi)}, \tag{8e, f}$$

where $A(\phi,\Phi)$, $m(\phi,\Phi)$, $n(\phi,\Phi)$, $B(\phi,\Phi)$ and $k(\phi,\Phi)$ are material functions specifying the effects of irradiation on the creep and creep damage. As regards these material functions,

†Here, the Bailey–Norton equation is employed because of the simplicity of the equation and the small number of material constants. However, for more accurate analyses, the Blackburn equation (Kraus, 1980) can also be employed (Murakami *et al.*, 1986) to provide a distinct stage of steady-state creep.

we can employ the material functions discussed in the previous paper (Murakami *et al.*, 1991; Murakami and Mizuno, 1991) as follows:

$$A(\phi, \Phi) = A_0[1+a_1(1-e^{-a_2\phi})][1+a_3(1-e^{-a_4\Phi})], \tag{9a}$$

$$m(\phi, \Phi) = m_0, \qquad n(\phi, \Phi) = n_0, \tag{9b, c}$$

$$B(\phi, \Phi) = B_0[1+b_1(1-e^{-b_2\phi})][1+b_3(1-e^{-b_4\Phi})], \qquad k(\phi, \Phi) = k_0, \tag{9d, e}$$

where A_0, m_0, n_0, B_0 and k_0 are material constants of unirradiated material, and can be determined by fitting eqns (7) to the creep curves of unirradiated condition. The material constants $a_1, a_2, a_3, a_4, b_1, b_2, b_3$ and b_4, on the other hand, specify the effects of irradiation. The material function $\lambda(\phi, \Phi)$, furthermore, is the parameter governing the rate of development of creep-hardening surface, and ranges from 0 to 1/2 usually. Thus, by assuming that the effect of irradiation on λ is insignificant, $\lambda(\phi, \Phi)$ is now assumed to be a material constant as follows:

$$\lambda(\phi, \Phi) = \lambda_0. \tag{9f}$$

To recapitulate the above equations (2), (8) and (9), the constitutive equations of creep, swelling and damage under irradiation under multiaxial and variable states of stress are expressed as follows:

$$\dot{\varepsilon}_{ij}^{C} = \dot{\varepsilon}_{ij}^{IIC} + \dot{\varepsilon}_{ij}^{ITC} = \tfrac{1}{3}\dot{S}\delta_{ij} + \tfrac{3}{2}P\phi\sigma_{Dij} + \tfrac{3}{2}m_0 A(\phi, \Phi)^{1/m_0} q^{(m_0-1)/m_0}\left(\frac{\sigma_{EQ}}{1-D}\right)^{(n_0-m_0)/m_0}\frac{\sigma_{Dij}}{1-D}, \tag{10a}$$

$$q = \frac{1}{2\lambda_0}\left[\rho + (\varepsilon_{ij}^{ITC} - \alpha_{ij})\frac{\sigma_{Dij}}{\sigma_{EQ}}\right], \tag{10b}$$

$$\dot{\alpha}_{ij} = \begin{cases}(1-\lambda_0)\dot{\varepsilon}_{kl}^{ITC} n_{kl} n_{ij}, & g = 0 \quad \text{and} \quad (\partial g/\partial \varepsilon_{ij}^{ITC})\dot{\varepsilon}_{ij}^{ITC} > 0 \\ 0, & g < 0 \quad \text{or} \quad (\partial g/\partial \varepsilon_{ij}^{ITC})\dot{\varepsilon}_{ij}^{ITC} \leqslant 0\end{cases}, \tag{10c}$$

$$\dot{\rho} = \begin{cases}\sqrt{(2/3)}\lambda_0 \dot{\varepsilon}_{ij}^{ITC} n_{ij}, & g = 0 \quad \text{and} \quad (\partial g/\partial \varepsilon_{ij}^{ITC})\dot{\varepsilon}_{ij}^{ITC} > 0 \\ 0, & g < 0 \quad \text{or} \quad (\partial g/\partial \varepsilon_{ij}^{ITC})\dot{\varepsilon}_{ij}^{ITC} \leqslant 0\end{cases}, \tag{10d}$$

$$n_{ij} = \frac{\varepsilon_{ij}^{ITC} - \alpha_{ij}}{[(\varepsilon_{kl}^{ITC} - \alpha_{kl})(\varepsilon_{kl}^{ITC} - \alpha_{kl})]^{1/2}}, \qquad \dot{D} = B(\phi, \Phi)\left(\frac{\sigma^{(1)}}{1-D}\right)^{k_0}, \tag{10e, f}$$

$$\dot{S} = C\langle 1 + Q\sigma_{kk}\rangle\phi\left[1 - \frac{e^{R(\chi-\Phi)}}{1+e^{R(\chi-\Phi)}}\right]. \tag{10g}$$

By taking $\phi = \Phi = 0$, eqn (10) is reduced to the constitutive equation of thermal creep under unirradiated conditions, while the case $\phi = 0$, $\Phi =$ constant accounts for the post-irradiation creep. By taking $\phi =$ constant and $\Phi = \int \phi \, dt$, furthermore, eqn (10) describes the creep under constant neutron flux. Thus, eqn (10) furnishes a unified constitutive equation of creep under the arbitrary condition of irradiation.

3. ANALYSIS OF CREEP UNDER IRRADIATION

Cyclic burn of plasma in fusion reactors induces significant changes of stress in the first wall both in magnitude and in direction. Therefore, the constitutive equations for the analysis of nuclear reactor components are required to express these creep behaviors in a general state of stress and irradiation. The validity and the utility of the constitutive equation (10) elaborated in this paper are demonstrated below under unirradiated, post-irradiation and irradiation conditions subjected to some non-steady stress conditions, e.g. uniaxial stress reversals and stress change in direction.

3.1. *Material constants*

The material constants of eqn (10) are determined for 20% cold-worked type 316 stainless steel at 650 C, which is currently employed as a structural material for cladding tubes in fast breeder reactors as well as for the core structures of fusion reactors (Ehrlich, 1981; Harries and Zolti, 1986). The constitutive equation (10) is reduced to a constant uniaxial state of stress as follows:

$$\dot{\varepsilon}^{C} = \tfrac{1}{3}\dot{S} + P\phi\sigma + m_0 A(\phi,\Phi)^{1/m_0} q^{(m_0-1)/m_0}\left(\frac{\sigma}{1-D}\right)^{n_0/m_0}, \tag{11a}$$

$$\dot{D} = B(\phi,\Phi)\left(\frac{\sigma}{1-D}\right)^{k_0}, \qquad \dot{S} = C\langle 1+Q\sigma\rangle\phi\left[1-\frac{e^{R(\chi-\Phi)}}{1+e^{R(\chi-\Phi)}}\right]. \tag{11b, c}$$

Thus, all material constants in eqn (10) except λ_0 can be determined by fitting eqn (11) to the experimental results of creep under irradiation subjected to constant uniaxial stress. The procedure to determine these material constants has been discussed in previous papers (Murakami *et al.*, 1991; Murakami and Mizuno, 1991).

The material constants λ_0 in eqn (10), furthermore, are determined so that eqn (10) can describe the transient increase of creep rate after uniaxial stress reversal.

The material constants used in the following analyses are summarized in Table 1.

3.2. *Analysis of creep under irradiation subjected to variable states of stress*

Figure 1 shows the comparison of the predictions by eqn (10) with the experimental results of creep by Gilbert and Chin (1981) under unirradiated, post-irradiation and irradiation conditions subjected to uniaxial constant stress $\sigma_{11} = 70$ MPa. Irradiation conditions are entered in the figure. It will be observed in Fig. 1 that eqn (10) can describe both brittle behavior of post-irradiation creep and ductile behavior of creep under irradiation taking into account the effects of irradiation on creep curves, e.g. variations of rupture time and rupture strain and delay of tertiary creep.

Table 1. Material constants for 20% cold-worked type 316 stainless steel at 650 C employed for constitutive equation (10).

Description	Symbol	Value	Source of data
Unirradiated creep	A_0	1.25×10^{-11} $\mathrm{hr}^{-1/m_0}\cdot\mathrm{MPa}^{-n_0}$	Gilbert and Chin (1981)
($\phi = 0$ n cm$^{-2}\cdot$hr,			Gilbert *et al.* (1987)
$\Phi = 0$ n cm^{-2})	m_0	0.55	Gilbert and Chin (1981)
	n_0	3.50	Gilbert *et al.* (1987)
	B_0	2.50×10^{-10} $(\mathrm{MPa}^{k_0}\cdot\mathrm{hr})^{-1}$	Gilbert and Chin (1981)
	k_0	3.00	Gilbert and Chin (1981)
	λ_0	0.50	
Post-irradiation creep	a_3	-0.09	Bloom and Weir (1972)
($\phi = 0$ n cm$^{-2}\cdot$hr,	a_4	2.60×10^{-21} (n cm^{-2})$^{-1}$	Ehrlich (1981)
$\Phi = 5\times10^{22}$ n cm^{-2})	b_3	1.30	Gilbert and Chin (1981)
	b_4	2.60×10^{-21} (n cm^{-2})$^{-1}$	Ehrlich (1981)
Swelling	C	4.00×10^{-25} (n cm^{-2})$^{-1}$	Gilbert and Chin (1981)
			Porter *et al.* (1983)
	Q	4.75×10^{-3} MPa^{-1}	Porter *et al.* (1983)
	R	1.25×10^{-22} (n cm^{-2})$^{-1}$	Porter *et al.* (1983)
	χ	5.00×10^{22} n cm^{-2}	Porter *et al.* (1983)
Creep under irradiation	a_1	0.05	Gilbert *et al.* (1987)
($\phi = 1\times10^{19}$ n cm$^{-2}\cdot$hr,	a_2	2.60×10^{-19} (n cm$^{-2}\cdot$hr^{-1})$^{-1}$	
$\Phi = \int\phi\,dt$ n cm^{-2})	b_1	-0.95	Gilbert and Chin (1981)
	b_2	4.50×10^{-19} (n cm$^{-2}\cdot$hr^{-1})$^{-1}$	
	P	7.00×10^{-28} (MPa$\cdot$n cm^{-2})$^{-1}$	Ehrlich (1981)

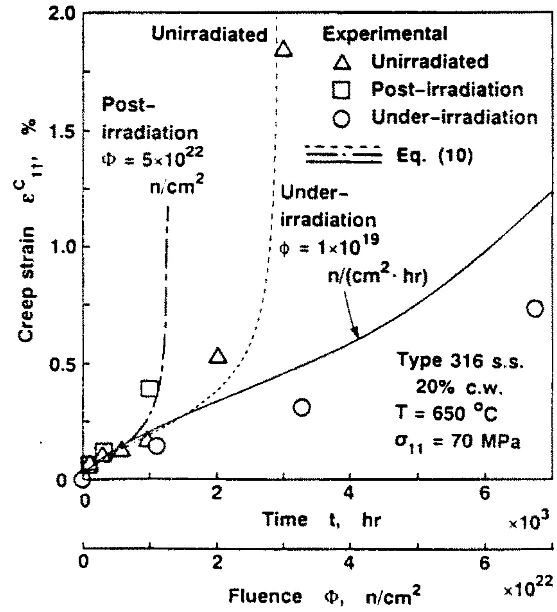

Fig. 1. Creep strain ε_{11}^{c} under uniaxial constant stress $\sigma_{11} = 70$ MPa.

Figure 2 shows the creep curves under stepwise increasing uniaxial stress σ_{11} as shown in the figure. The increment of stress and the intervals of stress increases are 20 MPa and 1000 hours, respectively. As observed in Fig. 2, the transient increase of creep rate after stress change is rather insignificant because of the monotonic increase in stress. The creep under irradiation, on the other hand, is about twice as large as the creep under the other two conditions, and this is accounted for by the significant swelling under irradiation.

In Fig. 2, though the dependence of final rupture times on the irradiation conditions is smaller than that observed in Fig. 1, this is due to the difference in magnitude of stress between Figs 1 and 2.

Figure 3 shows the creep curves under three different conditions of irradiation subjected to uniaxial stress reversals between $\sigma_{11} = 70$ MPa and -70 MPa with the intervals of 1000 hours as shown in the figure. It will be observed that eqn (10) describes well the transient increase of creep rate after stress reversals under each irradiation condition. Conventional

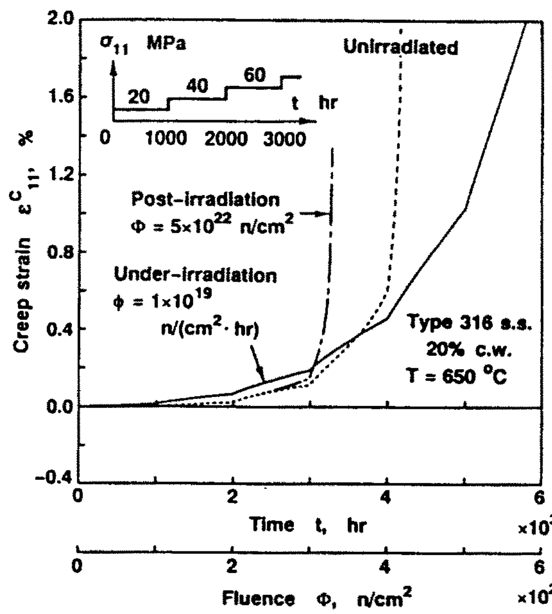

Fig. 2. Creep strain ε_{11}^{c} under uniaxial step-up stress conditions.

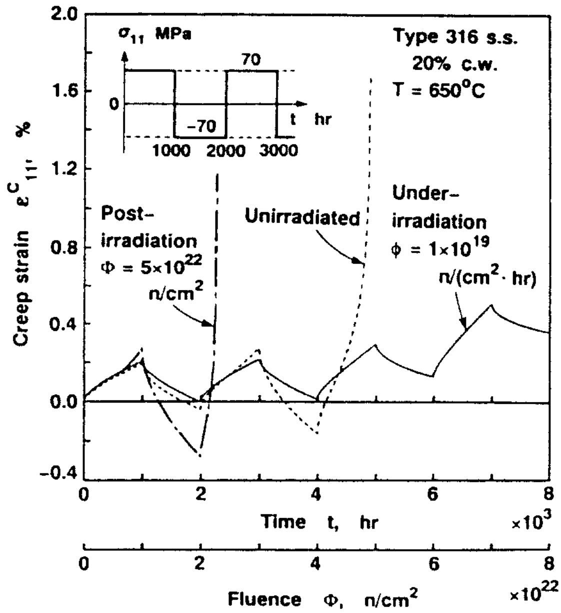

Fig. 3. Creep strain ε^c_{11} under uniaxial stress reversals between $\sigma_{11} = 70$ MPa and -70 MPa with an interval of 1000 hours.

strain-hardening theory expressed in eqn (3), in general, cannot describe this increase in creep rate, and accordingly underestimates the relaxation of stress. It means that convenient strain-hardening theory predicts little redistribution of stress in the materials.

The effects of irradiation on creep under variable states of stress show similar tendencies as those under the uniaxial constant stress condition of Fig. 1. Rupture time under stress reversal conditions in Fig. 3, however, becomes about twice as long as the rupture time under the constant stress conditions of Fig. 1. It is because the maximum principal stress, which governs the progress of creep damage [see evolution equation of creep damage (10f)] is zero when stress is negative $\sigma_{11} = -70$ MPa. Noting the behavior of creep under irradiation, the absolute value of creep rate under positive stress $\sigma_{11} = 70$ MPa is found to be larger than that under negative stress $\sigma_{11} = -70$ MPa beyond a neutron fluence of about $\Phi = 5 \times 10^{22}$ n cm^{-2}, and this can be accounted for by the swelling at a constant rate after the incubation period. Thus, creep strain under irradiation is found to increase with stress cycles in contrast to the creep under other irradiation conditions.

Finally, Figs 4(a,b) show the axial and shear creep strain predicted by eqn (10) under different irradiation conditions brought about by the multiaxial and non-proportional loading. The direction of stress change between 0 and 150° alternatively in $\sigma_{11}-\sqrt{3}\sigma_{12}$ stress plane under constant equivalent stress of 70 MPa at intervals of 1000 hours are shown in the figure. Unfortunately, there are no experimental data corresponding to Fig. 4 under post-irradiation and irradiation conditions to confirm the validity of the constitutive equation (10). However, the constitutive equation (10) under unirradiated conditions is confirmed to adequately describe the transient increase of creep rate after salient stress change by comparing the experimental data with eqn (10) under unirradiated conditions (Murakami and Ohno, 1982; Murakami *et al.*, 1986). The effects of irradiation on creep show similar tendencies under uniaxial stress conditions.

4. CONCLUSION

The constitutive equations of creep, swelling and damage under different irradiation conditions for multiaxial and variable states of stress were formulated by extending the creep-hardening surface model to include the effects of irradiation and damage. The creep behavior under various irradiation conditions and under variable magnitude, sign and direction of stress were predicted by the resulting equation.

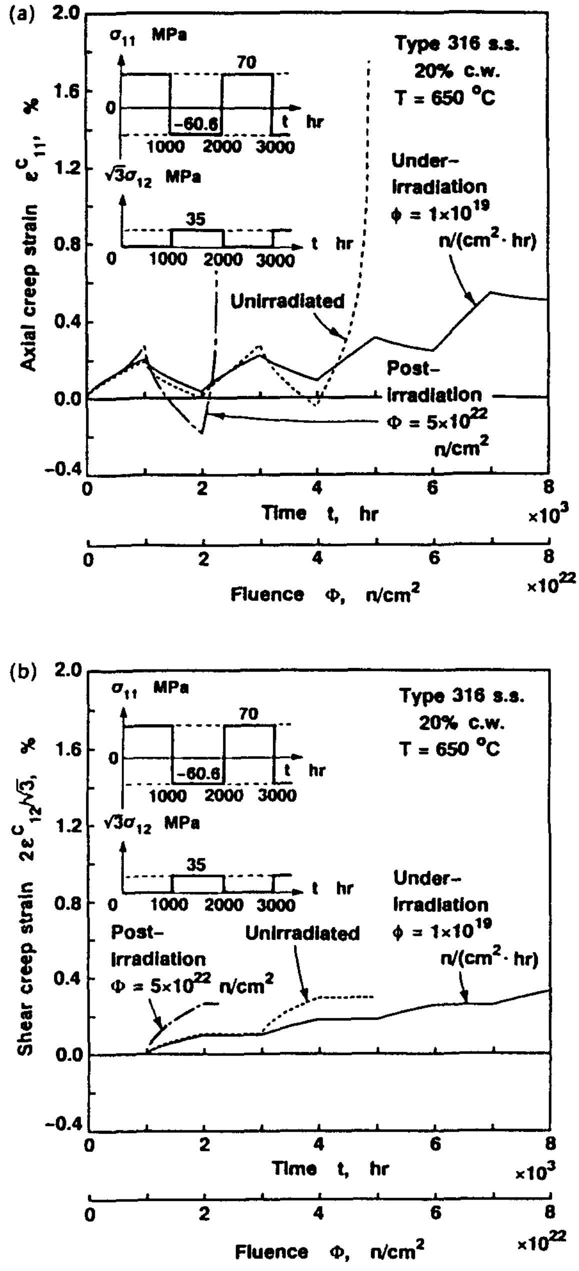

Fig. 4. Creep strain under change of stress direction between 0° and 150° at the interval of 1000 hours. (a) Axial creep strain ε^C_{11}. (b) Shear creep strain $2\varepsilon^C_{12}/\sqrt{3}$.

The results and conclusions of the present paper may be summarized as follows:

(1) The effects of neutron irradiation and creep damage were adequately incorporated into the creep-hardening surface model. The constitutive equations elaborated in the present paper can describe the transient increase of creep rate after salient stress change under unirradiated, post-irradiation and irradiation conditions.

(2) For the stepwise increase in stress, the effect of irradiation on rupture times is different from that under constant stress. For every irradiation condition, the rupture times under reversed stress become twice as long as the corresponding rupture times under constant tension. This is accounted for by the suppression of development of damage under compressive stress during stress reversals.

(3) Incorporation of the constitutive equations proposed here into the computer algorithms enables accurate analyses of creep, creep damage and fracture process of nuclear

reactor components under general multiaxial and variable states of stress under arbitrary irradiation conditions.

REFERENCES

Bloom, E. E. and Weir, J. R. (1972). Effect of neutron irradiation on the ductility of austenitic stainless steel. *Nucl. Tech.* **16**, 45–54.

Boyle, J. B. and Spence, J. (1983). *Stress Analyses for Creep*. Butterworths, London.

Ehrlich, K. (1981). Irradiation creep and interrelation with swelling in austenitic stainless steels. *J. Nucl. Mater.* **100**, 149–166.

Gilbert, E. R. and Chin, B. A. (1981). In-reactor creep measurements. *Nucl. Tech.* **52**, 273–283.

Gilbert, E. R., Chin, B. A. and Duncan, D. R. (1987). Effect of irradiation on failure mode during creep. *Metall. Trans. A.* **18A**, 79–84.

Gittus, J. (1978). *Irradiation Effects in Crystalline Solids*. Applied Science Publishers, London.

Harries, D. R. and Zolti, E. Z. (1986). Structural mechanics and material aspects of the next European Torus. *Nucl. Engng Design/Fusion* **3**, 331–344.

Kraus, H. (1980). *Creep Analysis*. Wiley, New York.

Murakami, S. and Ohno, N. (1982). A constitutive equation of creep based on the concept of a creep-hardening surface. *Int. J. Solids Structures* **18**, 597–609.

Murakami, S., Ohno, N. and Tagami, H. (1986). Experimental evaluation of creep constitutive equations for type 304 stainless steel under nonsteady multiaxial states of stress. *J. Engng Mater. Tech., Trans ASME* **108**, 119–126.

Murakami, S. and Mizuno, M. (1991). Elaborated constitutive equations for structural analysis for creep, swelling and damage under irradiation. *Nucl. Tech.* **96**, 219–227.

Murakami, S., Mizuno, M. and Okamoto, T. (1991). Mechanical modeling of creep, swelling and damage under irradiation for polycrystalline metals. *Nucl. Engng Design* **131**, 147–155.

Ohno, N. (1990). Recent topics in constitutive modeling of cyclic plasticity and viscoplasticity. *Appl. Mech. Rev.* **43**, 283–295.

Porter, D. L., Takata, M. L. and Wood, E. L. (1983). Direct evidence for stress-enhanced swelling in type 316 stainless steel. *J. Nucl. Mater.* **118**, 272–276.