A Phenomenological Theory for Ductility Loss of Neutron Irradiated Iron and Iron Alloys*

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The neutron irradiation induced embrittlement is one of the most important problems in nuclear structural materials.¹⁻³⁾ The authors⁴⁻⁶⁾ have been investigating about the loss of ductility due to irradiation, and clarified the relation between uniform elongation and work hardening coefficient and also the effects of alloying elements on the ductility after irradiation.

The objective of this study is to clarify the loss of total elongation including both uniform elongation and post-uniform elongation of neutron irradiated iron and iron alloys.

The chemical compositions of used materials were Fe-70wt.ppmN(Fe-N), Fe-0.5wt.%Mo-70wt.ppmN(Fe-Mo-N) and Fe-0.2wt.%Cu-70wt.ppmN(Fe-Cu-N). The specimen for tensile testing was cut out to the size 1×3×24 mm (parallel part). The specimens were annealed at 800 °C for 1 hr in vacuum of 1×10⁻⁵ torr, and subsequently quenched into water. The irradiation was carried out at JRR-2 to a fluence of 3×10¹⁹ n/cm² (E>1 MeV). The irradiation temperature was about 60 °C. Tensile tests were performed at room temperature by using an Instron type testing machine. The strain rate was at the range from 3.47×10⁻⁴ to 1.39×10⁻³ sec⁻¹.

The general relation between true stress σ and true strain ϵ , at constant temperature and strain rate, can be expressed by the next equation.

$$\sigma = A\epsilon^n \dots\dots\dots(1)$$

where, A : materials constant

n : work hardening coefficient.

From the Eq. (1), the work hardening coefficient can be expressed as follows.

$$n = \frac{d \log \sigma}{d \log \epsilon} \dots\dots\dots(2)$$

As generally accepted the strain at load maximum ϵ_u is equal to n .

Figure 1 shows the relation between ϵ_u and n for both unirradiated and irradiated iron and iron alloys. After irradiation, ϵ_u decreases with decreasing n . As for the strain rate dependence of flow stress, the relation can be expressed as the next equation.

$$\sigma = K\dot{\epsilon}^m \dots\dots\dots(3)$$

where, $\dot{\epsilon}$: strain rate

K : materials constant

m : strain rate sensitivity coefficient.

From the Eq. (3), the strain rate sensitivity coefficient can be expressed as follows.

$$m = \frac{d \log \sigma}{d \log \dot{\epsilon}} \dots\dots\dots(4)$$

This m value is considered to be controlling factor for necking strain. Since it is very difficult to measure the local ductility in irradiated materials, the conventional total strain ϵ_t is taken as shown in the next equation.

$$\epsilon_t = \ln \frac{l_f}{l_0} \dots\dots\dots(5)$$

where, l_0 : original gauge length

l_f : current length after fracture including both uniform strain and local necking strain.

And post-uniform strain ϵ_l was taken as $\epsilon_t - \epsilon_u$.

Figure 2 shows the relation between local necking strain $\epsilon_t - \epsilon_u (= \epsilon_l)$ and m value. The linear relation between ϵ_l and m values is obtained. Therefore, total strain as defined in the Eq. (5) can be expressed as the next equation phenomenologically.

$$\begin{aligned} \epsilon_t &= \epsilon_u + \epsilon_l \\ &= Cn + Dm \dots\dots\dots(6) \end{aligned}$$

Fig. 1. The relation between observed ϵ_u value and n value.

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where, C : coefficient of nearly 1
 D : coefficient for post-uniform strain.
Figure 3 shows the relation between frictional stress

Fig. 2. The relation between local necking strain and m value.

Fig. 3. The observed n value and m value vs. frictional stress σ_i .

$\sigma_i (= \sigma_0 + \sigma_\phi)$ obtained by Rosenfield's method⁷⁾ and n and m values. After irradiation, both n and m values decrease with increasing the frictional stress. The reason why n and m values decrease with increasing the frictional stress can be understood as the following. When we denote static stress as σ_s and dynamic stress as σ_d , the total stress can be expressed as the next equation.

$$\sigma = \sigma_d + \sigma_s \dots\dots\dots(7)$$

In the above equation, σ_d and σ_s can be expressed as follows.

$$\sigma_d = \beta \dot{\epsilon}^{m'} \dots\dots\dots(8)$$

$$\sigma_s = \sigma_0 + \sigma_\phi + \alpha' \epsilon^{n'} \dots\dots\dots(9)$$

where, β, m' : materials parameter
 σ_0 : frictional force
 σ_ϕ : irradiation hardening
 $\alpha' \epsilon^{n'}$: strain hardening in which α' and n' are materials parameter.

Then from the Eqs. (2), (7) to (9), the next equation can be deduced approximately,

$$\begin{aligned} n &= \frac{d \log \sigma}{d \log \dot{\epsilon}} \\ &= n' \left(1 - \frac{\sigma_0 + \sigma_\phi + \sigma_d}{\sigma} \right) = \frac{n' \alpha' \epsilon^{n'}}{\sigma} \dots\dots\dots(10) \end{aligned}$$

From the Eqs. (4), (7) to (9), the next equation follows approximately,

$$\begin{aligned} m &= \frac{d \log \sigma}{d \log \dot{\epsilon}} \\ &= m' \left(1 - \frac{\sigma_0 + \sigma_\phi + \alpha' \epsilon^{n'}}{\sigma} \right) = \frac{m' \beta \dot{\epsilon}^{m'}}{\sigma} \dots\dots\dots(11) \end{aligned}$$

In Eqs. (10) and (11), it is shown that the increase of σ_ϕ value makes n or m value smaller. The values of n and m are also related to values of $n' \alpha' \epsilon^{n'}$ and $m' \beta \dot{\epsilon}^{m'}$ after irradiation.

Table 1 shows the each parameters in Eqs. (10) and (11). From this table the relation between $n' \alpha' \epsilon^{n'}$ and $m' \beta \dot{\epsilon}^{m'}$ values and σ_i can be shown in Fig. 4. This shows that the increase of σ_i , which is due to irradiation hardening, makes the decrease of $n' \alpha' \epsilon^{n'}$ and $m' \beta \dot{\epsilon}^{m'}$. Therefore, from Eqs. (10) and (11) it is clear that the decrease of n and m values is attributed to the irradiation hardening directly and the change of $n' \alpha' \epsilon^{n'}$ and $m' \beta \dot{\epsilon}^{m'}$ indirectly.

Figure 5 shows the relation between irradiation hardening and the decrease of total ductility. The

Table 1. Materials parameters of iron and iron alloys. ($\epsilon = \epsilon_{load \max.}$)

		σ_0 (kg/mm ²)	σ_ϕ (kg/mm ²)	$\alpha' \epsilon^{n'}$ (kg/mm ²)	$\beta \dot{\epsilon}^{m'}$ (kg/mm ²)	n'	$n_{cal.}$	$n_{obs.}$	m'	$m_{cal.}$	$m_{obs.}$
Before irradiation	Fe-N	10.7	0	15.9	2.3	0.66	0.36	0.28	0.32	0.03	0.07
	Fe-Mo-N	13.3	0	16.2	2.7	0.59	0.30	0.26	0.34	0.03	0.06
	Fe-Cu-N	14.0	0	12.9	1.0	0.57	0.26	0.27	0.42	0.02	0.06
After irradiation	Fe-N	10.7	15.6	6.4	1.0	0.63	0.12	0.15	0.52	0.02	0.04
	Fe-Mo-N	13.3	14.6	9.1	1.5	0.45	0.11	0.11	0.53	0.02	0.03
	Fe-Cu-N	14.0	16.7	4.4	0.5	0.29	0.03	0.06	0.61	0.01	0.01

Fig. 4. The relation between $n'\sigma'\epsilon^n$ and $m'\beta'\epsilon^m$ values and frictional stress σ_i .

ductility is strongly affected by irradiation hardening. In the irradiation hardening, the behavior of nitrogen atoms and vacancies complex is considered to be essential factor, and the yield stress increases with the square root of the total neutron dose.⁸⁾

Therefore, when we compare the results of Fe-N or Fe-Mo-N with Fe-V-N,⁴⁾ less nitrogen-vacancy complex defects may be formed, in the latter, due to stronger trapping effect of vanadium for nitrogen compared with molybdenum,⁵⁾ and less irradiation hardening and less the decrease of total ductility is observed. Furthermore, when we compare the results of Fe-N and Fe-Cu-N, other than nitrogen-vacancy complex defects, copper-vacancy complex defects⁹⁾ may be formed and more irradiation hardening and more the decrease of total ductility is observed in the

Fig. 5. The relation between irradiation hardening and the decrease of total strain.

latter.

After all, the way to keep post irradiation ductility is to suppress irradiation hardening through controlling of interstitial nitrogen atoms and substitutional atoms or impurities such as copper atoms.

REFERENCES

- 1) J. O. Stiegler and J. R. Weir, Jr.: Ductility, ASM, Ohio, (1967), 311.
- 2) L. E. Steele: Neutron Irradiation Embrittlement of Reactor Pressure Vessel Steels, Int'l Atomic Energy Agency, Vienna, (1975), 93.
- 3) J. Gittus: Irradiation Effects in Crystalline Solids, Applied Science Publishers, Ltd., London, (1978), 167.
- 4) N. Igata, R. R. Hasiguti and K. Watanabe: Proceedings of the Third International Conference on the Strength of Metals and Alloys, The Inst. Metals and ISI, Cambridge, (1973), 21.
- 5) N. Igata, K. Watanabe and S. Sato: *ASTM, Spec. Tech. Pub.*, **529** (1973), 63.
- 6) N. Igata, H. Kayano and K. Watanabe: *ASTM Spec. Tech. Publ.*, **570** (1975), 24.
- 7) A. R. Rosenfield: *J. Inst. Metals*, **91** (1962), 104.
- 8) S. B. McRickard: *Phil. Mag.*, **18** (1968), 915.
- 9) F. A. Smidt, Jr. and H. E. Watson: *Met. Trans.*, **3** (1972), 2065.