Neutron Irradiation Dependence of Threshold Stress Intensity Factor for Stress Corrosion Cracking of Type 304 Stainless Steels

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ABSTRACT

This paper presents a quantitative formulation to predict the neutron irradiation dependence of the threshold stress intensity factor (K_{ISCC}) for stress corrosion cracking (SCC) of type 304 stainless steels in high temperature water. The neutron irradiation dependence of K_{ISCC} is described by incorporating irradiation effects of material into Smith's theoretical model of K_{ISCC}. In terms of the yield stress, Young's modulus and the process zone size, the neutron irradiation dependence is taken into consideration, respectively. According to the analysis results, the decreasing trend in K_{ISCC} can be predicted with neutron fluence and the effect of neutron flux on K_{ISCC} is much smaller than expected. Compared to studies with K_{ISCC}=9MPa√m or 15MPa√m for unirradiated type 304 stainless steels in high temperature water, K_{ISCC} approaches nearly the same 6MPa√m at the neutron fluence of $1\text{x}10^{26}$(n/m^2).

INTRODUCTION

Austenitic stainless steels are commonly used in core structural components of light water reactors (LWRs). Lifetime prediction of components subjected to neutron irradiation exposure[1] is of great importance if integrity of component materials is to be kept. In the case of life evaluation of structural materials regarding irradiation-assisted stress corrosion cracking (IASCC) of stainless steels[2], it is of significance to predict IASCC initiation and propagation behavior[3].

Since IASCC propagates at stress intensity factors higher than the stress intensity threshold, K_{ISCC}, i.e. the critical stress intensity required for the onset of IASCC, the value of K_{ISCC} during irradiation is crucial to developing an analytical methodology of IASCC in reactor core internals[4]. The critical combinations of applied stress level and defect size below which stress corrosion cracking should not occur can be established if K_{ISCC} is known. Then, this information can be used to determine limiting design stresses and nondestructive inspection criteria[5].

ANALYTICAL PROCEDURE

In order to predict how the threshold stress intensity factor, K_{ISCC} for IASCC varies with neutron irradiation, a quantitatively analytical method is developed by incorporating neutron irradiation effects for material properties into Smith's theoretical model of K_{ISCC}[6]. The neutron irradiation dependence is taken into account in terms of the yield stress, Young's modulus and the process zone size.

Smith's Theoretical Model [6]- [8]

Smith has developed a theoretical model of K_{ISCC} based on an analytical procedure using a critical stress intensity required for the onset of stress corrosion cracking. Smith presented the threshold stress intensity factor, K_{ISCC}, in terms of a crack opening stretch criterion and a fracture process zone size for plane strain stable crack growth.

Considering that the process zone is imbedded in the plastic zone as shown in Fig.1, the value of the J-integral required to maintain a plastic zone size, r_p, is related to the deformation state at an advancing crack tip in that the plastic zone size increases as the crack advances. Therefore, the J-integral satisfies the following differential equation which expresses how J-integral value increases as the crack extends. The criterion for stress corrosion crack growth is that the crack tip moves forward a distance, Δ, i.e. fracture process zone size, if the displacement accumulated while a material point is within a crack extension increment, Δ from the tip, attains a critical value, δ, i.e. final crack stretch displacement. The final stretch criterion is equivalent to the crack tip opening angle, the CTOA criterion used in other models[9] with $6 \equiv \delta / \Delta$.

$$\frac{dJ}{da} = \frac{8(1-\nu^2)\sigma_y{}^2}{\pi E} \cdot \frac{dr_p}{da} \cong \frac{4(1-\nu^2)\sigma_y{}^2}{\pi E} \cdot \ln\left\{ \frac{\Delta}{4er_p} \cdot \exp\left(\frac{\pi E \theta}{4(1-\nu^2)\sigma_y} \right) \right\} \tag{1}$$

where σ_y is yield stress, E is Young's modulus, ν is Poisson's ratio, r_p is plastic zone size, *e* is Napierian base, Δ is process zone size and θ is crack tip opening angle.

Eq. (1) indicates that there is a J-level at which the value of dJ/da required for continued crack growth approaches zero. If J_{ISCC} is the J value appropriate to this steady state condition, Eq. (1) may be written as

$$\frac{dJ}{da} = \frac{4(1-\nu^2)\sigma_y^{\,2}}{\pi E} \cdot \ln\left(\frac{J_{ISCC}}{J}\right) \tag{2}$$

with J_{ISCC} being given by

$$J_{ISCC} = \frac{2(1-\nu^2)\sigma_y^{\,2}\Delta}{\pi e E} \cdot \exp\left(\frac{\pi E \theta_0}{4(1-\nu^2)\sigma_y}\right) \tag{3}$$

where θ_0 is a limiting value of the crack tip opening angle.

The threshold stress intensity factor, K_{ISCC} is described by the following expression, using the correlation of $J_{ISCC} \equiv K_{ISCC}^2(1-\nu^2)/E$.

$$K_{ISCC} = \left\{\frac{2\sigma_y^{\,2}\Delta}{\pi e} \cdot \exp\left(\frac{\pi E \theta_0}{4(1-\nu^2)\sigma_y}\right)\right\}^{1/2} \tag{4}$$

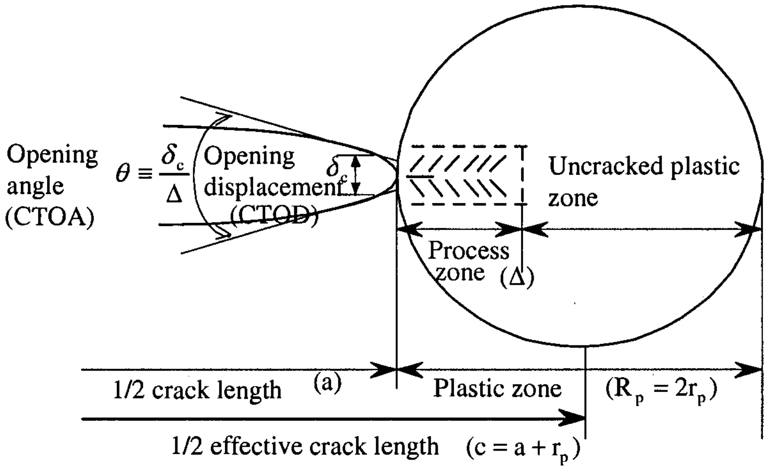

Fig.1 Process Zone Model for Crack Growth Advancing with Plastic Zone

Formulation for Irradiation Effects

Neutron irradiation effects on the threshold stress intensity factor may be taken into account by representing the material constants as functions of neutron fluence. The material functions of yield stress, Young's modulus and process zone size to describe the effects of the irradiation are formulated next.

Yield Stress vs. Irradiation Relation

Under neutron irradiation, the increase in yield stress is caused by irradiation defects and therefore irradiation hardening occurs. Kodama and Nishimura[10] proposed the following relation for the increment of yield stress due to neutron irradiation,

$$\Delta\sigma_y = A_0(\phi^{0.5} \cdot (1-e^{-A_1 \cdot \phi t}))^{0.5} \tag{5}$$

where $\Delta\sigma_y$ is yield stress increment, ϕ is neutron flux, ϕt is neutron fluence and A_0, A_1 are constants.

Therefore, the increase in yield stress due to irradiation may be expressed as follows:

$$\sigma_y = \sigma_y^0 + \Delta\sigma_y = \sigma_y^0 + A_0(\phi^{0.5} \cdot (1-e^{-A_1 \cdot \phi t}))^{0.5} \tag{6}$$

where σ_y and σ^0_y are yield stresses in irradiated and unirradiated conditions, respectively.

Young's Modulus vs. Irradiation Relation

Young's modulus may be affected by neutron fluence[11] and the relation between the change rate of Young's modulus and neutron fluence is assumed to be formulated as follows:

$$\Delta E/E_0 = A_2(\phi t)^{A_3} \tag{7}$$

where ΔE is the increment in Young's modulus, E_0 is Young's modulus in the unirradiated condition and A_2, A_3 are constants.

Therefore, Young's modulus may be expressed by the following function of neutron fluence.

$$\mathrm{E} = \mathrm{E}_0(1 + \mathrm{A}_2(\phi t)^{\mathrm{A}_3}) \tag{8}$$

Process Zone vs. Irradiation Relation

The true fracture strain, ε_f may be obtained from the relationship,

$$\varepsilon_{\mathrm{f}} = \ln(1 + e_{\mathrm{f}}) \tag{9}$$

where e_f is engineering fracture strain.

Now, the fracture strain is normalized by dividing it by the fracture strain in the unirradiated condition, i.e.

$$\langle \varepsilon_{\mathrm{f}} \rangle = \varepsilon_{\mathrm{f}} / \varepsilon_{\mathrm{f}}^0 \tag{10}$$

where $\langle \varepsilon_{\mathrm{f}} \rangle$ is normalized fracture strain and $\varepsilon_{\mathrm{f}}^0$ is fracture strain in the unirradiated condition. Then the normalized fracture strain may be expressed by the following function of neutron fluence,

$$\langle \varepsilon_{\mathrm{f}} \rangle = 1 - \mathrm{A}_4(\phi t)^{\mathrm{A}_5} \tag{11}$$

where A_4 and A_5 are constants.

Therefore, the fracture process zone size, Δ, may be assumed to be described in terms of the process zone size in the unirradiated condition and the normalized fracture strain, giving

$$\Delta = \Delta_0 \langle \varepsilon_{\mathrm{f}} \rangle = \Delta_0(1 - \mathrm{A}_4(\phi t)^{\mathrm{A}_5}) \tag{12}$$

where Δ_0 is process zone size in the unirradiated condition.

Formula of K_{ISCC} under Irradiation

The threshold stress intensity factor K_{ISCC} of irradiated materials may be given by modifying the material constants in Smith's relation of the unirradiated materials as functions of neutron fluence. Then, Eqs. (6), (8) and (12) are substituted into Eq. (4) and the relation of K_{ISCC} under neutron irradiation is expressed by the following equation.

$$\mathrm{K}_{\mathrm{ISCC}} = \left\{ \frac{\dfrac{2(\sigma_{\mathrm{y}}^0 + \mathrm{A}_0(\phi^{0.5}(1 - e^{-\mathrm{A}_1\phi t}))^{0.5})^2 \Delta_0 (1 - \mathrm{A}_4(\phi t)^{\mathrm{A}_5})}{\pi \cdot e}}{\exp\left(\dfrac{\pi \mathrm{E}_0(1 + \mathrm{A}_2(\phi t)^{\mathrm{A}_3})\theta_0}{4(1-\nu^2)(\sigma_{\mathrm{y}}^0 + \mathrm{A}_0(\phi^{0.5}(1 - e^{-\mathrm{A}_1\phi t}))^{0.5})} \right)} \right\}^{1/2} \tag{13}$$

IRRADIATION DEPENDENCE OF K_{ISCC} FOR TYPE 304 STAINLESS STEELS

The above analytical procedure is applied to type 304 stainless steels irradiated by neutron flux in a commercial BWR.

Irradiation Dependence of Yield Stress

Fig.2 presents the correlation of the increase in yield stress versus neutron flux, along with data[10] representing the effect of neutron flux on the increment in yield stress. Then, irradiation dependence of the increase in yield stress may be formulated by Eq.(5) [10] in this way. This indicates that the increase in yield stress increases continuously with increasing neutron flux.

$$\Delta\sigma_{\mathrm{y}} = 4.5\mathrm{x}10^{-2} \cdot \left\{\phi^{0.5} \cdot (1 - e^{-5.8\mathrm{x}10^{26} \cdot \phi t})\right\}^{0.5} \tag{14}$$

Given the yield stress in the unirradiated condition, $\sigma^0_y = 171$ MPa, the dependence of the yield stress on neutron irradiation may be expressed by the following function in terms of neutron flux and neutron fluence, as shown in Fig.3.

$$\sigma_{\mathrm{y}} = 171 + 4.5\mathrm{x}10^{-2} \cdot \left\{\phi^{0.5} \cdot (1 - e^{-5.8\mathrm{x}10^{26} \cdot \phi t})\right\}^{0.5} \tag{15}$$

The yield stress of type 304 stainless steels remains almost unchanged up to a fluence of $1\mathrm{x}10^{22}$ n/m^2 and thereafter increases continuously with increasing neutron fluence. Saturation appears to take place at a fluence of about $1\mathrm{x}10^{26}$ n/m^2. It is noted that the effect of neutron flux on the yield stress is remarkable at higher fluence levels above $1\mathrm{x}10^{24}$ n/m^2 and the higher neutron flux becomes, the more the yield stress increases. This may be attributed to the number of irradiation-produced defects due to survival of point defects generated per neutron. Exposure to the highest fluence ($1\mathrm{x}10^{26}$ n/m^2) causes about a two- or threefold increase in yield stress of type 304 stainless steels unirradiated, depending on the neutron flux.

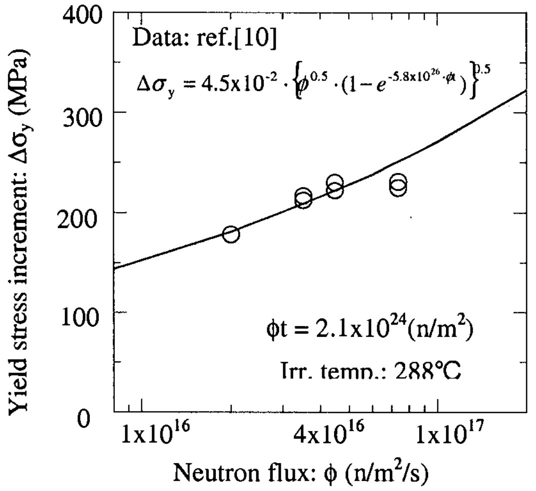

Fig.2 Yield Stress Increment vs. Neutron Flux

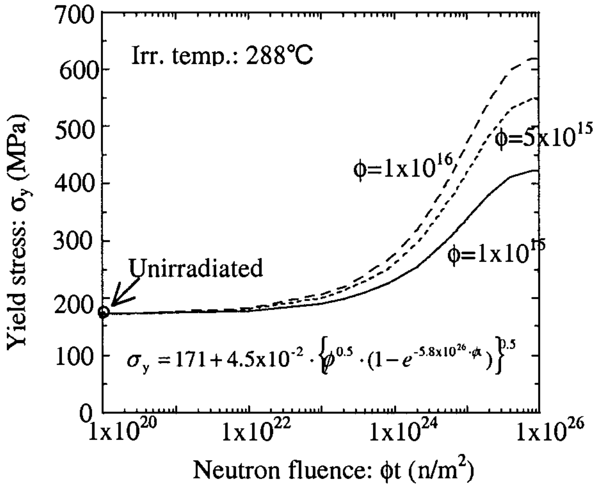

Fig.3 Yield Stress vs. Neutron Fluence

Irradiation Dependence of Young's Modulus

There are very few available data pertaining to the effect of neutron fluence on the change in Young's modulus of type 304 stainless steels, but Joseph[12] reported measurements of Young's modulus in type 304 stainless steels irradiated below the temperature of 150℃. As shown in Fig. 4, the change rate of Young's modulus increases continuously with increasing neutron fluence. The following equation fits Joseph's data points in which the unirradiated value of Young's modulus is 1.93x10⁵ MPa.

$$\Delta E/E_0 = 9.61\text{x}10^{-8}\cdot(\phi t)^{0.31} \tag{16}$$

On the assumption that the same trend exists, the dependence of Young's modulus in type 304 stainless steels at 288℃ on neutron fluence is described by the following expression, with the unirradiated value of Young's modulus at 288℃ being 1.77x10⁵ MPa.

$$E = 1.77\text{x}10^{5}\cdot\{1+9.61\text{x}10^{-8}\cdot(\phi t)^{0.31}\} \tag{17}$$

For type 304 stainless steels, it is found that Young's modulus increases gradually with neutron fluence, especially beyond about $1\text{x}10^{22}$ n/m², as shown in Fig. 5.

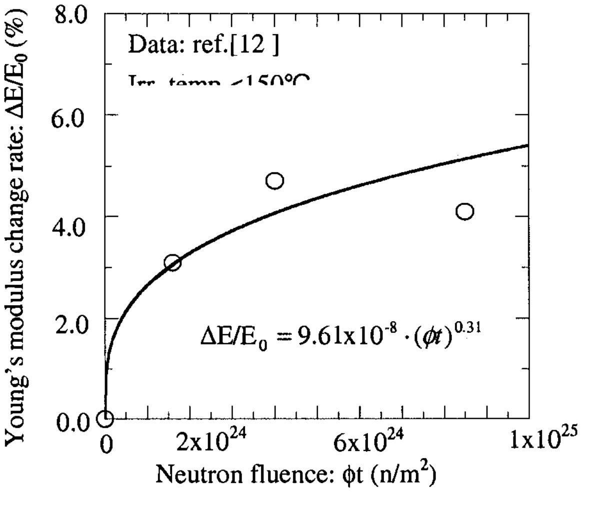

Fig.4 Young's Modulus Change Rate vs. Fluence

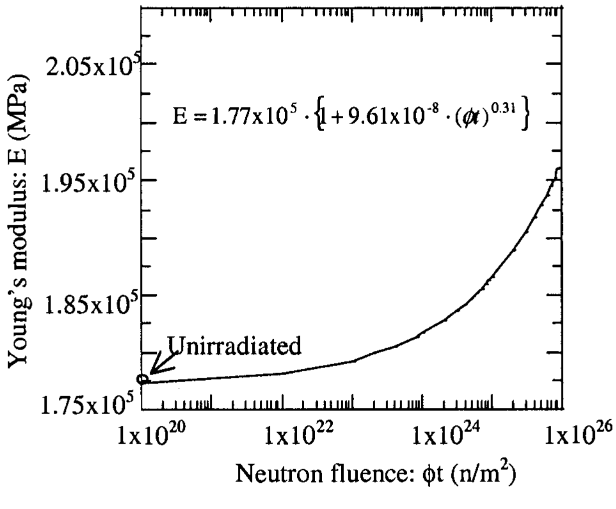

Fig.5 Young's Modulus vs. Neutron Fluence

Irradiation Dependence of Process Zone

The fracture strain of type 304 stainless steels irradiated and tested at 288℃ exhibits a drastic decrease initially and then a continuous decrease with neutron fluence, as reported in ref.[13]. Fracture strains normalized by the unirradiated fracture strain are plotted against the neutron fluence in Fig. 6. When a best curve correlation of the data is taken, the functional relationship between normalized fracture strain and neutron fluence may be expressed by the following equation in the same form as Eq. (11).

$$\langle \varepsilon_f \rangle = 1 - 3.4\text{x}10^{-6} \cdot (\phi t)^{0.2} \tag{18}$$

If the process zone size in the unirradiated condition Δ_0 is assumed to be 200μm[14], the dependence of the process zone size on neutron fluence is described by the following expression in the same form as Eq. (12).

$$\Delta = 200 \cdot \{1 - 3.4\text{x}10^{-6} \cdot (\phi t)^{0.2}\} \tag{19}$$

As shown in Fig. 7, the process zone size is plotted as a function of neutron fluence and it decreases continuously with increasing neutron fluence.

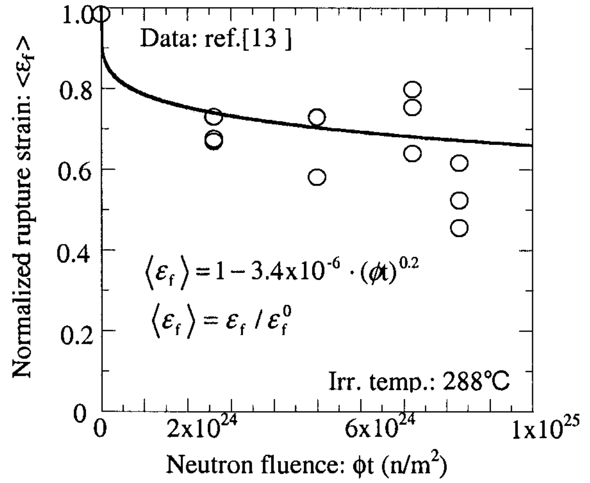

Fig.6 Normalized Rupture Strain vs. Fluence

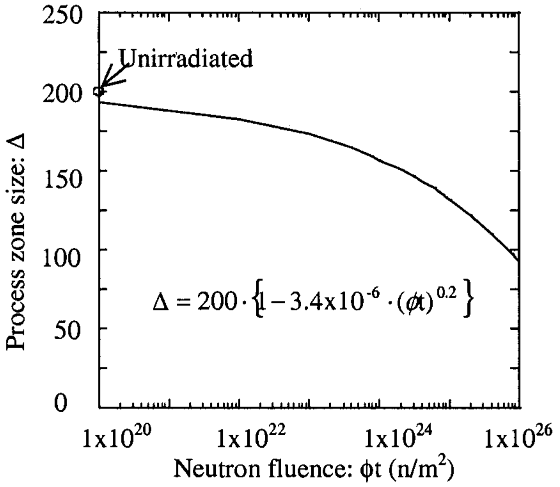

Fig.7 Process Zone Size vs. Neutron Fluence

Irradiation Dependence of K_{ISCC}

The threshold stress intensity factor K_{ISCC} is not well known for type 304 stainless steels, especially in high temperature water. However, the K_{ISCC} value for type 304 stainless steels[15],[16] is reported to be in the range of 6MPa√m – 15MPa√m, depending on the environment and material conditions. Therefore, for case study, two values of 9MPa√m and 15MPa√m are taken as the K_{ISCC} for unirradiated type 304 stainless steels.

As seen from Eq. (4), a quantitative estimate of K_{ISCC} requires prior knowledge of the limiting value of crack tip opening angle θ_0 as an input parameter. The evaluation of θ_0 can be done from Eq. (4) in which unirradiated material constants of type 304 stainless steels are given. For K_{ISCC} =9MPa√m or 15MPa√m, the limiting value of crack tip opening angle θ_0 turns out to be $4.5\text{x}10^{-3}$ or $5.7\text{x}10^{-3}$, respectively. The limiting value of the angle remains a fairly constant value during crack growth, in the sense that the crack tip opening angle is apparently the most suitable criterion[17].

Consequently, the irradiation dependence of K_{ISCC} as a function of neutron flux and fluence is established by substituting Eqs. (15), (17) and (19) into Eq. (13) and using the above mentioned θ_0 value.

For K_{ISCC} =9MPa√m in the unirradiated condition, irradiation dependence of K_{ISCC} is described in the following expression, using θ_0=$4.5\text{x}10^{-3}$.

$$K_{ISCC} = \left\{ \frac{2 \cdot (171 + 4.5\text{x}10^{-2} \cdot (\phi^{0.5} \cdot (1 - e^{-5.8\text{x}10^{26} \cdot \phi t}))^{0.5})^2 \cdot (2\text{x}10^{-4} \cdot (1 - 3.4\text{x}10^{-6} \cdot (\phi t)^{0.2}))}{\pi \cdot e} \cdot \exp\left(\frac{\pi \cdot (1.77\text{x}10^5 \cdot (1 + 9.61\text{x}10^{-8} \cdot (\phi t)^{0.31})) \cdot 4.5\text{x}10^{-3}}{4 \cdot (1 - 0.32^2) \cdot (171 + 4.5\text{x}10^{-2} \cdot (\phi^{0.5} \cdot (1 - e^{-5.8\text{x}10^{26} \cdot \phi t}))^{0.5})} \right) \right\}^{1/2} \tag{20}$$

Fig.8 indicates how the predicted K_{ISCC} varies with neutron fluence for different neutron fluxes. It is seen that as neutron fluence increases, the calculated K_{ISCC} values continuously decrease by an amount dependent on the neutron flux. Though the fluence dependence of K_{ISCC} is slightly affected by the neutron flux, the neutron flux is not of major significance. It should be noted that the decrease of K_{ISCC} with neutron fluence asymptotically approaches a value of about 5.5MPa√m at the highest fluence of $1x10^{26}$ n/m^2, regardless of the neutron flux.

For K_{ISCC}=15MPa√m in the unirradiated condition, irradiation dependence of K_{ISCC} is described in the following expression, using $\theta_0=5.7x10^{-3}$.

$$K_{ISCC}=\left\{\frac{2\cdot(171+4.5x10^{-2}\cdot(\phi^{0.5}\cdot(1-e^{-5.8x10^{26}\cdot\phi t}))^{0.5})^2\cdot(2x10^{-4}\cdot(1-3.4x10^{-6}\cdot(\phi t)^{0.2}))}{\pi\cdot e}\cdot \exp\left(\frac{\pi\cdot(1.77x10^5\cdot(1+9.61x10^{-8}\cdot(\phi t)^{0.31}))\cdot 5.7x10^{-3}}{4\cdot(1-0.32^2)\cdot(171+4.5x10^{-2}\cdot(\phi^{0.5}\cdot(1-e^{-5.8x10^{26}\cdot\phi t}))^{0.5})}\right)\right\}^{1/2} \quad (21)$$

As illustrated in Fig. 8, K_{ISCC} is predicted to decrease continuously with increasing neutron fluence and become a value of about 6MPa√m at the highest fluence of $1x10^{26}$ n/m^2, which is nearly the same value for K_{ISCC}=9MPa√m in the unirradiated condition. Also, Fig. 8 indicates that the effect of neutron flux has little influence on the fluence dependence of K_{ISCC}.

Nair and Tien[18] argued the yield strength dependence of K_{ISCC} according to their model based on hydrogen-induced fracture, suggesting that the increase in yield strength could play a main role in the decrease of K_{ISCC}. Bibilashvili et al.[19] studied the influence of irradiation on K_{ISCC} of Zr-1%Nb cladding and concluded that the neutron irradiation reduced the K_{ISCC} for iodine induced SCC, compared to the unirradiated alloy. In the present study, the saturation of K_{ISCC} for irradiated type 304 stainless steels at higher fluence indicates that a major factor affecting the K_{ISCC} value under neutron irradiation is likely to be irradiation hardening such as the increase in yield stress. Specifically, it is apparent that the K_{ISCC} value under neutron irradiation cannot be treated as a constant for type 304 stainless steels.

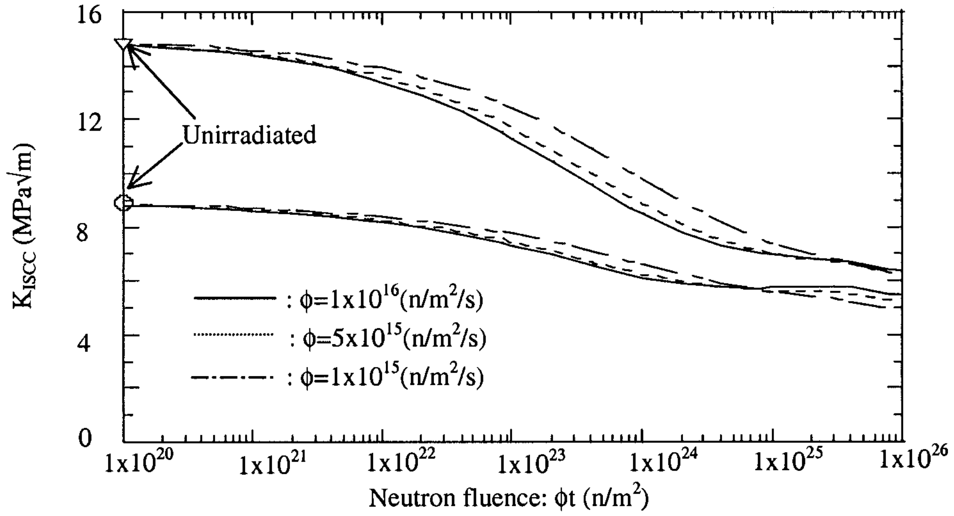

Fig.8 Neutron Fluence Dependence of K_{ISCC} for Type 304 Stainless Steels

SUMMARY

The neutron irradiation dependence of K_{ISCC} was quantified by incorporating irradiation effects of material into Smith's theoretical analysis, in which K_{ISCC} is modeled by considering crack opening stretch criterion and a fracture process zone.

Irradiation effects on the yield stress, Young's modulus and the process zone size were considered to make a quantitative evaluation and prediction of the threshold stress intensity factor under neutron irradiation for type 304 stainless steels in high temperature water.

In two cases of 9MPa√m and 15MPa√m as the K_{ISCC} for unirradiated type 304 stainless steels, the analytical results indicated that as neutron fluence increased, the calculated K_{ISCC} values continuously decreased by an amount dependent on the neutron flux. Though the fluence dependence of K_{ISCC} was slightly affected by the neutron flux, the neutron flux was not of major significance.

At the highest neutron fluence of $1x10^{26}$(n/m^2), the value of K_{ISCC} of type 304 stainless steels in high temperature water was predicted to be nearly 6MPa√m, regardless of the initial value of K_{ISCC} in the unirradiated condition.

NOMENCLATURE

a = crack length
A_1- A_5 = numerical constants
E = Young's modulus
E_0 = Young's modulus in unirradiated condition
ΔE = increment in Young's modulus
J = J-integral value
J_{ISCC} = J-integral value for SCC
K_{ISCC}= threshold stress intensity factor for SCC
r_p = plastic zone size
δ = final crack stretch displacement
Δ = fracture process zone size
Δ_0 = process zone size in unirradiated condition
ε_f = true fracture strain
ε_f^0 = fracture strain in unirradiated condition
$\langle \varepsilon_f \rangle$ = normalized fracture strain
θ = crack tip opening angle
θ_0 = limiting value of crack tip opening angle
ν = Poisson's ratio
σ_y = yield stress
σ^0_y = yield stress in unirradiated condition
$\Delta\sigma_y$ = yield stress increment
ϕ = neutron flux
ϕt = neutron fluence
e = Napierian base

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