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The body can be viewed from the next page.

Embrittlement of Steel Plates and Forgings and Their Weldments by Neutron Irradiation*

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1 Introduction

The material of nuclear reactor pressure vessels is irradiated by neutrons during the reactor operation and becomes increasingly embrittle with time. From the viewpoint of safety, therefore, it is very important to know the extent of embrittlement of the material used during its service. Though much research has been performed concerning neutron embrittlement of materials[1-7], most such works have been phenomenological, and the mechanism of neutron irradiation embrittlement of steel is not yet been clearly understood. The factors which control neutron irradiation embrittlement of steel include chemical composition, metallurgical structure, neutron energy distribution, total neutron fluence, irradiation temperature, neutron flux and stress. Among these, only chemical composition and metallurgical structure are related to the material itself.

A great deal of research has been done in an effort to correlate the chemical composition of steel with neutron irradiation embrittlement. On this basis, the following formulae have been proposed for evaluating the neutron irradiation embrittlement of steels for light water reactor pressure vessels.

(1) NRC Regulatory Guide 1.99 Rev. 1[8)]

$$\Delta RT_{NDT} = [22 + 556(\%Cu - 0.08) + 2\,778(\%P - 0.008)]f^{0.5} \cdots (1)$$

where

ΔRT_{NDT}: Shift of reference temperature RT_{NDT} (°C)

f: Neutron fluence divided by 10^{19} (n/cm^2, E > 1 MeV)

(2) NRC Regulatory Guide 1.99 Rev. 2 (Draft)[9)]

$$\text{Adjusted } RT_{NDT} = \text{Initial } RT_{NDT} + \Delta RT_{NDT} + M \cdots\cdots (2)$$

$$\Delta RT_{NDT} = \Delta RT_{NDT,\ surface} \exp(-0.0026x)$$

$$\Delta RT_{NDT,\ surface} = CF \times f^{(0.28-0.10 \log f)}$$

$$M = 2\sqrt{\sigma_1^2 + \sigma_\Delta^2}$$

where

x: Depth into the vessel wall from the vessel inner surface

CF: Chemical factor (CF = 11°C for base metal and weld metal with Cu content not exceeding 0.01%)

M: Margin

$\sigma_1 = 0$ if a measured value of initial RT_{NDT} is used

$\sigma_\Delta = 9$ °C (base metal), 16 °C (weld metal)

(3) NRC 10CFR50-50.61 Toughness Requirement for

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Preventing PTS (Pressurized Thermal Shock)[10]

Lower temperature between the values calculated by the following equations:

$$RT_{PTS} = I + M + \Delta RT_{NDT} \cdots\cdots\cdots (3a)$$

$$RT_{PTS} = I + M + 156f^{0.194} \cdots\cdots\cdots (3b)$$

where

$\Delta RT_{NDT} = (-6 + 261Cu + 194Cu \times Ni)f^{0.27}$ (Guthrie's prediction[11])

RT_{PTS}: Reference temperature for PTS criterion (°C)

I: Initial RT_{NDT}

M: Margin (M = 27°C if the initial RT_{NDT} is used)

The above formulae for prediction indicate that Cu, P and Ni in steel raise the sensitivity to neutron irradiation embrittlement. Among these elements, it was formerly claimed that P intensified neutron irradiation embrittlement[8], while recently Ni is claimed[9] to be a problem with a higher content of Cu. As mentioned above, however, the mechanism of neutron irradiation embrittlement of steel is not clear and the studies which have been done so far on the effects of elements on neutron irradiation embrittlement have not necessarily reflected the chemical composition of steels produced by the modern steel making techniques currently in practice. It is important, therefore, to study the steels actually used as to their sensitivity to neutron irradiation embrittlement.

With respect to metallurgical structure, on the other hand, the studies using various steels have made it clear that such transformation structures made at lower temperatures as tempered martensites and lower bainites are less sensitive to neutron irradiation embrittlement than those made at higher temperatures such as tempered upper bainites and mixtures of upper bainite and ferrite[12, 13].

As mentioned above, the sensitivity of steels to neutron irradiation embrittlement strongly depends on chemical composition and metallurgical structure. Since the plates (JIS SQV2A) and the forgings (JIS SFVQ1A) for light water reactor pressure vessels have almost the same chemical composition and metallurgical structure, no significant difference in the sensitivity to neutron irradiation embrittlement exists between them.

This paper makes a quantitative evaluation of changes in mechanical properties, including the effect of Ni, of heavy section plates JIS SQV2A (ASME SA533B Cl.1), forgings JIS SFVQ1A (ASME SA508 Cl.3) and their welded joints for light water reactor pressure vessels induced by neutron irradiation which simulates the conditions in light water reactors.

2 Test Procedures

2.1 Materials

The materials subjected to neutron irradiation test were 163-mm and 250-mm thick steel plates SQV2A, 115 to 290-mm thick steel forgings SFVQ1A, and the weld metal and heat affected zone (HAZ 1 mm) of their welded joints made by submerged arc welding.

The chemical composition and mechanical properties of the materials tested are listed in **Tables 1** and **2**. The F1 and F3 are forgings produced from hollow ingots and F4 is a forging whose Ni content was increased within the range allowed by the standard JIS G3204. **Table 3** shows the welding conditions used in making welded joints.

Table 1 Chemical composition (wt%)

Steel		Thickness (mm)	C	Si	Mn	P	S	Ni	Cu	Cr	Mo
Plate SQV2A	JIS G3120		≦0.25	0.15 ~0.30	1.15 ~1.50	≦0.035	≦0.04	0.40 ~0.70			0.45 ~0.60
	P1	163	0.18	0.21	1.41	0.006	0.002	0.68	0.01	0.09	0.49
	P2	250	0.18	0.24	1.40	0.004	0.003	0.69	0.01	0.09	0.53
	P2(WM*1)	—	0.05	0.33	1.55	0.010	0.003	0.76	0.01	0.06	0.40
Forging SFVQ1A	JIS G3204		≦0.25	≦0.40	1.20 ~1.50	≦0.030	≦0.030	0.40 ~1.00		≦0.25	0.45 ~0.60
	F1	260	0.18	0.25	1.44	0.004	0.002	0.70	0.01	0.14	0.51
	F1(WM*1)	—	0.07	0.33	1.62	0.010	0.003	0.78	0.01	0.07	0.45
	F2	115	0.19	0.27	1.43	0.004	0.002	0.77	0.01	0.12	0.53
	F3	290	0.17	0.25	1.44	0.004	0.002	0.75	0.01	0.20	0.51
	F4	270	0.18	0.25	1.45	0.004	0.002	0.94	0.01	0.18	0.52

*1 Weld metal

Table 2 Mechanical properties

Steel		Tensile test				Charpy impact test				
		YP (MPa)	TS (MPa)	El (%)	RA (%)	${}_{\mathrm{v}}T_{rs}$*1 (°C)	${}_{\mathrm{v}}T_{r68}$*2 (°C)	${}_{\mathrm{v}}T_{r0.9}$*3 (°C)	${}_{\mathrm{v}}E_{S}$*4 (J)	${}_{\mathrm{v}}E_{0}$*5 (J)
Plate SQV2A	P1	529	625	25	70	−26	−47	−66	237	226
	P2	500	674	28	70	−26	−46	−43	236	183
Forging SFVQ1A	F1	470	607	29	77	−10	−27	−25	225	147
	F2	451	598	25	72	−30	−41	−44	254	187
	F3	487	635	25	77	−19	−34	−30	257	197
	F4	497	631	24	71	−24	−34	−32	233	179

*1 50% fracture appearance transition temperature
*2 68J (50 ft·lb) transition temperature
*3 0.9 mm (35 mils) transition temperature
*4 Upper shelf energy
*5 Impact energy at 0°C

Table 3 Welding conditions

Steel		Welding method	Welding material	Temp. (°C) Preheat/interpass	Current (A)	Voltage (V)	Velocity (cm/min)
Plate SQV2A	P1	SAW	Y204 +YF200 (3.2 φ)	200/260	350-500	28-35	20-40
			Y204 +YF200 (4.8 φ)	〃	650-750	28-35	20-40
	P2	SAW	US-56B + MF-27	150/260	600-650	28-29	50-70
Forging SFVQ1A	F1	N-SAW	KW101B + KB125	150/200	500-550	27-29	25-31

2.2 Tensile Test

The tensile test was performed on base metal before and after neutron irradiation. The specimens were standard ones for the JMTR high temperature tensile test. The specimen geometry is shown in **Fig. 1**. Each specimen was machined from a quarter of thickness so that the testing direction is normal to the major working direction.

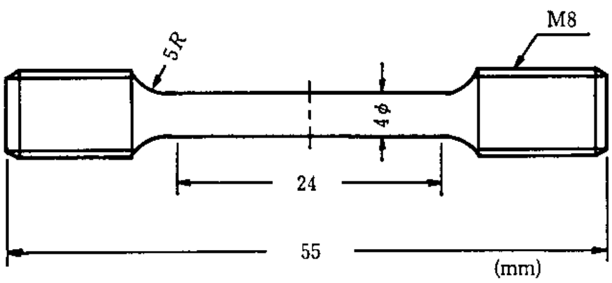

Fig. 1 Tensile test specimen geometry

2.3 Charpy Impact Test

The 2-mm V-notched Charpy impact test was performed on base metal, weld metal and heat affected zone before and after neutron irradiation. The specimens were JIS Z2202 No. 4 specimens. Each specimen was machined from a quarter of thickness so that the testing direction is normal to the major working direction.

2.4 Static Fracture Toughness Test

The static fracture toughness test was performed on base metal and heat affected zone before and after neutron irradiation. The specimen geometry is shown in **Fig. 2**. The specimens were 10-mm thick compact specimens, each of which was machined from a quarter of thickness so that the testing direction is normal to the major working direction. To facilitate specimen temperature control during neutron irradiation, the open space of the specimen was filled with the same material. As a result, the clip gage was mounted not on the load line, but on the specimen edge. Each specimen was precracked by cyclic loading at $K_{f\,max} \leqq 21\ \mathrm{MPa}\sqrt{m}$ before

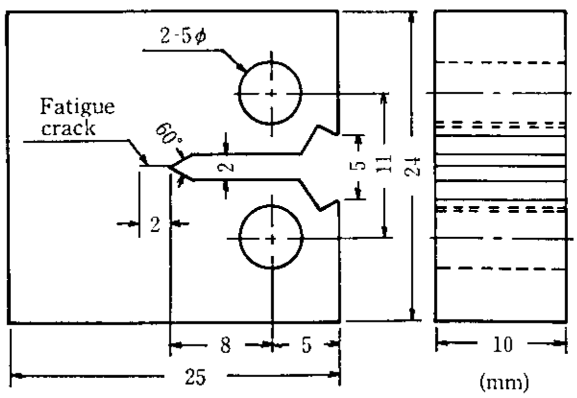

Fig. 2 Compact test specimen geometry

irradiation.

When fracture was elastic, fracture toughness K_Q was calculated from fracture load P_Q according to ASTM E399[14)] using the following equation:

$$K_Q = \frac{P_Q}{B\sqrt{W}} f(a/W) \cdots\cdots\cdots\cdots\cdots\cdots (4)$$

where

$$f(a/W) = (2 + a/W)[0.886 + 4.64a/W - 13.32(a/W)^2 + 14.72(a/W)^3 - 5.6(a/W)^4]/(1 - a/W)^{3/2}$$

a: Notch length
B: Specimen thickness
W: Specimen width

When K_Q satisfied the plane strain fracture toughness conditions as defined by the ASTM standard, it was regarded as K_{IC}.

When ductile crack was not initiated because of elastic-plastic fracture, the J-integral was calculated from the energy (U) absorbed by the specimen up to fracture using the following equation[15)]:

$$J = \frac{U}{Bb} \times \frac{2(1 + \alpha)}{(1 + \alpha^2)} \cdots\cdots\cdots\cdots\cdots\cdots (5)$$

$$\alpha = \sqrt{(2a_0/b)^2 + (2a_0/b) + 2} - (2a_0/b + 1)$$

$$b = W - a_0$$

a_0 = Initial notch length

When ductile crack was initiated, electric resistance method and unloading compliance method were used for SQV2A plate and SFVQ1A forging to obtain the J-integral corresponding to ductile crack initiation, J_{IC}.

In the present experiment, the displacement at specimen edge, V, had to be measured instead of the load line displacement Δ from the necessity of neutron irradiation test as mentioned above. In the determination of energy absorbed by the specimen, U, in Eq. (5), therefore, the displacement at specimen edge, V, was converted to load line displacement Δ using the following equation[16)]:

$$V/\Delta = 0.190072 + 1.78633(a_0/W) - 1.89443(a_0/W)^2 + 0.71899(a_0/W)^3 \cdots\cdots\cdots\cdots (6)$$

2.5 Neutron Irradiation

The neutron irradiation of specimens which were placed in vacuum temperature control type capsules was performed in the nuclear reactor for material testing, JMTR, at Oarai Laboratory of Japan Atomic Energy Research Institute. An example of layout of specimens, flux monitors and thermocouples for temperature measurement in a capsule is shown in **Fig. 3**. The neutron irradiation conditions are listed in **Table 4**.

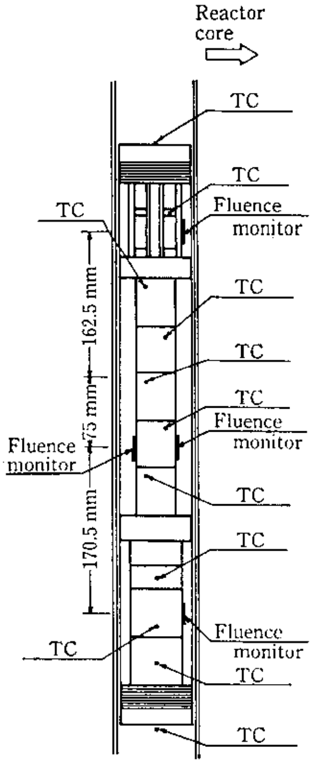

Fig. 3 An example of layout of thermo-couples (TC) and fluence monitors in a capsule

Table 4 Irradiation conditions

Steel	Temperature (°C)	Fluence (n/cm²)
P1	280	3.7×10^{18}
P1 (HAZ)	280	3.8×10^{18}
P2	306	2.8×10^{19}
P2 (HAZ)	284	2.9×10^{19}
P2 (WM)	284	2.9×10^{19}
F1 (HAZ)	290	6×10^{19}
F2	290	6×10^{19}
F3	290	6×10^{19}
F4	290	6×10^{19}

3 Experimental Results and Discussion

3.1 Tensile Test

Table 5 shows the tensile test results of base metal. Each material exhibited such embrittlement induced by neutron irradiation that strength increased and elongation decreased. The increase in yield strength was 3 to 9%, the increase in tensile strength, 2 to 5%, and the decrease in elongation, 0 to 13%. Though the neutron fluence for F3 and F4 was 6×10^{19} n/cm² which is 22

Table 5 Effect of neutron irradiation on tensile test results

Steel	Test temperature (°C)	YS (MPa)			TS (MPa)			El (%)		
		Irradiation		Difference (%)	Irradiation		Difference (%)	Irradiation		Difference (%)
		Before	After		Before	After		Before	After	
P1	20	529	547	+3	625	641	+3	25	22	−12
	150	478	491	+3	578	600	+4	22	—	—
	286	446	484	+9	600	625	+4	22	—	—
P2	20	481	509	+6	611	627	+3	24	21	−13
	150	441	466	+6	583	599	+3	20	19	− 5
	290	425	460	+8	614	629	+2	23	20	−13
F3	24	468	511	+9	610	637	+4	25	25	0
	298	465	505	+9	580	610	+5	—	—	—
F4	24	461	495	+7	593	610	+3	23	20	−13
	298	421	443	+5	580	602	+4	—	—	—

Table 6 Effect of neutron irradiation on Charpy impact test results

Steel	Charpy impact test result								
	$_vT_{rs}$ (°C)			$_vT_{r68}$*1 (°C)			$_vT_{r41}$*2 (°C)		
	Before	After	Difference	Before	After	Difference	Before	After	Difference
P1	−26	−12	14	−47	−43	4	−57	−57	0
P1 (HAZ)	−57	−46	8	−68	−63	5	−80	−75	5
P2	−26	16	42	−46	− 2	44	−58	−20	38
P2 (HAZ)	−61	−49	12	−69	−69	0	−86	−72	14
P2 (WM)	−43	8	51	−49	7	42	−55	−19	36
F1 (HAZ)	−24	17	41	−43	0	43	−57	−26	31
F2	−30	16	46	−41	−11	30	−55	−22	33
F3	−19	31	50	−34	− 5	29	−49	−26	23
F4	−24	21	45	−34	3	37	−42	−12	30

*1 68J transition temperature
*2 41J transition temperature

times as large as those for P1 and P2, respectively, no significant difference was observed in the increase in strength and the decrease in elongation among them. The difference in Ni content between F3 and F4 did not give any difference in tensile test results as well.

3.2 Charpy Impact Test

Figure 4 shows the effect of neutron irradiation on 2-mm V-notched Charpy impact test results for base metal and heat affected zone of P4, and base metals of F3 and F4. All cases exhibited the general phenomena that the transition temperature was raised and the upper shelf energy was lowered by neutron irradiation. The shifts in 50% fracture appearance transition temperature and, 68 and 41-J transition temperatures induced by neutron irradiation are shown in **Table 6** for all the materials and welded joints tested. The steels F3 and F4 were irradiated in the same conditions, though the latter had the Ni content of 0.94% which is higher than the former by 0.19 point. The shifts of 68 and 41-J transition temperatures were larger in F4 steel whose Ni content was higher, while the shifts of fracture appearance transition temperature and the decrease in upper shelf energy as observed in Fig. 4 were smaller. It can be concluded, therefore, that the increase in Ni content within the range allowed by the standard does not affect the sensitivity to neutron irradiation embrittlement.

In the present research, three kinds of transition tem-

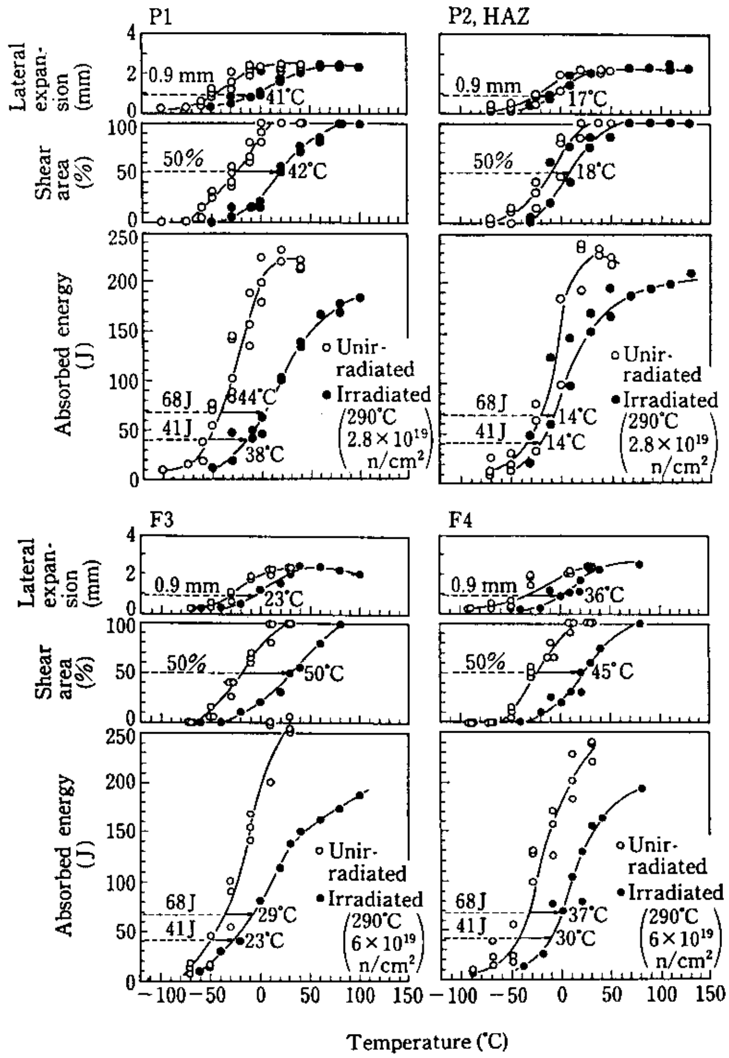

Fig. 4 Examples of effect of neutron irradiation on Charpy test results

perature are used as in Table 6. The relation between these three different transition temperatures is plotted in **Fig. 5**. As observed in Fig. 5 and Table 6, the shift induced by neutron irradiation decreased in the order of the 50% fracture appearance transition temperature, the 68-J transition temperature, and the 41-J transition temperature. However, the difference between these three parameters was within ±15°C except one point. This is attributed to the facts that the shift of the transition temperature for higher energy is larger since neutron irradiation lowers upper shelf energy, and the 50% fracture appearance transition temperature is a transition temperature for an energy higher than 68J.

Figure 6 plots the shift of 41-J transition temperature induced by neutron irradiation vs. neutron fluence. Since the shift of 41-J transition temperature is generally used as a parameter representing the extent of neutron irradiation embrittlement, the 41-J transition temperature was used as a reference temperature. The figure

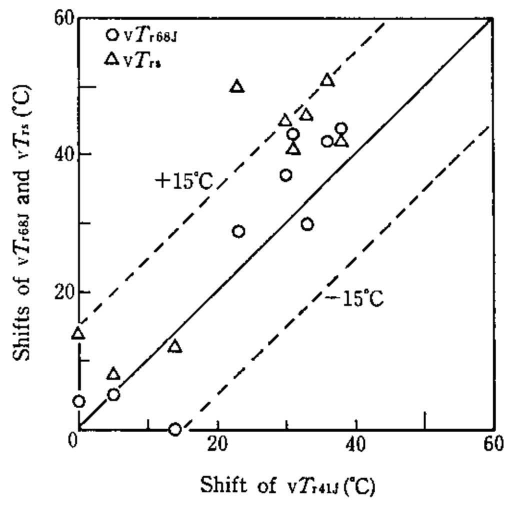

Fig. 5 Plot of shifts of 68-J and 50% shear area transition temperature vs. shift of 41-J transition temperature

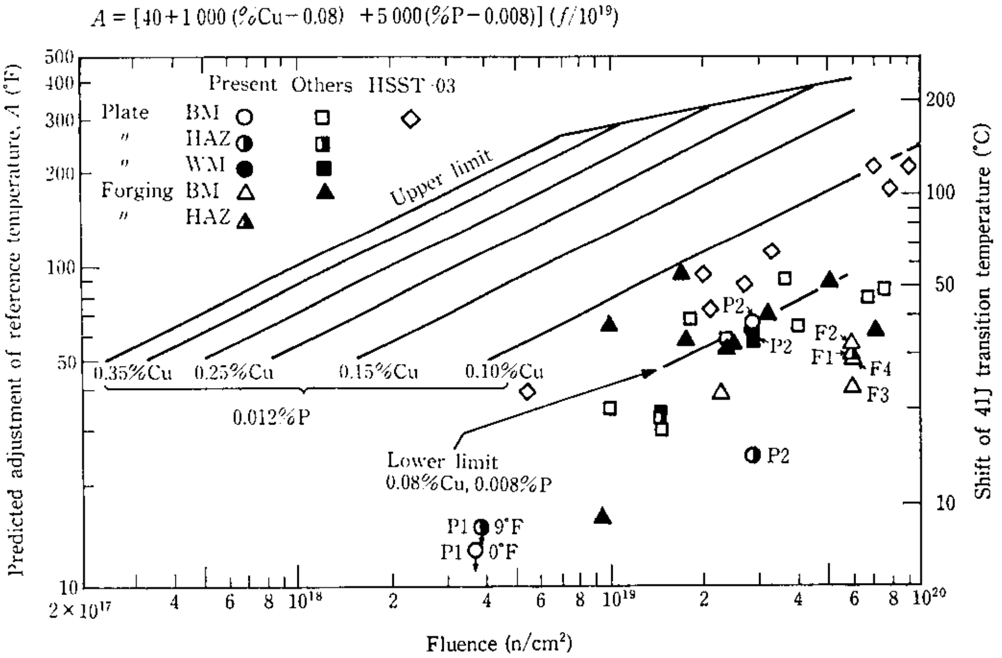

Fig. 6 Plot of the shift of 41-J transition temperature vs. neutron fluence (E > 1MeV)

shows not only the data of the steels tested in the present research, but also the data of the steels produced recently in Japan and the A533B Cl.1 steel plate made for the HSST program in U.S.A.[7], and the prediction lines of NRC Regulatory Guide 1.99 Rev. 1[8]. The data obtained in the present research lie below the lower limit of the prediction lines and prove to be as good as other steels produced recently in Japan. The steel plate made for the HSST program exhibited strong embrittlement as a whole. This is attributed to the fact that Cu and P were as high as 0.12% and 0.011% respectively, though Ni was as low as 0.56%. The embrittlement induced by neutron irradiation became larger as the fluence was increased. The neutron fluence as low as 3.8×10^{18} n/cm², however, did not shift the 41-J transition temperature.

The total evaluation of the data of the steels used in the present research and produced recently in Japan indicates that no significant difference exists between plate and forging. This is attributed to the fact that not much difference exists between plate and forging in chemical composition and metallurgical structure.

Three different equations for predicting the shift of transition temperature induced by neutron irradiation have been presented by NRC. **Table 7** compares the shift experimentally obtained with that predicted. The NRC Regulatory Guide 1.99 Rev. 1 gave the prediction of the shift of 41-J transition temperature as large as the experimentally obtained shift for the base metal and weld metal of P2, though it gave the prediction 20 to 30°C higher than the experiment when the neutron fluence was as large as 6×10^{19} n/cm². The NRC Regulatory Guide 1.99 Rev. 2 gave an excessive prediction at a neutron fluence as low as 3.7×10^{18} n/cm², though it gave a reasonable prediction at a higher fluence. The NRC 10CFR50-50.61 which is a requirement for preventing PTS fracture and was made on the basis of surveillance data mainly, on the other hand, overestimated the neutron irradiation embrittlement as a whole. The overestimation of embrittlement induced by neutron irradiation is attributed to the facts that though each prediction regards the Cu content as an effective factor, NRC Regulatory Guide Rev. 1 and Rev. 2 treat the Cu content in such a way that values 0.08% and 0.03% and under,

Table 7 Experimental and estimated shifts of $_{v}T_{r41}$ induced by neutron irradiation

Steel	Shift of $_{v}T_{r41}$ (°C)			
	Experiment	NRC RG1.99 Rev. 1	NRC RG1.99 Rev. 2	NRC 10CFR50
P1	0	13	26	51
P1 (HAZ)	5	14	26	51
P2	38	37	32	50
P2 (HAZ)	14	37	32	50
P2 (WM)	36	37	46	50
F1 (HAZ)	31	54	34	51
F2	33	54	34	51
F3	23	54	34	51
F4	30	54	34	51

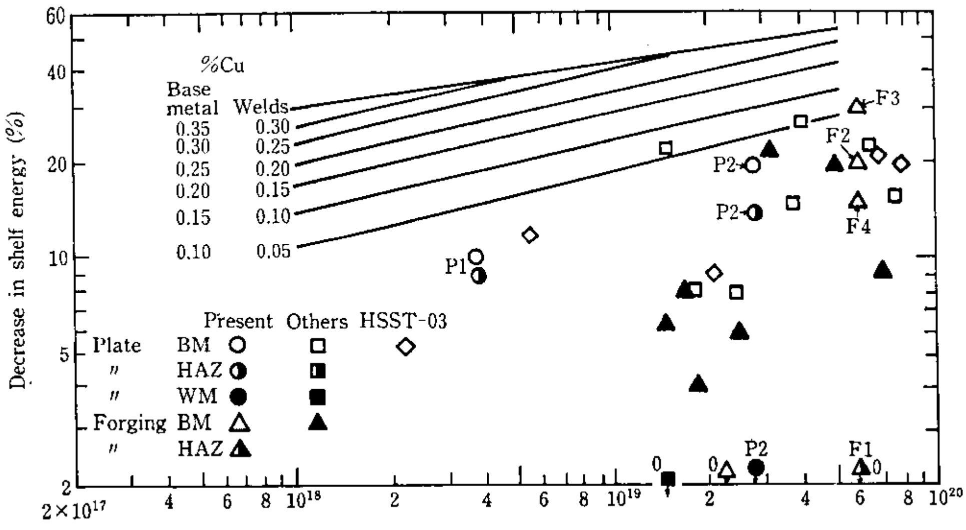

Fig. 7 Plot of decrease in upper shelf energy vs. neutron fluence (E > 1MeV)

respectively, are disregarded and treated as 0.08% and 0.03% respectively, and thus the predicted value for steels with low Cu content is magnified, and NRC 10CFR50 was made on the basis of the data of steels with relatively high Cu content and also gives a 27°C margin to the shift of reference temperature.

Figure 7 plots the decrease in upper shelf energy induced by neutron irradiation vs. neutron fluence. The figure also shows the data of the recently produced Japanese steels and the steel produced for the HSST program[7] and the prediction lines given by NRC Regulatory Guide 1.99[8]. Though difference depending on the type of steel is not clearly observed because of much variance in data, the decrease in upper shelf energy for the steels tested in the present research lies below the lowest prediction line.

The evaluation of toughness of structural materials for light water reactors is made using the reference temperature RT_{NDT}, which is determined as the temperature at which both Charpy absorbed energy of 68 J and lateral expansion of 0.9 mm are obtained. This means that the values of 68 J and 0.9 mm are used as equivalents. **Figure 8** shows the relation between absorbed energy and lateral expansion for the present materials. Though a linear relation exists between the two parameters, the slope differs above and below the lateral expansion of 1.5 mm. Below this value, Eq. (7) was obtained between absorbed energy ${}_vE$(J) and lateral expansion LE(mm). Therefore, the ASME Code which regards the absorbed energy of 68 J and the lateral expansion of 0.9 mm as equivalents seems reasonable before and after neutron irradiation.

$${}_vE = 67 \times \text{LE} \pm 20 \quad \cdots\cdots(7)$$

As the lateral expansion exceeds 1.5 mm, on the other hand, the slope becomes double or 120 J/mm and the correlation between two parameters becomes bad.

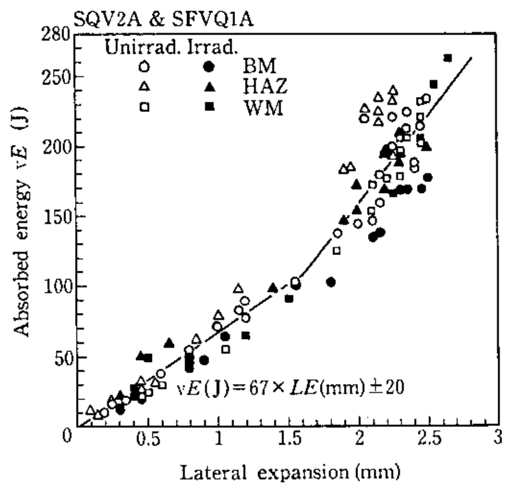

Fig. 8 Plot of Charpy absorbed energy vs. lateral expansion

3.3 Static Fracture Toughness Test

Figure 9 shows the effect of neutron irradiation on the fracture toughness $K(J_{IC})$ of plate P2 and its heat affected zone. The value of $K(J_{IC})$ was calculated from J_{IC} using the following equation:

$$K(J_{IC}) = \sqrt{J_{IC}E/(1-\nu^2)} \quad \cdots\cdots(8)$$

where E and ν are elastic modulus and Poisson's ratio, respectively.

The neutron irradiation shifts the transition curves for plate and heat affected zone towards higher temperatures and reduces the upper shelf energy. In the case of

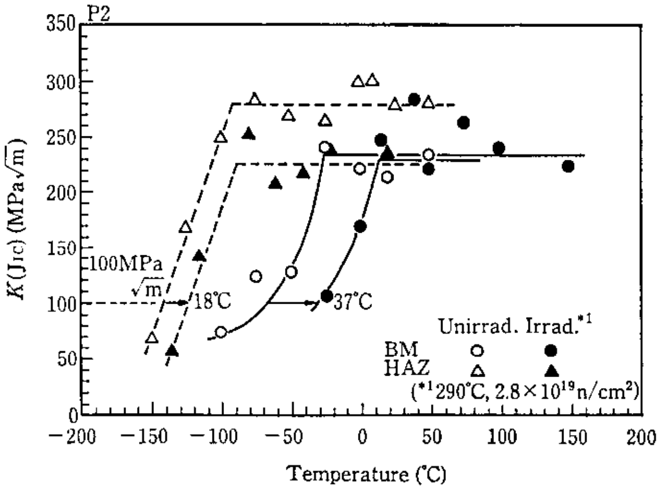

Fig. 9 Effect of neutron irradiation on fracture toughness of plate and its heat affected zone

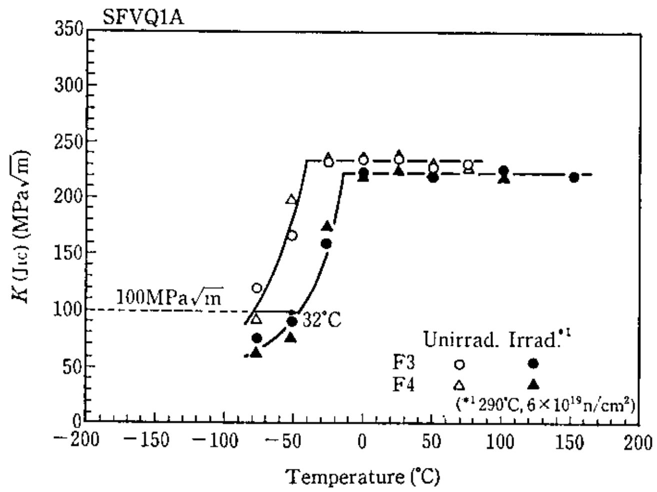

Fig. 10 Effect of neutron irradiation on fracture toughness of forgings

the plate, the transition curve moved toward higher temperature by about 37°C at $K(J_{IC}) = 100\ \text{MPa}\sqrt{m}$. This shift is similar to that for 41-J transition temperature. In the upper shelf, on the other hand, $K(J_{IC})$ decreased by such a small amount that neutron irradiation did not seem to affect the toughness significantly if a variance in data is taken into account. In the case of the heat affected zone, the shift of transition curve was 18°C at $K(J_{IC}) = 100\ \text{MPa}\sqrt{m}$ which is similar to that for 41-J transition temperature. However, the decrease in $K(J_{IC})$ induced by neutron irradiation was almost the same as that for the plate, and the difference in $K(J_{IC})$ between plate and heat affected zone disappeared after neutron irradiation. Though both plate and heat affected zone were embrittled by neutron irradiation, therefore, the plate was hardly degraded as long as ductile fracture is concerned, while the heat affected zone was degraded to the level of the plate.

Figure 10 shows the effect of neutron irradiation on fracture toughness of forgings F3 and F4. The shift of transition temperature was about 32°C at $K(J_{IC}) = 100\ \text{MPa}\sqrt{m}$, which is similar to that of 41-J transition temperature as in the case of plate. The decrease in upper shelf fracture toughness, on the other hand, was small.

For the present materials tested, the shift of $K(J_{IC}) = 100\ \text{MPa}\sqrt{m}$ transition temperature induced by neutron irradiation was almost the same as that of 41-J transition temperature determined by Charpy impact test as observed in the cooperative research work of IAEA[7]. Though the shift of transition temperature represents the sensitivity of steel to neutron irradiation embrittlement, the value which is truly necessary when applied to a real pressure vessel is an absolute transition temperature after neutron irradiation. According to JEAC4206[17] which specifies the method of verification tests of the fracture toughness for nuclear power plant components, the transition temperature after neutron irradiation must not exceed 93°C and the upper shelf energy must not be less than 68 J. In this study the plates, forgings and their welded joints gave the 41-J transition temperature below −10°C and the 100-MPa$\sqrt{m}$ transition temperature below −30°C after neutron irradiation whose fluence was either 3×10^{19} *or* 6×10^{19} n/cm^2, indicating that they had very good toughness.

4 Conclusions

An evaluation was made concerning the change in mechanical properties, including the effect of Ni, of heavy section steel plates JIS SQV2A, forgings JIS SFVQ1A and their welded joints for light water reactor pressure vessels induced by neutron irradiation which simulated the conditions in light water reactors. The main results obtained are as follows:

(1) The neutron irradiation caused embrittlement of material, which included an increase in strength and a decrease in elongation.

(2) The shift of 41-J transition temperature induced by neutron irradiation was the same for plate and forging, and was smaller than the lower limit of the predicted shift in NRC Regulatory Guide 1.99 Rev. 1. The neutron fluence as small as 3.8×10^{18} n/cm^2 did not affect the transition temperature significantly.

(3) The increase in Ni content within the range allowed by the standard did not affect the sensitivity to neutron irradiation embrittlement.

(4) The NRC Regulatory Guide 1.99 Rev. 1 overestimated the shift of transition temperature by 20 to 30°C when the neutron fluence was as high as 6×10^{19} n/cm^2.

(5) The NRC Regulatory Guide 1.99 Rev. 2 overestimated the shift of transition temperature when the neutron fluence was as low as 3.7×10^{18} n/cm^2, while it gave reasonable estimation when the neutron fluence was high.

(6) The NRC 10CFR50-50.61 gave an overestimation of neutron irradiation embrittlement as a whole.

(7) The rate of decrease in Charpy upper shelf energy induced by neutron irradiation was lower than the lowest estimation given by NRC Regulatory Guide 1.99.

(8) The relation of $_vE = 67 \times \mathrm{LE} \pm 20$ stood between absorbed energy $_vE$(J) and lateral expansion LE(mm) not more than 1.5 mm.

(9) The shift of transition temperature for static fracture toughness $K(J_{IC}) = 100$ MPa$\sqrt{m}$ induced by neutron irradiation was as large as that of 41-J transition temperature.

(10) All of the plates, forgings and their welded joints tested had high toughness even after neutron irradiation.

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