Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

Fracture Toughness Evaluation by Precracked Charpy Specimens in the Transition Temperature Range of RPV Steels

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ABSTRACT

To evaluate the fracture toughness of RPV steels from the surveillance test, the applicability of a precracked Charpy (PCCv) specimen has been studied. Several RPV steels, including an IAEA reference material JRQ, of ASTM A533B class 1 made by Japanese steel fabricators are used for this study. Neutron irradiation to the specimen was performed at Japan Materials Testing Reactor (JMTR). The statistical approach based on the weakest link theory is applied to PCCv and 1TCT data. The scatter of fracture toughness is analyzed by fitting to a Weibull type distribution and studied on the irradiation effect. The fracture toughness transition curves before and after neutron irradiation are determined by the PCCv data according to the master curve approach. The shift of fracture toughness transition curves due to neutron irradiation was evaluated to be slightly larger than the Charpy 41J shift.

INTRODUCTION

To assure RPV structural integrity throughout its operational life, fracture toughness after neutron irradiation is needed. To do this, the surveillance program for the RPV is performed according to regulations. The results obtained from the Charpy impact tests in the surveillance program are used for the estimation of fracture toughness after irradiation[1,2]. Most codes related to the surveillance program assume that the degree of irradiation embrittlement obtained from Charpy impact tests is equivalent to that of fracture toughness for the material concerned. Recent research, however, has indicated that the correlation is not always conservative in predicting the degree of irradiation embrittlement in terms of fracture toughness[3,4]. Fracture mechanics methodology is, therefore, necessary for the precise evaluation of irradiation embrittlement to assure the RPV structural integrity.

A methodology to evaluate fracture toughness of RPV steels has not been established completely, particularly in the transition temperature range. Since fracture toughness values from test specimens of RPV steels show a large scatter in the transition temperature range, fracture toughness should be evaluated statistically. This means that a certain statistical approach is necessary for the evaluation of fracture toughness. Although intensive research[e.g. 4] has been conducted to establish the statistical treatment and the evaluation method of specimen size effect, the methods need a large number of specimens and/or relatively large size specimens[5]. Since only a small number of small size specimens are available from a surveillance capsule, further research is desired to establish an improved test and evaluation method for surveillance program specimens to evaluate the irradiation effect on fracture toughness.

The objective of this paper is to investigate the methodology to evaluate fracture toughness of RPV steels using precracked Charpy-V (PCCv) specimens which are available in the surveillance test program. Based on the results of the fracture toughness tests by PCCv, and standard 1T and 4T-CT specimens, a statistical analysis is performed to study the scatter on fracture toughness in the transition temperature range. The shift of fracture toughness curve due to neutron irradiation is also compared with a Charpy transition temperature shift.

EXPERIMENTS

Materials

Five kinds of RPV steels of ASTM A533B class 1 were used in this study. One is designated as JRQ, which was used as a correlation monitor material in the IAEA CRP[6]. Two other kinds of A533B-1 steels, called Steel A and Steel B, were also used[7,8]. These steels correspond to RPV steels of the 1970's and the late 1980's, respectively. Steel L was also used as a modern RPV steel having very low impurities. The material designated as JSPS A533B-1 was used in the round robin study organized by the Japan Society for Promoting of Science (JSPS)[9]. The last material was chosen because of its large database of cleavage fracture toughness for small size specimens to large ones. Chemical compositions of the materials are summarized in Table 1. Mechanical properties at room temperature for the materials are listed in Table 2.

Table 1 Chemical compositions of materials used in this study (wt.%)

Material	C	Si	Mn	P	S	Ni	Cr	Cu	Mo
JRQ	0.18	0.24	1.42	0.017	0.004	0.84	0.12	0.14	0.51
Steel A	0.19	0.30	1.30	0.015	0.010	0.68	0.17	0.16	0.53
Steel B	0.19	0.19	1.43	0.004	0.001	0.65	0.13	0.04	0.50
Steel L	0.17	0.24	1.36	0.003	0.003	0.61	0.07	0.02	0.47
JSPS A533B-1	0.24	0.41	1.52	0.028	0.023	0.43	0.08	0.19	0.49

Table 2 Tensile properties at room temperature of materials used in this study

Material	σ_{ys} (MPa)	σ_{uts} (MPa)	Elongation (%)	Note
JRQ	477	615	22.2	
Steel A	469	612	26.4	
Steel B	462	597	24.9	
Steel L	461	603	24.8	
JSPS A533B-1	504	692	20.2	Ref. [9]

Fracture Toughness Tests

Four types of specimens were used in this study, namely PCCv, 0.5T-DCT, 1T-CT and 4T-CT[8]. In most cases, the specimens were side-grooved by 10% on each side of the specimen after precracking. For JSPS A533B-1 steel, one of the authors performed fracture toughness tests using PCCv specimens machined from halves of broken 2T-CT specimens at SCK•CEN[10]. The notch orientation is T-L direction for all specimens. Each specimen was machined from the approximately quarter thickness position of the material. Fracture toughness tests were performed at mainly lower transition temperatures where a cleavage fracture was observed before the peak of a load-displacement curve.

Testing and evaluation for fracture toughness were performed according to the ASTM test methods. Valid fracture toughness, K_{IC}, was obtained only from 4T-CT specimens according to ASTM E399-90. When smaller specimens were used, ASTM E1921-97 method was applied to obtain cleavage fracture toughness. Fracture toughness at cleavage fracture, J_C, was calculated based on the cleavage fracture load and the area under the load-displacement curve up to the sudden load drop. K_{JC} values were then converted from J_C by Eq. (1).

$$K_{JC} = \sqrt{E \cdot J_C} \tag{1}$$

Neutron Irradiation

PCCv specimens of JRQ, Steel A, Steel B and Steel L were irradiated in Japan Materials Testing Reactor (JMTR, thermal output 50MW). Fast neutron fluence values for those specimens were calculated to be about 2.2 x 10^{19} n/cm^2 (E>1 MeV) for JRQ, 13x10^{19} for Steel A, 11x10^{19} for Steel B and 2.7x10^{19} for Steel L. The displacements per atom (dpa) for iron by the irradiation to 2 x 10^{19} n/cm^2 (E>1 MeV) was about 3 x 10^{-2}. Fast neutron flux was 1.2 to 1.5 x 10^{13} n/cm^{2}s (E>1 MeV). Temperature for the specimens during irradiation was controlled in the range from 280°C to 300°C. Charpy-V and tensile specimens were irradiated at the same time and almost the same condition. The shifts of Charpy transition temperatures due to neutron irradiation are summarized in Table 3.

Table 3 Charpy transition temperature shifts by neutron irradiation at JMTR

Material	Neutron fluence (n/cm^2, E>1MeV)	Irradiation temperature (°C)	ΔT_{41J} (°C)	ΔT_{68J} (°C)	$\Delta T_{0.9mm}$ (°C)
JRQ	2.3 x 10^{19}	291	88	90	87
Steel A	12.9 x 10^{19}	287	155	162	144
Steel B	11.3 x 10^{19}	288	71	73	66
Steel L	2.9 x 10^{19}	286	80	82	69

RESULTS AND DISCUSSION

The Scatter of Fracture Toughness

As is known well, the scatter of cleavage fracture in the transition temperature range is significant. The scatter has been explained by the weakest link theory[11,12] that is based on the local inhomogeneity in the material. The theory treats the probability of finding a particle located randomly in the material and leads to the fracture of the specimen. In addition to this, fracture toughness from a small specimen can be higher than that from a large specimen. The reason is that the small specimen has insufficient thickness to assure small scale yielding and maintain a certain level of constraint at a crack tip, as compared with a large size specimen or a real heavy-section structure[13].

Wallin[14] has proposed the following equation for adjusting specimen size applicable to RPV steels based on the weakest link theory.

$$K_{JC\_y} = K_{min} + (K_{JC\_x} - K_{min}) \cdot (B_x / B_y)^{1/b} \quad (2)$$

where $K_{JC\_x\ or\ y}$: K_{JC} for specimens of thickness, $B_{x\ or\ y}$,

$K_{min} = 20\ MPa\sqrt{m}$, b = 4.

Using three parameters, K_{min}, b and K_0, the fracture probability based on Weibull statistics can be expressed by the following equation[13].

$$P_f = 1 - \exp\left(-\left(\frac{K_{JC\_1T} - K_{min}}{K_0 - K_{min}}\right)^b\right) = 1 - \exp\left(-\left(\frac{K_{JC\_1T} - 20}{K_0 - 20}\right)^b\right) \quad (3)$$

where P_f: Cumulative fracture probability ($= (i-0.3)/(N+0.4)$),

K_0: Fitting parameters, b: Weibull slope (theoretically 4).

All data obtained by the same-size specimens at a certain temperature can be analyzed by Eqs. (2) and (3). The theory assumes that the distribution of the fracture toughness values of a material can be described using Weibull type statistics. These equations have been incorporated into the ASTM E1921 to describe the statistics of cleavage fracture toughness. To study the scatter of fracture toughness data, the Weibull slope b was treated as a fitting parameter in this study.

Figure 1 compares Weibull plots of PCCv data and 1T-CT data of JRQ. PCCv data were adjusted by Eq. (2) to 1T-CT thickness (25 mm). The figure also includes the fitting curve by Eq. (3). The size-adjusted PCCv data and 1T-CT data of unirradiated JRQ are in good agreement. The fitted parameter b in Eq. (3) was 2.6 and 2.5 for the corrected PCCv data and 1T-CT data, respectively. These values were much less than the theoretical value of four. The b values for the irradiated PCCv data were 2.8 and 3.1 at 17°C and 35°C, respectively. The slopes were again slightly smaller than the theoretical values. Figure 2 shows the Weibull plots of PCCv data of Steel L. In this case, Weibull slope b values from unirradiated and irradiated PCCv data are almost equal to the theoretical four.

Figure 3 shows a specimen size dependence of the Weibull slope b. The b values obtained in this study were ranged from 2 to 8. When a linear fitting is performed, data points show a slight size-dependence of b as indicated by a dotted line. However, the points above six were obtained only form JSPS A533B-1. The data trend except JSPS A533B-1 seems to be less size dependent. Figure 4 indicates the effect of neutron irradiation on the

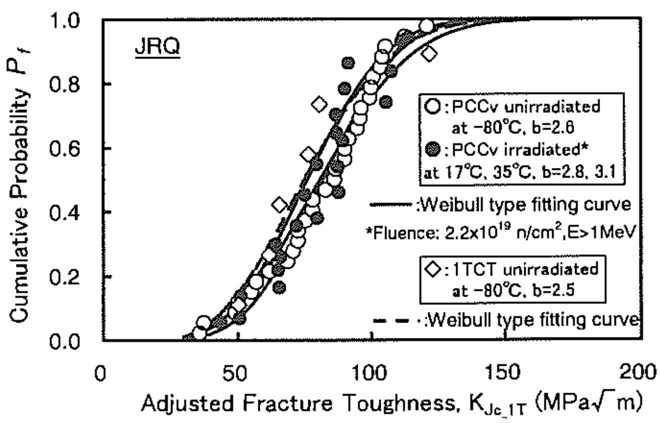

Figure 1 Weibull plots of adjusted fracture toughness of unirradiated and irradiated JRQ

Weibull slope b for Steels A, B, L and JRQ. The b values are ranging from 2 to 5 both before and after irradiation. It seem that the Weibull slope b, in other words, the scatter of fracture toughness, is unaffected by neutron irradiation.

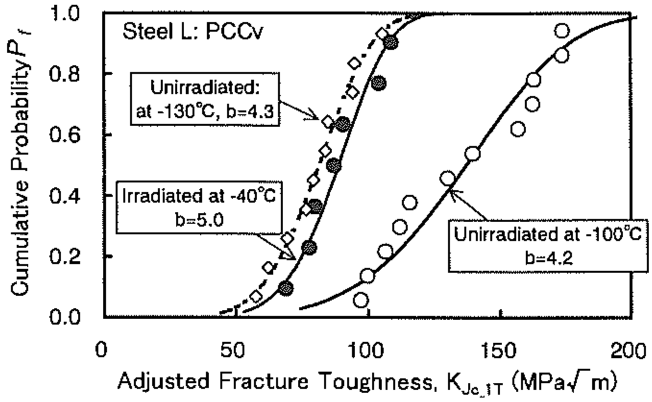

Figure 2 Weibull plots of adjusted fracture toughness of unirradiated and irradiated Steel L

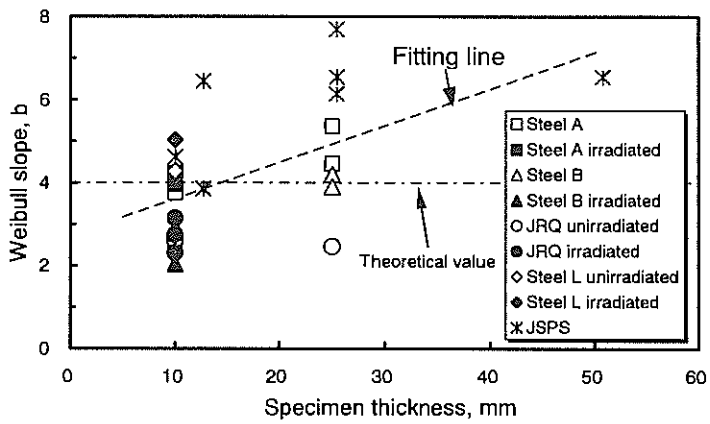

Figure 3 Weibull slope b calculated from Eq. (3) as a function of specimen thickness

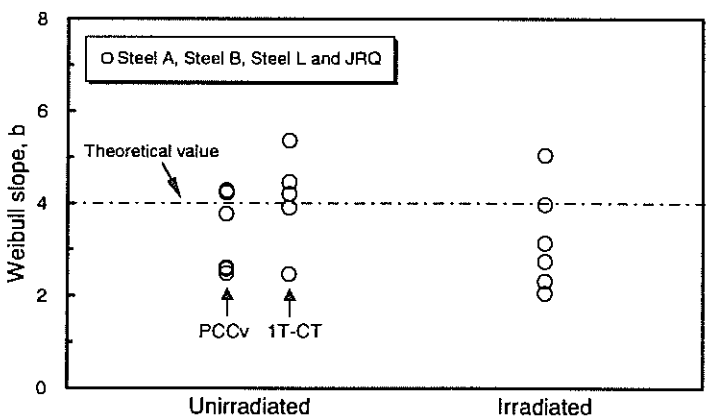

Figure 4 Weibull slope b before and after neutron irradiation

Shift of Fracture Toughness Transition Curve

Using the median value equivalent to 1T thickness (25 mm), the temperature dependence of cleavage fracture toughness within the transition range is expressed by the following equation[14].

$$K_{JC\_1T(med)} = 30 + 70 \cdot \exp\{0.019 \cdot (T - T_0)\} \tag{4}$$

This equation has been established by statistical analyses using a huge database including unirradiated and irradiated RPV steels. This Eq. (4), which is called a master curve, uniquely defines a cleavage fracture toughness transition curve by a reference temperature, T_0.

To identify the effect of irradiation on T_0, we obtain the shift of fracture toughness by comparing the T_0 values before and after irradiation. Figure 5 shows the master curve for JRQ steel before and after irradiation. The master curve before irradiation was determined by the average of two T_0 values obtained from tests at –80°C and –50°C. The master curve after irradiation was also based on the average of three T_0 values calculated from three PCCv data sets at 0, 17 and 35°C. The shift of T_0 by irradiation to JRQ was then calculated as 94°C. This shift is larger than the Charpy shift, 88°C. The figure also indicates 1% lower tolerance bound curves according to the master curve approach. Reflecting a large scatter of fracture toughness, the 5% of actual data points fell below the tolerance limits.

Figure 6 shows the effect of irradiation on the fracture toughness of Steel L. The T_0 value after irradiation were determined by seven PCCv specimens at -40°C. The shift of T_0 value by irradiation was slightly larger than the Charpy shift again. The master curves together with 5% lower tolerance bounds before and after irradiation were indicated in the figure. All the data points are above the tolerance bounds.

Figure 7 compares the shifts of T_0 and Charpy 41J transition temperature by neutron irradiation. As mentioned above, the T_0 shift is 13% larger than the Charpy 41J shift. This result is in good agreement with Reference [15]. This suggests that the prediction of irradiation embrittlement based on Charpy shift may underestimate the change in fracture toughness, which is directly related to RPV integrity.

CONCLUSIONS

To establish the method to evaluate fracture toughness in the transition range, fracture toughness tests were performed using various specimens from PCCv to 4T-CT of five Japanese RPV steels. The following conclusions were drawn for the evaluation of fracture toughness using PCCv specimens;

(1) For data scatter, the experimental data points from PCCv specimens are fitted well with a Weibull type distribution equation based on the weakest link theory.
(2) The slope of Weibull distribution was not much affected by neutron irradiation.
(3) According to the master curve approach, the shift of the fracture toughness curve by irradiation was evaluated to be somewhat greater than the Charpy 41J shift.

ACKNOWLEDGEMENTS

A part of this work was carried out under the contract between JAERI and the Science and Technology Agency of Japan under the auspices of the special account law for electric power development promotion. A part of this study was also performed at JAERI in the framework of the IAEA Coordinated Research Program. The authors thank many staffs at the Department of Hot Laboratories of JAERI for their careful testing of irradiated specimens.

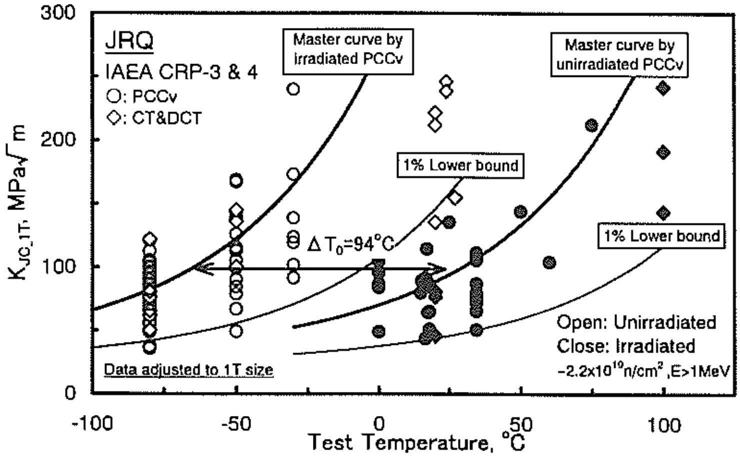

Figure 5 Cleavage fracture toughness data of JRQ before and after neutron irradiation

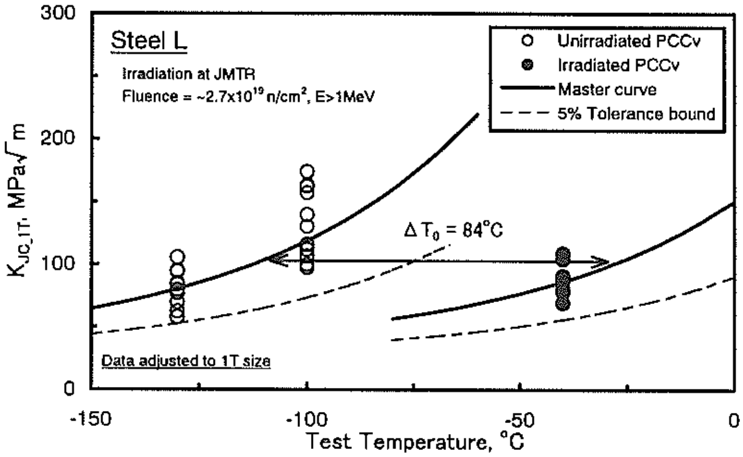

Figure 6 Cleavage fracture toughness data of Steel L before and after neutron irradiation

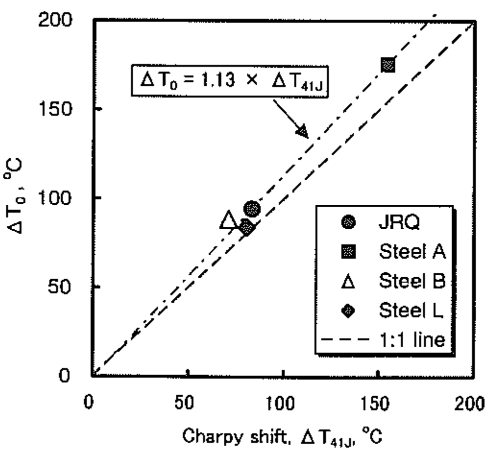

Figure 7 Comparison of the shifts on fracture toughness reference temperature and Charpy 41J shift

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