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《Technical Note》

Statistical Evaluation of Fracture Characteristics of RPV Steels in the Ductile-Brittle Transition Temperature Region

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Abstract

The statistical analysis method was applied to the evaluation of fracture toughness in the ductile-brittle transition temperature region. Because cleavage fracture in steel is of a statistical nature, fracture toughness data or values show a similar statistical trend. Using the three-parameter Weibull distribution, a fracture toughness vs. temperature curve (K-curve) was directly generated from a set of fracture toughness data at a selected temperature. Charpy V-notch impact energy was also used to obtain the K-curve by a K_{IC}-CVN (Charpy V-notch energy) correlation. Furthermore, this method was applied to evaluate the neutron irradiation embrittlement of reactor pressure vessel (RPV) steel. Most of the fracture toughness data were within the 95% confidence limits. The prediction of a transition temperature shift by statistical analysis was compared with that from the experimental data.

1. Introduction

The reactor pressure vessel (RPV) is irradiated by fast neutrons during the operation of the power plant. The effect of neutron irradiation on the materials is generally to degrade the material properties. The degree of degradation is dependent on the chemical composition, irradiation temperature, neutron fluence level and process history of the material. The degree of degradation is measured by increases in tensile strengths (yield and ultimate), decreases in Charpy upper shelf energy and fracture toughness, and shift of the ductile-to-brittle transition temperature (DBTT). Of these several phenomena, the increase in the transition temperature is of prime consideration in assessing the potential for failure at the events of pressurized thermal shock (PTS) or any other scenarios under which relatively low RPV temperature (much less than 288℃) may be accompanied by high system pressure.

In recognition of such concerns, Appendix G and §50.61 of 10 CFR 50 (Title 10, Part 50, Code of U.S. Federal Regulations) [1] have established a

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PTS screening criterion of 132°C(270°F) for plates, forgings, and axial weld materials, and 149 °C(300°F) for circumferential weld materials. In each case, the criterion gives upper limit on the RT_{NDT} (reference nil-ductility transition temperature) as defined in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. RT_{NDT} is also used in an analytical sense to index the K_{IR} (reference stress intensity factor) curve in Appendix G of Section III of the ASME Code. To account for irradiation effects, the Code states "adjusted reference temperature". It means the reference temperature as adjusted for irradiation effects by adding the initial RT_{NDT} and the temperature shift ΔRT_{NDT} (measured at the 30 ft-lb (41J) level) in the average Charpy curve for the irradiated material relative to that for the unirradiated material. Thus, the degree of irradiation embrittlement is evaluated by the ΔRT_{NDT} (nil-ductility temperature shift) and ΔUSE (changes of upper shelf energy). In connection with these we introduced a statistical methodology for initial RT_{NDT} determination and its problems as well as the Code description of RT_{NDT} in the earlier works [2,3]. Since the initial RT_{NDT} determination and indexing the K_{IR} curve etc. are closely associated with the DBTT region, it is important to understand the fracture characteristics in the DBTT region.

On the other hand, measurement of fracture toughness K_{IC} within the ductile-brittle transition region is often accompanied by large scatters. The reasons for the scatter are not fully understood, which causes a significant practical problem. The solution for this problem should include a statistical analysis combined with an understanding of the fracture mechanisms, which is also used for the prediction of cleavage fracture probabilities of cracked structures operating in the transition temperature region [4,5]. In this work, we described the characteristics of fracture toughness in the transition temperature region and a theoretical approach for statistical analysis, and discussed a proposed ASTM test method for determining material fracture toughness in the transition region. We also predicted the irradiation embrittlement using this statistical analysis from a set of fracture toughness tests and Charpy impact tests data at one test temperature, and compared the predicted values with the experimental values covering full range of test temperature.

2. Statistical Description of Fracture in the Transition Temperature Region

The K_{IC} test method, as described in ASTM E 399, is a widely used testing method for measuring the fracture toughness of materials. However, the validity is limited to the lower shelf and the ductile-brittle transition temperature region [11], where cleavage fracture takes place. The common mode of brittle fracture in steel is the cleavage formation. Therefore, the K_{IC} test can be taken as a measure of resistance to the cleavage-nucleated fracture. Brittle cleavage fracture differs in mechanism from ductile fracture. Cleavage fracture is initiated by a critical stress-induced statistical mechanism, governed by the fracture of brittle precipitates such as carbides [8-10]. Cleavage fracture will also be affected by changes in the stress distribution, and by the probability of finding a weak particle [4]. Because the cleavage fracture in steels has a statistical nature [8,9] and extensive scatter, there will also be a similar statistical scatter in K_{IC} results. Although several factors affect the result of a fracture toughness test, most of them can be accounted for with the help of a statistical brittle fracture model [4,6,7]. The Weibull probability distribution [10,12-14] is widely used to describe scatter in fracture toughness results of materials in the brittle (or ductile-brittle transition) regime.

Before describing the fracture probability distribution in the transition temperature region, we have to consider the following relationships for treating the results from fracture toughness tests : Fracture toughness can either be determined using large specimens applying linear-elastic formula or be derived from the elastic-plastic critical J-integral (J_c) value corresponding to brittle fracture with the equation

$$K_{JC} = \sqrt{\frac{J_c \cdot E}{(1-\mu^2)}} \tag{1}$$

where E is the Young' s modulus and μ the Poisson' s ratio. In the transition region where valid fracture toughness values cannot be obtained, the fracture toughness can be determined as the value of the J-integral at the onset of cleavage fracture (J_c). It is defined as the instant when the instantaneous load drop occurred. The J_c values corresponding to cleavage fracture initiation are converted into elastic plastic K_{JC} values using the above equation.

When the fracture toughness data is obtained from the specimens having different thicknesses, for both K_{IC} and K_{JC}, the data can be corrected by following equation to the values for the same thickness[6]

$$K_{B2} = (K_{B1} - K_{min}) \left(\frac{B_1}{B_2}\right)^{1/4} + K_{min} \tag{2}$$

where K_{min} is the lower bound fracture toughness which is close to 20 MPa · $m^{1/2}$ for steels and B_1 and B_2 are the respective thickness. By applying equation (2), it is possible to compare the fracture toughness results obtained from the specimens of different thicknesses. Although the definitive proof of the statistical model (Eq. (2)) is very difficult, it has been validated for a large number of materials and for specimen thicknesses ranging from 10 mm to 200 mm [6,15]. Thus, Eq. (2) can be used for analyzing fracture toughness data in the transition region.

2.1. Fracture Probability Distribution

A statistical theory of brittle fracture assumes that the specimen with a statistically-homogeneous state is divided into many volume elements, each containing a single crack. The usual simplifying assumption is that there is no interaction between the cracks in the different volume elements. The strength of the specimen is determined by the element with the longest crack, for this results in the lowest value of fracture stress. This concept of brittle fracture is called the "weakest-link theory" [26,27]. Let us consider a theoretical model based on the Weibull distribution. It allows us to write the probability of cleavage fracture, in the case of a sharp crack, as [6,16]

$$P_f = 1 - \exp\left(-\left(\frac{K_I - K_{min}}{K_o - K_{min}}\right)^b\right) \tag{3}$$

where P_f is the cumulative fracture probability (or, cumulative distribution function, CDF) at a load level K_I, K_o is a specimen thickness and temperature dependent normalization parameter (scale parameter), K_{min} is a lower limiting fracture toughness (location parameter), and b is a Weibull slope (shape parameter). It is called a three parameter Weibull distribution for fracture toughness. This is consistent with the critical tensile stress criterion, according to which the catastrophic failure is assumed to take place when the tensile stress ahead of the crack makes it possible for an existing flaw to propagate through the whole structure.

The temperature dependence of K_o in MPa · $m^{1/2}$ can successfully be described with [16]

$$K_0 = \alpha + \beta \exp[\gamma (T - T_0)] \tag{4}$$

where $\alpha + \beta = 108$ MPa · $m^{1/2}$ (for a 25 mm thickness compact tension (CT) specimen) and, in this case, T_o is the temperature (in ℃) at which the mean fracture toughness is 100 MPa · $m^{1/2}$ and γ is a material constant. Experimentally it has been found that the shape of the fracture toughness transition curve (or K-curve) is only slightly material dependent. Therefore, the values of α, β and γ are practically material independent. The resulting equation for the temperature dependence of K_o, corresponding to 25 mm thickness, can thus be written as [16]

$$K_0 = 31 + 77 \exp [0.019 (T - T_0)]. \quad (5)$$

It is called the "master curve" for fracture toughness in the transition region. For the case of standard Charpy-type specimens, the master curve is corrected to the following equation by the equation (2)

$$K_0 = 34 + 97 \exp [0.019 (T - T_0)]. \quad (6)$$

By combining equations (2), (3), and (5), it is possible to predict the whole fracture toughness transition curve as a function of temperature, specimen thickness and fracture probability.

From the view point of fracture toughness, it is thus worthwhile to choose a temperature corresponding to a fracture toughness describing brittle fracture. The fracture toughness at the chosen temperature must be clearly below the fracture toughness for ductile fracture initiation so that ductile fracture won' t affect the result. At the same time it must be clearly higher than the lower shelf in order to be in a region where the effect of temperature upon toughness is large. One commonly used transition temperature fulfilling these requirements is the temperature showing the fracture toughness value of K_{JC} = 100 MPa · $m^{1/2}$ [16].

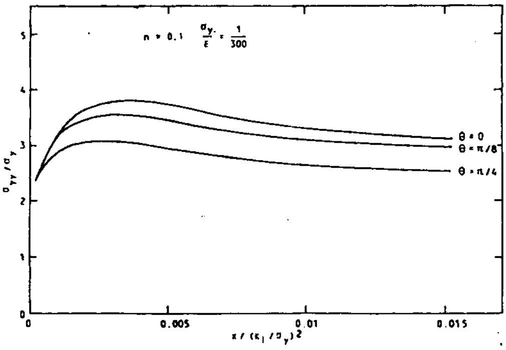

Fig. 1. Stress Field Ahead of a Blunted Crack (After McMeeking[17])

2.2. Theoretical Value for the Weibull Slope

By rearranging the terms in equation (3) using logarithms, it is clear that if the magnitude of the scatter is large, then b is small and vice versa. Experimentally determined values for b vary between 2 and 10. This would suggest that b depends on several variables. It is, however, possible to evaluate a theoretical value for b in the case of sharp crack testing.

For a pre-fatigued crack being loaded, the loading causes the crack tip to be blunted to some extent. In this case the tensile stresses ahead of the crack are described by the McMeeking [17] stress field solutions. According to the results, the stress field is independent of the amount of loading and the stress field changes angularly off the crack plane (see Fig.1). Because of the angular stress field dependence, the effective volume V_{eff} taking part in the fracture process becomes

$$V_{eff} \sim B \cdot X_{eff} \cdot X_{eff} \cdot \sin \theta_{eff} \quad (7)$$

where B is the specimen thickness which is considered to be constant, X_{eff} is the distance ahead of the crack tip and θ_{eff} is the effective angle which is taken to be approximately constant.

Because there is a linear dependence between X_{eff} and K_I^2 as seen in Fig.1, the dependence for V_{eff} is of the form

$$V_{eff} = constant \cdot K_I^4. \tag{8}$$

Because the form of the stress field is independent of the applied loading K_I, all the changes in the fracture probability, which are due to the changes in K_I are described by the effective volume. Therefore, the probability of fracture must have the same dependence on K_I as the effective volume assuming the existing flaws to be distributed randomly in the volume. This reads to b = 4, according to the fracture probability equation (3).

The same result is obtained when considering the following Weibull distribution which is the critical stress-induced statistical micromechanism for cleavage fracture:

$$P_f = 1 - \exp\left\{ -\frac{V_{eff}}{V_o} \left[\frac{\sigma}{\sigma_o} \right]^{b*} \right\} \tag{9}$$

where V_o and σ_o are normalization factors, σ is the tensile stress (maximum normal stress) and b^* is the Weibull inhomogeneity factor. The maximum normal stress at cleavage fracture decreases for increasing stressed volume. This points towards a weakest link approach, which incorporates volume effects in the fracture prediction, as for instance proposed by Wallin, Saario, and Torronen[4] and Beremin[5]. The distribution is cut off at a maximum normal stress equal to the material yield stress, since cleavage fracture must always be preceded by some amount of plastic deformation. For a sharp crack stressed by a non-uniform maximum normal stress distribution $\sigma_{yy(x)}$, the weakest link assumption leads to a failure probability according to :

$$P_f = 1 - \exp\left(-\int_0^{X_{eff}} \frac{V_{eff}}{V_o} \left(\frac{\sigma_{yy(X)}}{\sigma_o} \right) \right)^{b*} \tag{10}$$

By making the same assumptions as in the case above, it has been shown that equation (10) becomes [18]

$$1 - \exp -\left[\frac{B \sin\theta \ \sigma_y^{b*-4} \cdot K_I^4}{V_o \ \sigma_o^{b*}} \int_0^{U_{eff}} \cdot \sigma_{yy}(U)^{b*} \cdot U \cdot dU \right] \tag{11}$$

where σ_y is the yield stress and U is $X/(K_I/\sigma_y)^2$.

Since there are no K_I-dependent variables in equation (11), it can be rewritten as

$$P_f = 1 - \exp\{-const. \cdot K_I^4\} \tag{12}$$

Equation (12) is essentially the same as equation (3) with b equal to 4.

From the above it is evident that both equations (3) and (10) can be used to describe the scatter in results obtained with sharp crack tests. It is, however, important to notice that b $\neq$ b^*. The slope factor b represents the scatter of the test result, the theoretical value being always equal to 4. The factor b^* represents the inhomogeneity in the flaws possible to the trigger fracture. It affects only the mean value of K_{IC} and does not affect the scatter of the test result. Since we are interested in the fracture toughness test result, equation (3) is used for statistical analysis in this work.

3. Applications of Statistical Analysis

3.1. Evaluation of Irradiation Embrittlement

To confirm the liability or applicability of the statistical analysis as mentioned in section 2.1 for evaluating fracture toughness, the analysis was evaluated by using the ASME reference fracture curve (K_{IR} and K_{IC} curves).

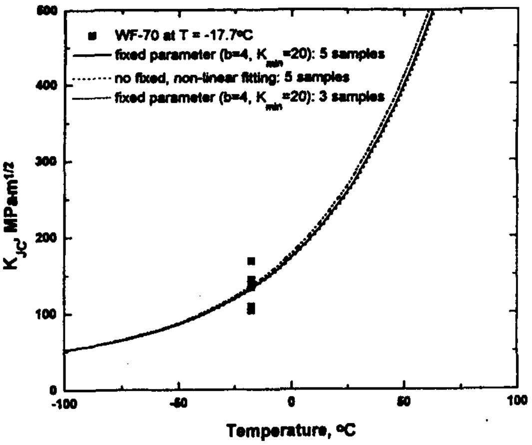

Fig. 2. Comparison of Median K_{JC} Curves

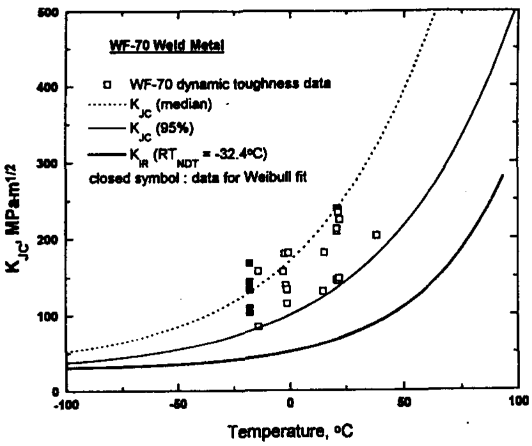

Fig. 3. Fracture Toughness Curves and Dynamic Toughness Data

First of all, we compared the proposed ASTM method [19] of analyzing fracture toughness in the transition region with the non-linear fitting method. According to the proposed method, the parameters in the Weibull equation (3) are fixed as 4 and 20 for b and K_{min} respectively, and the median fracture toughness K-curve (master curve) is obtained by combining equations (3) and (5) through the Weibull plot [19]. Fig.2 shows the median (50%) K_{JC} master curves obtained by the proposed ASTM procedure (b=4, K_{min}=20, and using 5 data samples) and by non-linear fitting with no fixed parameter. The data used in the Weibull distribution function were dynamic fracture toughness values of WF-70 weld metal (Linde 80 flux). This weld metal has a similar chemical composition and the same fabrication procedure (Babcock & Wilcox Company) with that of the RPV weld of the KORI-1 power plant. To obtain the median K_{JC} master curve, cleavage fracture toughness (J_c) data at -17.7°C of WF-70 weld metal were converted to K_{JC} values by equation (1). And, according to the following median ranking relationship [25], we obtained a median K_{JC} master curve by fitting equations (3) and (5) through the Weibull plot:

$$\textit{median rank}\ (50\%) = \left(\frac{j-0.3}{N+0.4}\right) \tag{13}$$

where j is the sample order number and N is the sample size. It is a failure probability in the cumulative distribution function of the Weibull equation (3). So it is possible to obtain a median K curve if a data set of fracture toughness at a specific temperature is prepared with the combination of the equations (3), (5), and (13). Of course, for the case of another thickness specimen we need to modify the equation (5) by the equation (2) like equation (6). As shown in Fig.2, the median master curve obtained by the Weibull plot with 2 parameters fixed (proposed ASTM method) was similar to that obtained by non-fixed, non-linear fitting. Although the non-linear fitting shows similar results and has some advantages in calculation procedure, it is not fully validated and still under study. On the other hand, Fig.2 shows the possibility that, when there are not sufficient data, the median master curve may be obtained from 3 samples (specimens), even though the proposed ASTM method recommends a minimum of 5 samples. However, because the standard deviation and the confidence level are dependent on the sample size, it will be more desirable to use a minimum of 5 samples or more. Therefore, all the statistical analysis used in this study was conducted by the proposed ASTM method [19].

To compare the median K_{JC} master curve and 95% confidence curve with a reference ASME K_{IR} curve, these three curves and backup fracture toughness data (open symbol) were added to Fig.3. Since the data show dynamic fracture toughness, the ASME Code reference K_{IR} curve was selected for comparison. The K_{IR} curve is given by the following equation, which is a lower bound for crack initiation fracture toughness (K_{IC}), dynamic fracture toughness (K_{Id}), and crack arrest fracture toughness (K_{Ia}):

$$K_{IR} = 26.78 + 1.223 \exp[0.0145(T-RT_{NDT}+160) \quad [\mathrm{ksi} \cdot \mathrm{in}^{1/2}], \tag{14}$$

where T is temperature in ℉. For this unirradiated WF-70 weld metal, initial RT_{NDT} is the same as T_{NDT} (−32.4℃) obtained by a drop weight test [20]. The K_{IR} curve of $RT_{NDT} = T_{NDT}$ (−32.4℃) is plotted in Fig.3 to compare with the K master curves obtained by the present statistical analysis, and to see its conservatism. It is clear in Fig.3 that this K_{IR} curve shows the lower bound of the dynamic fracture toughness curve (95% confidence limit).

To compare the method on static fracture toughness data, the static fracture toughness data were used for the statistical Weibull analysis. Fig.4 shows the median K_{JC} master curve, 95% confidence curve, data (closed symbols) for statistical Weibull analysis, and backup data (open symbols) to confirm the confidence. The material for the static test was SA508 Cl.3 pressure vessel steel. These curves are compared with the Code K_{IC} curve generated by the following equation.

$$K_{IC} = 33.2 + 2.806 \exp[0.02(T-RT_{NDT} + 100)] \quad [\mathrm{ksi} \cdot \mathrm{in}^{1/2}] \tag{15}$$

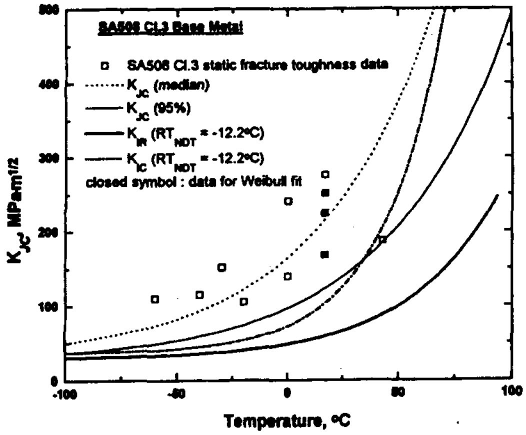

Fig. 4. Fracture Toughness Curves and Static Toughness Data

For SA508 Cl.3 pressure vessel steel, initial RT_{NDT} is the same as T_{NDT} (-12.2℃) obtained by a drop weight test. Fig.4 shows the reference K_{IC} curve and the reference K_{IR} curve constructed by $RT_{NDT} = T_{NDT}$ (−12.2℃). It is also clear that this K_{IC} curve forms the lower bound of the static fracture toughness curve (95% confidence limit) in Fig.4.

From the above two comparisons (static and dynamic fracture toughness curves in Figs.3 and 4), it is thought that the statistical Weibull analysis may be a simple and economic method for obtaining the fracture toughness curve in the ductile-brittle transition temperature region. Further, it seems that the degree of irradiation embrittlement in the transition region can be predicted by the statistical Weibull analysis using a data set at a specific temperature. To confirm the justification of this simple embrittlement evaluation method, which is the main object of this paper, we applied the statistical analysis to the weld metals (72W and 73W weld metals) which were made by submerged arc welding to the SA508 Cl.2 steel. These weld metals were originally used for one of the HSSI programs, irradiation effects on fracture toughness of two high copper submerged arc

Table 1. Chemical Compositions of the Two Submerged-Arc Welds

Material	Chemical Composition, wt%									
	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	V
72W	0.093	1.60	0.006	0.006	0.44	0.27	0.60	0.58	0.23	0.003
73W	0.098	1.56	0.005	0.005	0.45	0.25	0.60	0.58	0.31	0.003

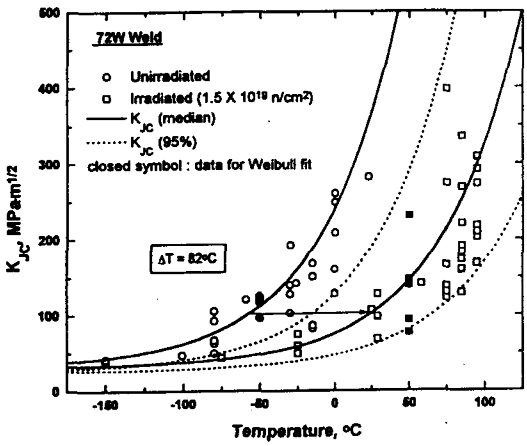

Fig. 5. Variation of Transition Temperature by Irradiation and K_{JC} Data of HSSI Weld 72W

welds [21]. These weld metals were irradiated at 288℃ in an ORNL reactor, and the neutron fluence was 1.5×10^{19}n/cm^2 (E>1MeV) [21]. Each chemical composition of the weld metals is shown in Table 1. Fig.5 shows the median K_{JC} master curve, 95% confidence curve, and fracture toughness data for unirradiated and irradiated 72W weld metal. To obtain the fracture toughness curve in this case, the unirradiated and irradiated fracture toughness data (closed symbols) which were tested at -50℃ and 50℃, respectively, were used. The data indicated by open symbols are backup data used for evaluating the confidence limit. As shown in Fig.5, both of the cases (unirradiated and irradiated cases) were satisfied with the 95% confidence limit. Therefore if a criterion for evaluating the irradiation embrittlement is established as the ΔT(41J) in the Charpy test, a transition temperature shift by irradiation can be obtained in Fig.5. In this work, the transition temperature shift at fracture toughness 100 MPa · m$^{1/2}$ was used, which was the criterion of indexing temperature T_o in the master curve (see section 2.1). Usually the shift of transition temperature due to irradiation is indexed to the energy level 41J in the Charpy impact test or 100 MPa · m$^{1/2}$ in the fracture toughness - temperature curve. This value is supported by correlations from Rolfe and Novak [22] and Sailors and Corten [23], using 41J for Charpy V-notch energy and 206800 MPa for Young' s modulus. For the case of 72W weld metal, the irradiation induced transition temperature shift was about 82 ℃ as shown in Fig.5. Table 2 shows a summary of irradiation-induced transition temperature shifts for HSSI welds 72W and 73W from the results of a totally conducted Charpy test and fracture test. Table 2 shows that the transition temperature shift of fracture toughness (totally experimental-mean value) at 100 MPa · m$^{1/2}$ is 83℃. It may be concluded from the comparison between Fig.2 and Fig. 5 that a simple statistical Weibull analysis can replace the current expensive and time consuming indexing method of transition temperature shift due to irradiation which needs curves from standard Charpy tests for the full transition temperature range.

Fig.6 shows a variation in transition temperature due to irradiation and fracture toughness data for the HSSI 73W weld metal of higher copper content than 72W weld metal. For the Weibull

Table 2. Summary of Irradiation-induced Transition Temperature Shifts for HSSI Welds 72W and 73W

Welds	Charpy 41J Shift, ℃				Fracture Toughness 100MPa · $m^{1/2}$ Shift[a], ℃			
	Mean	Temperature Interval for1σ	Total	Mean + Margin[b]	Mean	Temperature Interval for1σ	Total	Mean + Margin[b]
72W	72	20	92	87.6	83	37	120	98.6
73W	82	22	102	97.6	99	30	129	114.6

a Using linearized two-prarameter exponential fit

b Margin for R.G. 1.99, Rev.2 assuming credible surveillance data, 1σ=15.6℃

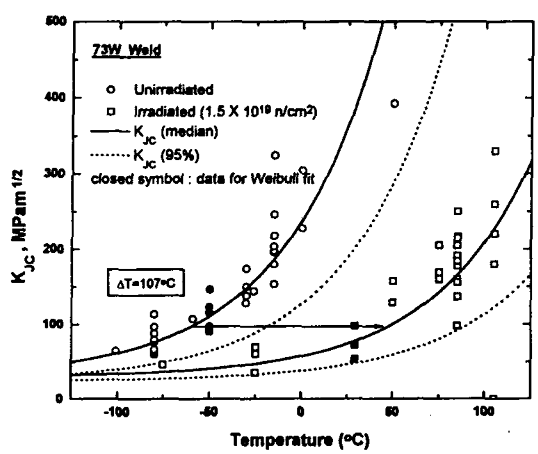

Fig. 6. Variation of Transition Temperature by Irradiation and K_{JC} Data of HSSI Weld 73W

analysis, the fracture toughness data at −50℃ for unirradiated material and at 29℃ for irradiated material was analyzed. They are indicated by the closed symbols in Fig.6. Like the procedure of Fig.5, the transition temperature shift determined by a median K curve at 100 MPa · $m^{\frac{1}{2}}$ was about 107℃. It was a more or less higher value in comparison with the value in Table 2, and more embrittled than 72W weld metal. Although there is some difference in the degree of irradiation embrittlement between the prediction (107℃ in Fig.6) by the statistical treatment and experimental result (99℃ in Table 2), the prediction value may be accepted if we consider the margin term as shown in Table 2. The greater shift in the transition region for 73W than 72W is attributed to the higher copper content of the former than the latter (see Table 1). As an interim conclusion, it is thought that the current indexing method of shift in transition temperature due to irradiation may be replaced by the simpler and economic method of statistical analysis as the one examined in this paper.

3.2. Prediction of K-curve and Irradiation Embrittlement from CVN Impact Test Results

Useful parameters for the assessment of critical structures are fracture mechanics parameters which are capable of describing components resistance against flaws. Fracture toughness K_{IC} parameter usually describes the material resistance against a brittle cleavage type fracture. However, in the case of irradiation embrittlement surveillance testing, the determination of K_{IC} is relatively expensive as well as difficult. Therefore there have been attempts to determine the value of K_{IC} from simpler tests such as fracture toughness - the Charpy-V notch (K_{IC}-CVN) relationship. The most common simple test for studying the irradiation effect on the fracture characteristics of steels is probably the Charpy-V notch test, which is presently used for the determination of ΔRT_{NDT} of steels. Therefore, many empirical correlations between fracture toughness and Charpy-V energy have been developed. Many different correlations have been used for a variety of materials in the past. Finding an empirical correlation that would be universally applicable has proven to be quite difficult because of differences in specimen size, loading rate, and flaw geometry etc.. Since the demonstration of the empirical correlation is beyond the bounds of this work, we use the Rolfe relation [24] which is well known as a K_{IC}-CVN correlation in the ductile-brittle transition temperature region. It was confirmed for the materials which have a yield stress of 39 - 246 ksi [24]:

$$\frac{K_{IC}^2}{E} = 2(CVN)^{3/2} \tag{16}$$

Using above equation, the K_{IC} values were obtained and the Weibull analysis was applied to the converted K_{IC} data for predicting the fracture toughness curve in the transition region. The data used for the Weibull analysis in Fig.7 were those at 0°C, and it was indicated by closed symbols and backup data were indicated by open symbols. Fig.7 shows a median K_{IC} curve, 95% confidence interval curve (lower and upper curve), and K_{IC} data converted by the K_{IC}-CVN correlation from the CVN test result. Most of the K_{IC} data were satisfied with the 95% confidence interval, thus we can get a K curve in the transition region by converted data from a Charpy test. Since the temperature region over 50°C in Fig.7 is not a ductile-brittle transition temperature region but an upper shelf region of a Charpy test, the K_{IC} data were not satisfied with the confidence limit curve. But, it is beyond our interest, and it is considered that other approaches are needed for the upper shelf region.

From the above K_{IC}-CVN correlation, we applied the statistical analysis to the CVN test results of

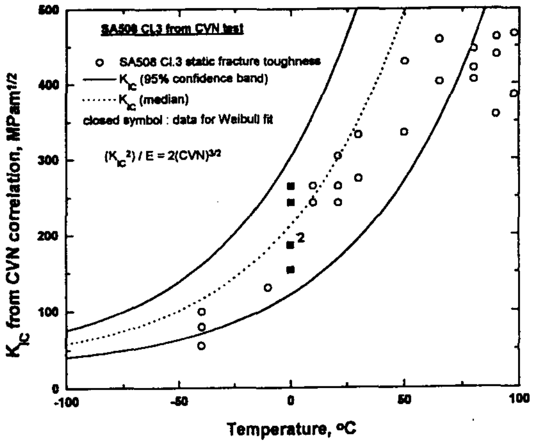

Fig. 7. K_{IC} Prediction Curves and K_{IC} data Obtained CVN Test

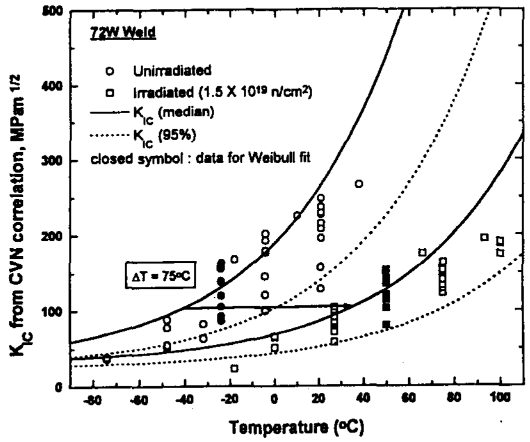

Fig. 8. Variation of Transition Temperature by Irradiation and K_{IC} Data Obtained by CVN Correlation (HSSI weld 72W)

72W and 73W weld metals which were mentioned in section 3.1. Fig.8 shows the median K_{IC} master curve, 95% confidence curve, and K_{IC} data converted by K_{IC}-CVN correlation for the unirradiated and irradiated 72W weld metal. Closed symbols are data used for a Weibull analysis to obtain the median fracture toughness curve, and open symbols are backup data used for evaluating the confidence limit. As shown in Fig.8, the data at -24°C for unirradiated material and at

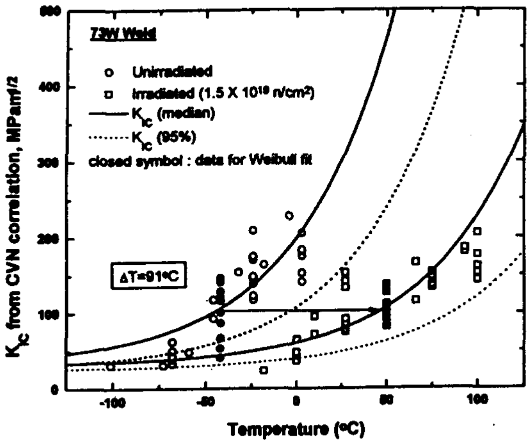

Fig. 9. Variation of Transition Temperature by Irradiation and K_{IC} Data Obtained by CVN Correlation (HSSI weld 73W)

50°C for irradiated material were used for a Weibull fitting. Substantially all data except a few were satisfied with the lower confidence limit (95%). From the median K curves predicted by a Weibull analysis, a transition temperature shift due to irradiation at 100 MPa · $m^{½}$ was 75°C as shown in Fig.8. It is known that the transition temperature shift due to irradiation (ΔT(41J)) at 41J was 72°C for this 72W weld metal (see Table 2), which was obtained by a hyperbolic tangent curve fitting from the Charpy impact test result over the entire test temperature range. Therefore it is considered that a prediction of the transition temperature shift by a statistical Weibull analysis can be a simple method for assessment of irradiation embrittlement in the transition temperature region. As in Fig.8, the same procedure was applied to 73W weld metal. The results are shown in Fig.9. Selected test temperatures were -42°C and 50°C for unirradiated and irradiated material, respectively. In comparison with the results between the predicted value (91°C, in Fig.9) and the mean value (82°C, in Table 2) from the total CVN test, there are some differences. But it is acceptable if the margin term in Table 2 is considered. Although the prediction of a transition temperature shift in this section is close to the measurement, the approach of a K_{IC}-CVN correlation has a limit point since the Charpy impact energy has never been systematically correlated with fracture toughness.

On the other hand, since the surveillance capsules have Charpy specimens for the Charpy impact test, it is useful to utilize these small specimens not for the Charpy impact test but for the three point bend tests. If the fracture toughness can be successfully obtained by the Charpy size three point bend test and statistical analysis used in this study, the results will ultimately replace the RT_{NDT} based indexing method, or at least, provide a more accurate and relevant alternative method. This approach is also interesting and valuable because broken Charpy specimens can be *reconstituted*. The broken Charpy specimens from the surveillance tests are a valuable source of additional irradiated specimens.

4. Summary

A Weibull distribution analysis was applied to obtain the fracture toughness curve in the ductile-brittle transition temperature region. It is a simple and economic method, which needs only a data set (minimum 5 samples) of fracture toughness at one specific temperature. It also seems that the statistical approach can evaluate the degree of irradiation embrittlement. The reference temperature T_0 (see section 2.1) in the master curve can be used to verify the present RT_{NDT} irradiation embrittlement indexing method which needs a curve from the standard Charpy impact test for a full range of test temperatures, or potentially this can be an alternative to the RT_{NDT} in use today. Therefore, it is considered that the approach of statistical analysis is promising for obtaining material fracture toughness directly and easily in the transition temperature region.

However, there are some problems with this approach. First, according to the proposed ASTM standand, the Weibull fitting was conducted by fixing the location parameter K_{min} (= 20 MPa · $m^{1/2}$). Since the fracture toughness considerably increases with the test temperature in the ductile-brittle transition temperature region, it is necessary to systematically consider the variation of the location parameter K_{min}. Second, it is assumed in this work that the slope of the fracture toughness curve is not changed after irradiation. Since the slope of the fracture toughness curve after irradiation decreases more or less, it is also necessary to study this point. Third is the selection of a test temperature for statistical analysis. Although the proposed ASTM standard referred to the selection of a test temperature for the unirradiated materials, an adequate test temperature selection is more or less difficult for the case of irradiated materials. It is also related to the undesirable increase in the number of testing. Above all, the key problem is that the test method for fracture toughness in the transition region is not currently standardized, it being underway in the ASTM Committee.

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