A Phenomenological Theory of Neutron Irradiation Sensitivity of Ductile-Brittle Transition Temperature of Ferritic Steels*

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Synopsis

The change of ductile-brittle transition temperature of ferritic steels due to neutron irradiation, ΔT_ϕ , which is called the irradiation sensitivity, was investigated and a phenomenological theory was presented. The theory predicts the change of sensitivity, $\delta(\Delta T_\phi)$, in terms of the changes of grain size, interstitial solute atom concentration, spacing of precipitates, and dislocation density.

I. Introduction

After neutron or other energetic particle irradiation, ferritic steels show hardening and embrittlement and their ductile-brittle transition temperatures shift to higher temperatures. This shift of transition temperature due to a given dose of irradiation, which we shall call the irradiation sensitivity, depends on microstructures of steels such as grain size, spacing of dispersed second phases, etc.

Theoretical investigations on the irradiation sensitivity have hitherto been rather scarce. Cottrell¹⁾ and Nichols²⁾ made some theoretical treatments of the shift of transition temperature, but they did not consider the microstructure dependence of irradiation sensitivity.

In this paper, we shall present a phenomenological theory, by which we can understand the irradiation sensitivity of ferritic steels in terms of grain size, interstitial solute atom concentration, spacing of dispersed phases, and dislocation density.

II. Theory of Irradiation Sensitivity

Let us make the following assumptions:

(1) The ductile-brittle transition occurs at the intersecting point of the yield stress*** and the nil-ductility fracture stress curve*** as shown in Fig. 1. This is so-called Ludwig-Davidenkov criterion.³⁾

(2) The temperature dependence of the fracture stress σ_f is small compared with that of the yield stress σ_y so that the fracture stress is assumed, for simplicity, to be independent of temperature.^{4),5)****}

(3) The change of the yield stress by irradiation at a given dose level ϕ will be expressed by $\Delta\sigma_{y\phi}$ which is assumed to be independent of temperature.*****

(4) The change of the fracture stress by irradiation

Fig. 1. Schematic diagram of yield stress and fracture stress as a function of temperature before (A) and after (B) irradiation. The fracture stress curves are drawn to conform to the assumption (2) in section II.

at a given dose level ϕ will be denoted by $\Delta\sigma_{f\phi}$ which is assumed to be independent of temperature.*****

Now in Fig. 1 the yield stress and the fracture stress are schematically shown as a function of temperature. After irradiation the yield stress curve and the fracture stress curve shift upward by an amount of $\Delta\sigma_{y\phi}$ and by an amount of $\Delta\sigma_{f\phi}$, respectively. If $\Delta\sigma_{y\phi}$ is larger than $\Delta\sigma_{f\phi}$, the ductile-brittle transition temperature, i.e., the intersection of the σ_y curve and the σ_f curve, shifts to a higher temperature, as shown in Fig. 1. Thus the shift of transition temperature due to a given dose of irradiation, i.e., the irradiation sensitivity, ΔT_ϕ , is expressed by

$$\Delta T_\phi = T_\phi - T_o = \frac{\Delta\sigma_{f\phi} - \Delta\sigma_{y\phi}}{\Delta\sigma_y/\Delta T} \quad \text{.....(1a)*****}$$

$$= \frac{\Delta\sigma_{f\phi} - \Delta\sigma_{y\phi}}{d\sigma_y/dT} \quad \text{.....(1b)*****}$$

where T_o and T_ϕ are the transition temperatures before and after irradiation, respectively.

A. Grain Size Dependence of Irradiation Sensitivity

Now let us assume that the yield stress and the frac-

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*** "Fracture stress" means "nil-ductility fracture stress" in this paper, if not otherwise stated. The yield (fracture) stress curve means the yield (fracture) stress vs. temperature curve (Fig. 1), the yield (fracture) stress vs. grain size curve, etc.

**** The assumptions (2), (3), and (4), i.e., the assumptions of the temperature independent fracture stress, the temperature independent $\Delta\sigma_{f\phi}$, and the temperature independent $\Delta\sigma_{y\phi}$, are made for the sake of simplicity. These assumptions can be eliminated without changing essential conclusions of the theory, if the simplicity is sacrificed.

***** Equation (1b) which uses $d\sigma_y/dT$ instead of $\Delta\sigma_y/\Delta T$ is an approximate expression of (1a). Equation (1b) can only be used in the case where the yield stress curve can be approximated by a straight line. The case, where Eq. (1b) can not be used, will be described later elsewhere.

ture stress are expressed by Petch's relations^{6),7)} as follows:

$$\sigma_y = \sigma_{oy} + k_y d^{-1/2} \dots \dots \dots (2)$$

$$\sigma_f = \sigma_{of} + k_f d^{-1/2} \dots \dots \dots (3)$$

where d is the grain diameter and σ_{oy} , σ_{of} , k_y , and k_f are the constants independent of d . We consider four parameters in this paper, *i.e.*, the grain diameter, d , the interstitial solute atom concentration, c , the spacing of dispersed phases, λ , and the dislocation density, ρ . In Eqs. (2) and (3) c , λ , and ρ are considered to be constants and are included in σ_{oy} and σ_{of} .

The grain size dependence of the irradiation sensitivity is obtained by differentiating Eq. (1) with respect to $(d^{-1/2})$, considering Eqs. (2) and (3), *i.e.*,

$$\frac{d(\Delta T_\phi)}{d(d^{-1/2})} = \frac{(\Delta k_{f\phi} - \Delta k_{y\phi}) \left(\frac{d\sigma_y}{dT} \right) - (\Delta \sigma_{f\phi} - \Delta \sigma_{y\phi}) \left(\frac{dk_y}{dT} \right)}{\left(\frac{d\sigma_y}{dT} \right)^2} \dots \dots \dots (4)$$

where

$$\Delta \sigma_{y\phi} = \Delta \sigma_{oy\phi} + \Delta k_{y\phi} d^{-1/2} \dots \dots \dots (5)$$

$$\Delta \sigma_{f\phi} = \Delta \sigma_{of\phi} + \Delta k_{f\phi} d^{-1/2} \dots \dots \dots (6)$$

with the constants $\Delta \sigma_{oy\phi}$, $\Delta \sigma_{of\phi}$, $\Delta k_{y\phi}$, and $\Delta k_{f\phi}$.

In calculating Eq. (4), we have to consider the behaviors of k_y and k_f as functions of temperature and radiation dose, from which we can obtain the values of $\Delta k_{y\phi}$, $\Delta k_{f\phi}$, and dk_y/dT .

The behaviors of k_y experimentally observed and found in literatures rather show diversity. For example, k_y changes⁸⁾⁻¹¹⁾ or does not change^{8),12)} with temperature; it decreases,^{10),13),14)} increases,¹⁵⁾ or does not change¹⁶⁾ with irradiation. We shall, therefore, consider below various combinations of the above behaviors.

(ai) The Case AI

k_y is independent of temperature and does not change with irradiation. In this case, we obtain from Eq. (4) the following result:

$$\frac{d(\Delta T_\phi)}{d(d^{-1/2})} = 0. \dots \dots \dots (7)$$

Here the irradiation sensitivity does not depend on the grain size.

(aia) The Case AII

k_y is independent of temperature and decreases with irradiation ($\Delta k_{y\phi} < 0$).^{*} Now we get from Eq. (4)

$$\frac{d(\Delta T_\phi)}{d(d^{-1/2})} = - \frac{\Delta k_{y\phi}}{d\sigma_{oy}/dT} \dots \dots \dots (8)$$

$$< 0. \dots \dots \dots (9)$$

It may not be easy to check the result shown by Eq. (8) quantitatively, because the numerical data available now are too scarce to calculate the quantity given by Eq. (8). It may be convenient, therefore, to know the sign of Eq. (8). This is negative as shown by the relation (9), because $\Delta k_{y\phi}$ is negative as mentioned above and $d\sigma_y/dT$ is negative as shown schematically in Fig. 1 which results in a negative $d\sigma_{oy}/dT$ if k_y is temperature independent. It should be pointed out that the negative value of Eq. (8) shows that the grain refinement is effective to reduce the irradiation sensitivity.

(aiii) The Case AIII

k_y depends on temperature and does not change with irradiation. In this case the grain size dependence of the sensitivity expressed by Eq. (4) will be

$$\frac{d(\Delta T_\phi)}{d(d^{-1/2})} = \frac{(\Delta \sigma_{y\phi} - \Delta \sigma_{f\phi})}{\left(\frac{d\sigma_y}{dT} \right)^2} \cdot \frac{dk_y}{dT} \dots \dots \dots (10)$$

$$< 0. \dots \dots \dots (11)$$

Now dk_y/dT is negative, when k_y is dependent on temperature.⁸⁾ As $(\Delta \sigma_{y\phi} - \Delta \sigma_{f\phi})$ is usually considered to be positive,¹⁷⁾ Eq. (10) is usually negative. We see here again that the grain refinement is effective in reducing the irradiation sensitivity.

(aiv) The Case AIV

k_y depends on temperature and decreases with irradiation ($\Delta k_{y\phi} < 0$).^{**} Now we obtain from Eq. (4)

$$\frac{d(\Delta T_\phi)}{d(d^{-1/2})} = \frac{-\Delta k_{y\phi} \frac{d\sigma_y}{dT} + (\Delta \sigma_{y\phi} - \Delta \sigma_{f\phi}) \frac{dk_y}{dT}}{\left(\frac{d\sigma_y}{dT} \right)^2} \dots \dots \dots (12)$$

$$< 0. \dots \dots \dots (13)$$

The relation (13) shows that the grain refinement in this case is also effective in reducing the irradiation sensitivity.

(av) The Case AV

k_y depends on temperature and increases with irradiation ($\Delta k_{y\phi} > 0$).^{**} In this case we get from Eq. (4)

$$\frac{d(\Delta T_\phi)}{d(d^{-1/2})} = \frac{-\Delta k_{y\phi} \frac{d\sigma_y}{dT} + (\Delta \sigma_{y\phi} - \Delta \sigma_{f\phi}) \frac{dk_y}{dT}}{\left(\frac{d\sigma_y}{dT} \right)^2} \dots \dots \dots (14)$$

The sign of Eq. (14) is positive or negative as the sign of

$$\left| \Delta k_{y\phi} \frac{d\sigma_y}{dT} \right| - \left| (\Delta \sigma_{y\phi} - \Delta \sigma_{f\phi}) \frac{dk_y}{dT} \right| \dots \dots \dots (15)$$

* The temperature independent k_y means the saturated or fully increased k_y as a result of full aging.⁶⁾ It is unlikely that the saturated k_y increases by irradiation. We consider, therefore, only the case where k_y decreases by irradiation. (The case AII).

** In the case of the temperature dependent k_y , k_y can still increase. We shall, therefore, consider the increase as well as the decrease of k_y by irradiation. (The cases AIV and AV).

is positive or negative. Thus the larger grains are effective in reducing ΔT_ϕ if Eq. (14) is positive, and the refined grains are effective to reduce ΔT_ϕ if Eq. (14) is negative.

B. Solute Concentration Dependence of Irradiation Sensitivity

Now we shall consider the effect of the interstitial solute atom concentration on the irradiation sensitivity. We shall assume the following equation^{4),9),18),19)}

$$\sigma_y = \sigma_{oc} + k_c c^m \dots (16)$$

where c is the interstitial solute atom concentration and σ_{oc} , k_c , and m are the constants. m is $1/2$ ^{18),19)} or 1 ^{4),9)} according to different authors. Here we keep d , λ , and ρ constant, which are included in σ_{oc} .

The fracture stress σ_f is assumed to be insensitive to the interstitial solute atom concentration for simplicity, so that we shall not provide an equation for σ_f similar to Eq. (16).

k_c in Eq. (16) is usually considered to be temperature dependent.⁴⁾ But a result by Heslop and Petch⁹⁾ shows a temperature independent k_c , in which interstitial solute atoms seem to be in some precipitated conditions. We shall not consider, therefore, the temperature independent k_c .

It is assumed that k_c may decrease, may increase, or may not change with irradiation. These three cases may all be possible according to the behaviors of radiation induced lattice defects which interact with solute atoms differently at different irradiation temperatures. Thus the following three combinations will be calculated.

(bi) The Case BI

k_c is temperature dependent and does not change with irradiation. Then we get the derivative of Eq. (1) with respect to c^m , $d(\Delta T_\phi)/d(c^m)$, in a similar way to that of Eq. (4). Thus we obtain

$$\frac{d(\Delta T_\phi)}{d(c^m)} = \frac{(\Delta\sigma_{y\phi} - \Delta\sigma_{f\phi}) \left(\frac{dk_c}{dT} \right)}{\left(\frac{d\sigma_y}{dT} \right)^2} \dots (17)$$

$$< 0. \dots (18)$$

The relation (18) is obtained because dk_c/dT is negative. This shows that interstitial solute atoms (*i.e.*, carbon or nitrogen) are effective in reducing the irradiation sensitivity.

(bii) The Case BII

k_c is temperature dependent and decreases with irradiation ($\Delta k_{c\phi} < 0$). Now we get

$$\frac{d(\Delta T_\phi)}{d(c^m)} = \frac{-\Delta k_{c\phi} \left(\frac{d\sigma_y}{dT} \right) + (\Delta\sigma_{y\phi} - \Delta\sigma_{f\phi}) \left(\frac{dk_c}{dT} \right)}{\left(\frac{d\sigma_y}{dT} \right)^2} \dots (19)$$

$$< 0. \dots (20)$$

The relation (20), which is easily obtained, shows

again that interstitial solute atoms are effective in reducing the irradiation sensitivity.

(biii) The Case BIII

k_c is temperature dependent and increases with irradiation ($\Delta k_{c\phi} > 0$). Then we obtain the same equation as Eq. (19). But as $\Delta k_{c\phi}$ is positive in this case, the sign of Eq. (19) changes as follows, *i.e.*,

$$\frac{d(\Delta T_\phi)}{d(c^m)} \geq 0 \dots (21)$$

according to the conditions

$$\left| \Delta k_{c\phi} \left(\frac{d\sigma_y}{dT} \right) \right| \geq \left| (\Delta\sigma_{y\phi} - \Delta\sigma_{f\phi}) \left(\frac{dk_c}{dT} \right) \right| \dots (22)$$

respectively. The relations (21) and (22) show that the interstitial solute atoms are not always effective in reducing the irradiation sensitivity, if $\Delta k_{c\phi}$ is positive.

C. Dependence of Irradiation Sensitivity on the Spacing of Dispersed Phases

We shall consider the effect of the spacing of dispersed second phases such as carbides and nitrides on the irradiation sensitivity. Now we shall assume the equations

$$\sigma_y = \sigma_{oy\lambda} + k_{y\lambda} \lambda^{-n} \dots (23)$$

$$\sigma_f = \sigma_{of\lambda} + k_{f\lambda} \lambda^{-n} \dots (24)$$

where λ is the spacing of the dispersed phases and $\sigma_{oy\lambda}$, $k_{y\lambda}$, $\sigma_{of\lambda}$, $k_{f\lambda}$, and n are the constants. n is $1/2$ ²⁰⁾ or 1 ²¹⁾ according to different authors. Here we keep d , c , and ρ constant, which are included in $\sigma_{oy\lambda}$ or in $\sigma_{of\lambda}$. We shall consider some possible cases in the followings.

(ci) The Case CI

$k_{y\lambda}$ is independent of temperature and does not change with irradiation, and $k_{f\lambda}$ does not either change with irradiation. The derivative of Eq. (1) with respect to λ^{-1} , $d(\Delta T_\phi)/d(\lambda^{-1})$, is obtained in a similar way to that of Eq. (4). Then we get

$$\frac{d(\Delta T_\phi)}{d(\lambda^{-n})} = 0 \dots (25)$$

in this case. This means, of course, there is no effect of dispersed phases on the irradiation sensitivity.

(cii) The Case CII

In deriving Eq. (1) in section II, it is assumed that the fracture stress increases by irradiation. But sometimes there occurs the case where the fracture stress decreases by irradiation. This occurs, for example, when the iron crystal contains precipitates of carbides or nitrides which are larger than a critical size. In this case the term $\Delta\sigma_{f\phi}$ in Eq. (1) should be replaced by $(-\Delta\sigma_{f\phi})$, where the value of $\Delta\sigma_{f\phi}$ is kept always positive.

Now the conditions for the case CII are as follows. The fracture stress decreases by irradiation, so that we use the modified Eq. (26) instead of Eq. (1). This is

$$\Delta T_\phi = \frac{-(\Delta\sigma_{f\phi} + \Delta\sigma_{y\phi})}{\left(\frac{d\sigma_y}{dT} \right)} \dots (26)$$

where $k_{y\lambda}$ is independent of temperature and does not change with irradiation, and $k_{f\lambda}$ decreases with irradiation ($\Delta k_{f\lambda} < 0$). These conditions are sometimes actually observed in steels with coarse precipitates.^{22),23)} Then we get the derivative of Eq. (26) with respect to λ^{-n} as follows:

$$\frac{d(\Delta T_\phi)}{d(\lambda^{-n})} = - \frac{\Delta k_{f\lambda\phi}}{\left(\frac{d\sigma_y}{dT}\right)} \dots\dots\dots (27)$$

$$< 0. \dots\dots\dots (28)$$

This shows that the dispersed phases are effective in reducing the irradiation sensitivity. In other words, the smaller the spacing, the less the shift of the transition temperature.

(ciii) The Case CIII

Here we use again Eq. (26) instead of Eq. (1). $k_{y\lambda}$ is independent of temperature and decreases with irradiation ($\Delta k_{y\lambda} < 0$) and $k_{f\lambda}$ also decreases with irradiation ($\Delta k_{f\lambda} < 0$). Then we obtain

$$\frac{d(\Delta T_\phi)}{d(\lambda^{-n})} = - \frac{\Delta k_{y\lambda\phi} + \Delta k_{f\lambda\phi}}{\left(\frac{d\sigma_y}{dT}\right)} \dots\dots\dots (29)$$

$$< 0. \dots\dots\dots (30)$$

This shows again that the dispersed phases are effective in reducing the irradiation sensitivity. Comparing the expressions (27) and (29), we can conclude that the case CIII is more effective than the case CII in reducing the sensitivity, if $\Delta k_{f\lambda\phi}$ in both cases are the same.

D. Dependence of Irradiation Sensitivity on the Dislocation Density

Now we shall consider the effect of dislocation density on the irradiation sensitivity. We assume the equations²⁴⁾

$$\sigma_y = \sigma_{oy\rho} + k_{y\rho} \rho^{1/2} \dots\dots\dots (31)$$

$$\sigma_f = \sigma_{of\rho} + k_{f\rho} \rho^{1/2} \dots\dots\dots (32)$$

where ρ is the dislocation density and $\sigma_{oy\rho}$, $k_{y\rho}$, $\sigma_{of\rho}$, and $k_{f\rho}$ are the constants. Here d , c , and λ are kept constant and are included in $\sigma_{oy\rho}$ and $\sigma_{of\rho}$. We shall consider the following one case.

(d) The Case D

$k_{y\rho}$ is independent of temperature and decreases with irradiation ($\Delta k_{y\rho} < 0$), while $k_{f\rho}$ does not change with irradiation. In this case we get the derivative of Eq. (1) with respect to $\rho^{1/2}$ as follows:

$$\frac{d(\Delta T_\phi)}{d(\rho^{1/2})} = - \frac{\Delta k_{y\rho\phi}}{\left(\frac{d\sigma_y}{dT}\right)} \dots\dots\dots (33)$$

$$< 0 \dots\dots\dots (34)$$

which shows that the increase in dislocation density is effective in reducing the irradiation sensitivity.

III. Discussions

Now let us examine the validity of Eq. (1) which is the basis of the present theory. In Table 1 the experimental values of $\Delta\sigma_{y\phi}$ and $\Delta\sigma_{f\phi}$, which are due to Trudeau,²⁵⁾ are shown together with the average values of $\Delta\sigma_y / \Delta T$ between -120°C and 0°C , which are estimated from the experimental results of Rees, Hopkins, and Tipler.²⁶⁾ The results of Trudeau are concerned with the binary alloys of iron, *i.e.*, Fe-0.021% C, Fe-1.5% Mn, Fe-3.25% Ni, Fe-1.0% Cr, and Fe-0.5% Mo. As the results of Rees *et al.* are not necessarily concerned with alloys of the same concentrations as those of Trudeau, the interpolations were made of the results of Rees *et al.*

Table 1. The change of yield stress $\Delta\sigma_{y\phi}$ and fracture stress $\Delta\sigma_{f\phi}$ * by irradiation and the average experimental temperature derivative of yield stress $\Delta\sigma_y / \Delta T$

Steel	10^{18} nvt**	$\Delta\sigma_{y\phi}^{25}$ (kg/mm ²)	$\Delta\sigma_{f\phi}^{25}$ (kg/mm ²)	$\Delta\sigma_y / \Delta T^{26}$ (kg/mm ² ·°C)
Fe-C	54	28.1	14.8	20.3
	109	23.4	11.3	120
Fe-Mn	55	32.8	19.5	16.3 120
	72	29.1	15.8	
	109	31.8	18.3	
Fe-Ni	68	34.8	24.4	14 120
	52	34.2	24.5	
	60	33.6	23.4	
	109	37.2	27.4	
Fe-Cr	25	26.1	12.1	19.6 120
	52	27.5	13.5	
	72	25.8	13.0	
	110	29.5	17.4	
Fe-Mo	51	15.2	5.7	19.3 120
	110	22.2	11.5	

* Here the tensile strength is used conventionally instead of fracture stress.

** Integrated neutron flux corresponding to $\Delta\sigma_{y\phi}$ and $\Delta\sigma_{f\phi}$.

From these experimental values in Table 1 we can calculate $\Delta T_{\phi\text{cal}}$ using Eq. (1). These values of $\Delta T_{\phi\text{cal}}$ are compared with the experimental values of $\Delta T_{\phi\text{exp}}$ obtained by Trudeau²⁵⁾ as shown in Fig. 2, where the abscissa shows $\Delta T_{\phi\text{exp}}$ and the ordinate shows $\Delta T_{\phi\text{cal}}$. The values in Fig. 2 fall approximately on the 45° straight line. This shows the validity of Eq. (1).

Now we shall discuss about the results of calculations described in section II. It is difficult at present to compare the calculated values of $d(\Delta T_\phi) / d(d^{-1/2})$, $d(\Delta T_\phi) / d(C^m)$, *etc.* with the corresponding experimental values, because there scarcely are experimental results which were obtained under well specified conditions which can be quantitatively compared with the theory. What we can do at this moment is to compare the theoretical results qualitatively with experimental results. In other words we can discuss signs (*i.e.*, plus or minus) of $d(\Delta T_\phi) / d(d^{-1/2})$, *etc.* and compare them with experimental results. We shall describe below the

Fig. 2. The experimental irradiation sensitivity $\Delta T_{\phi \text{exp}}$ vs. the calculated irradiation sensitivity $\Delta T_{\phi \text{cal}}$

cases where the experimental results are found in the literatures, with which the above mentioned signs of the irradiation sensitivity can be checked. It should be emphasized here that in all cases described below the experimental results agree well qualitatively, *i.e.*, in sign, with the theory.

(1) If the steel is fully aged, namely if k_y is independent of temperature,^{8),12)} and if k_y does not change with irradiation, then the grain refinement has no effect on the irradiation sensitivity²⁷⁾ (the case *AI*: Eq. (7)). But if k_y decreases with irradiation, the grain refinement reduces the irradiation sensitivity²⁸⁾⁻³²⁾ (the case *AII*: Eq. (9)).

The first case of the case *AV*, *i.e.*, the case where the value (15) from Eq. (14) is positive, seems to be found in the reference,³³⁾ where larger grains are effective in reducing the irradiation sensitivity.

(2) Two examples of the effects of interstitial solute atom concentrations are found in the literatures. In the case corresponding to *BII* (Eq. (20)) the higher solute concentration reduces the irradiation sensitivity,¹⁰⁾ whereas in the case corresponding to the second case of *BIII* (Eq. (21)) the higher solute concentration increases ΔT_{ϕ} .³⁴⁾⁻³⁶⁾

(3) If the steel contains precipitates of carbides or nitrides which are larger than a critical size, it occurs that the fracture stress decreases by irradiation. We find two cases concerning the effects of spacings between precipitations in the literatures, *i.e.*, *CII* (Eq. (28)) and *CIII* (Eq. (30)). In both cases the smaller the spacing, the smaller the sensitivity.^{37),38)}

(4) If the dislocation density is increased, the irradiation sensitivity is decreased (the case *D*: Eq. (34)).³⁹⁾

In this paper only the sensitivity, or the shift of the transition temperature, was discussed. But the transition temperature itself is affected by the metallurgical factors considered in this paper. This point will be discussed elsewhere later.

It is hoped that the irradiation experiments will be more extensively performed, in which metallurgical factors discussed in this paper will be more fully spe-

cified and controlled. Then the present theory will be more thoroughly examined.

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