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USE OF PRECRACKED CHARPY AND SMALLER SPECIMENS TO ESTABLISH THE MASTER CURVE

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DISCLAIMER

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ABSTRACT: The current provisions used in the *U.S. Code of Federal Regulations* for the determination of the fracture toughness of reactor pressure vessel steels employs an assumption that there is a direct correlation between K_{Ic} lower-bound toughness and the Charpy V-notch transition curve. Such correlations are subject to scatter from both approaches which weakens the reliability of fracture mechanics-based analyses. In this study, precracked Charpy and smaller size specimens are used in three-point static bend testing to develop fracture mechanics based K_{Jc} values. The testing is performed under carefully controlled conditions such that the values can be used to predict the fracture toughness performance of large specimens. The concept of a universal transition curve (master curve) is applied. Data scatter that is characteristic of commercial grade steels and their weldments is handled by Weibull statistical modeling. The master curve is developed to describe the median K_{Jc} fracture toughness for 1T size compact specimens. Size effects are modeled using weakest-link theory and are studied for different specimen geometries. It is shown that precracked Charpy specimens when tested within their confined validity limits follow the weakest-link size-adjustment trend and predict the fracture toughness of larger specimens. Specimens of smaller than Charpy sizes (5 mm thick) exhibit some disparities in results relative to weakest-link size adjustment prediction suggesting that application of such adjustment to very small specimens may have some limitations.

KEYWORDS: master curve, precracked Charpy, weakest-link theory, Weibull distribution, reactor pressure vessel, fracture toughness

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INTRODUCTION

The American Society of Mechanical Engineers (ASME) K_{Ic} curve is based upon data acquired by testing large specimens of unirradiated reactor pressure vessel (RPV) steels and weld metals that satisfy the validity requirements of the American Society for Testing and Materials (ASTM) Standard Test Method for Plane-Strain Fracture Toughness of Metallic Materials (E 399-90). Currently, the provisions for determination of the upward temperature shift of the ASME K_{Ic} curve due to irradiation are based on the Charpy V-notch (CVN) 41-J shift, and the shape of the fracture toughness curve is assumed to not change as a consequence of irradiation. The main reason for such assumptions was that it was not practical to generate the equivalent linear-elastic K_{Ic} data base for irradiated material in the transition region. In fact, the maximum size of compact specimens for irradiation studies is limited to 4T (101.6 mm) simply due to through-thickness fluence gradients.

In this study, precracked CVN (PCVN) and smaller specimens were used to characterize the fracture toughness of RPV steel in the transition region by means of three-point slow bending. The PCVN specimen as well as any fracture toughness specimen which could be made out of the broken halves of standard CVN specimens would have exceptional utility for reactor pressure vessels. The CVN specimen is the most commonly used specimen geometry in surveillance programs. Precracking and testing of irradiated Charpy surveillance specimens would allow one to determine and monitor directly actual fracture toughness of an irradiated vessel instead of requiring indirect predictions using correlations established with impact data.

However, with testing of small specimens in the transition region, some amount of local crack tip plasticity is unavoidable and fracture toughness up to cleavage instability is calculated in terms of size-dependent elastic-plastic K_{Jc} values. Therefore, a statistical size correction based upon weakest-link theory has been proposed [1]. Data scatter that is characteristic of commercial grade steels and their weldments is handled by Weibull statistical modeling and the concept of a universal shape curve (master curve) is applied to characterize fracture toughness in the transition region. The master curve is developed to describe the median K_{Jc} fracture toughness for 1T size compact specimens. Thus, the ability of the PCVN and some smaller size specimens to establish the master curve for large compact specimens will be examined in this paper.

ANALYSIS PROCEDURE

The analysis procedure is based on fitting replicate fracture toughness data generated at a fixed temperature to a three-parameter Weibull cumulative distribution function. It was determined [2], at least for RPV steels, that among these three parameters, the shape parameter (Weibull slope) is equal to 4 and the location parameter, K_{min}, is about 20 MPa$\sqrt{m}$. Fixing the slope b = 4 and K_{min} = 20 gives the Weibull cumulative probability distribution function as:

$$P_f = 1 - \exp\left[-\left(\frac{K_{Jc} - 20}{K_o - 20}\right)^4\right] , \quad (1)$$

where P_f is the cumulative fracture probability for $K \leq K_{Jc}$ and K_o is a specimen thickness and temperature-dependent scale parameter. Thus, only the scale parameter, K_o, needs to be determined. As a consequence, only a few replicate tests are needed to obtain this parameter with good accuracy. The proposed ASTM practice [3] requires at least six replicated tests. The procedure employs the maximum likelihood concept regarded as the most accurate method of obtaining K_o when there are so few replicate tests:

$$K_o = \left[\frac{\sum_{i=1}^{N} (K_{Jc(i)} - 20)^4}{N - 1 + \ln 2}\right]^{1/4} + 20 \text{ , MPa}\sqrt{m} \text{ ,} \quad (2)$$

where $K_{Jc(i)}$ represents each datum obtained at the given test temperature. The term N is the total number of replicate data at that test temperature. Occasionally with the testing of small specimens, a data set may contain K_{Jc} values which exceed a constraint limit, and, in such cases, Eq. (2) is modified to handle censored (invalid) data. The test specimen capacity currently set in Ref. [3] is calculated using the following:

$$K_{Jc(limit)} = \left(\frac{E b_o \sigma_y}{30}\right)^{1/2} \text{, MPa}\sqrt{m} \text{ ,} \quad (3)$$

where E is elastic modulus, b_o is the initial remaining ligament dimension, and σ_y is the yield strength. According to the proposed ASTM Draft Standard [3], the invalid data point is censored and assigned the $K_{Jc(limit)}$ toughness value. Then, the K_o is determined by:

$$K_o = \left[\frac{\sum_{i=1}^{N} (K_{Jc(i)} - 20)^4}{r - 1 + \ln 2}\right]^{1/4} + 20\text{, MPa}\sqrt{m} \text{ ,} \quad (4)$$

where r is the number of valid data and N is the total number of valid and invalid K_{Jc} values. This procedure is described in Ref. [3] and requires at least six valid data points to proceed.

For small specimen applications, size adjustment is a key point in this analysis procedure. Weakest-link theory is used [1] to explain statistical specimen size effects so that data, for example, equivalent to that for a 1T size specimen, $K_{Jc(1T)}$, can be calculated from data measured with specimens of different sizes, $K_{Jc(xT)}$:

$$K_{Jc(1T)} = 20 + [K_{Jc(xT)} - 20]\left[\frac{B_{(xT)}}{B_{(1T)}}\right]^{1/4}, \ \mathrm{MPa}\sqrt{\mathrm{m}}\ , \tag{5}$$

where $B_{(xT)}$ and $B_{(1T)}$ are the test specimen and 1T specimen thicknesses, respectively. Statistical size adjustment is based on the fact that cleavage fracture in the transition range is initiated by small microstructural defects that are always present in commercially produced RPV steels. Therefore, the thicker the specimen being tested, the higher the probability of encountering a trigger point of a critical size that is situated within the volume of material loaded to a critical stress state along the crack tip front. As a result, large specimens will display lower fracture toughness than specimens of smaller thickness. Equation (5) is the mathematical expression for these statistical effects. Finally, knowing all of the parameters of the distribution allows one to determine the median K_{Jc} toughness, $K_{Jc(med)}$ (the K_{Jc} value at $P_f = 0.5$), for a specimen of chosen reference size, usually a 1T C(T), at a given temperature.

Therefore, the current procedure provides a tool to describe the scatter of fracture toughness data in the transition region and to determine the median K_{Jc} (1T) value by means of performing a few replicate tests. However, the application of this procedure to small specimens has some limitations. On the high-temperature side, small specimens are limited by specimen capacity to maintain constraint. According to Eq. (3), the remaining ligament size, b_o, is a critical parameter to satisfy the constraint limit for a given material. As the lower-shelf toughness at low temperatures is approached, Eq. (3) becomes inapplicable because the statistical size effects diminish and the initiation criterion is no longer dominant. Fracture becomes more propagation-controlled. This means that the test temperature range for small specimens is quite narrow in order to provide data acceptable for the current analysis procedure.

For structural ferritic steels, however, $K_{Jc(med)}$ values tend to form transition temperature curves of the same universal shape which is known now as the "master curve." The master curve of $K_{Jc(med)}$ for 1T size specimens in the transition region is described by:

$$K_{Jc(med)}^{\ 1T} = 30 + 70\ \exp[0.019(T - T_{100})]\ ,\ \mathrm{MPa}\sqrt{\mathrm{m}}\ , \tag{6}$$

where T_{100} is the reference temperature at which $K_{Jc(med)}^{\ 1T}$ is 100 MPa√m. The lower (0.05) and upper (0.95) tolerance bounds are calculated using the following [3]:

$$K_{Jc(0.95)} = 34.6 + 102.2\exp[0.019(T - T_{100})],\ \mathrm{MPa}\sqrt{\mathrm{m}}\ . \tag{7}$$

$$K_{Jc(0.05)} = 25.4 + 37.8\exp[0.019(T - T_{100})].\ \mathrm{MPa}\sqrt{m}\ . \qquad \textbf{(8)}$$

Thus, having the temperature dependence of fracture toughness defined by Eq. (6) permits obtaining a value of $K_{Jc(med)}^{1T}$ from PCVN type specimens at one temperature and then estimating the whole transition region curve by means of the master curve.

MATERIAL AND SPECIMENS

Three types of specimens were tested in the present study. The first type is the standard full-size Charpy specimen with dimensions of 10 × 10 × 55 mm. The second type was made by thin-wire electrodischarge machine cutting along the axes of the full-size specimen. This specimen is 4.8 mm thick, 10 mm wide, and 55 mm long. Although this type of specimen is half as thick as a full-size specimen, it has the same remaining ligament size, which is the key size parameter in the constraint limit equation [Eq. (3)]. The third type of specimen was made from the broken half of a full-size specimen, has a 4.8 × 4.8 mm cross section, and is about 27 mm long. The latter two types of specimens may be useful when the number of standard specimens is too limited for a good material evaluation, which is often the case in plant life extension and annealing evaluations. All specimens were fatigue precracked to an a/W ratio of about 0.5 and tested in slow three-point bending. Load versus load-point displacement was measured. Both the 10 × 10 × 55 and 4.8 × 10 × 55 mm specimens were tested with the span of 40 mm, while the 4.8 × 4.8 × 27 mm specimens were tested with a 20-mm span. All 4.8-mm-thick specimens were 20% side-grooved. The standard size CVN specimens were tested without side grooves.

The ASTM A 533 grade B class 1 plate, designated Heavy-Section Steel Technology (HSST) Program Plate 02, was selected for the present study. The selection of this plate was based on the existence of an extensive fracture toughness database for Plate 02 accumulated by testing large specimens. Westinghouse tested 70 specimens of different sizes up to 11T thickness to establishing what is now known as the ASME lower-bound K_{Ic} curve [4]. Additionally, 25 1T compact specimens of the plate were subsequently tested in the transition range as a part of the HSST Program performed at Oak Ridge National Laboratory (ORNL) [5].

Initially, these 1T data were analyzed by the master curve procedure and the reference fracture toughness transition temperature, T_{100}, was determined to be −23°C [6]. Based on this value of T_{100}, most of the tests were performed at −50°C. At the temperature of −50°C, the value of $K_{Jc(med)}$ from 1T compact specimens is 71.9 MPa√m, which for 5-mm-thick specimens converts to about 100 MPa√m, based on the estimation by Eq. (5). The draft standard [3] recommends performing tests at a temperature close to that at which median K_{Jc} values will be about 100 MPa√m. Seven

10 × 10 × 55, eight 4.8 × 10 × 55, and twelve 4.8 × 4.8 × 27 mm specimens were tested at −50°C. Additionally, seven 10 × 10 × 55 and eight 4.8 × 10 × 55 mm specimens were tested at −30°C.

FULL-SIZE PRECRACKED CHARPY DATA

Test data for all specimens studied are summarized in Table 1. For the full-size PCVN specimens, the reference transition temperatures, T_{100}, as determined by rearranging Eq. (6), were −23 and −26°C after testing at −50 and −30°C, respectively. The difference between the two values is only 3°C, which indicates that median toughness values determined by PCVN specimens fit very well to the shape of the master curve. The average of these two values, −25°C, is used as the reference fracture toughness temperature determined by testing of PCVN specimens in the following evaluations of HSST Plate 02 properties.

Data from PCVN specimens are in very good agreement with 1T compact K_{Jc} data [5] (T_{100} = −23°C). However, a question remains regarding the relevance of properties evaluated by the "master curve" procedure to the ASME lower-bound K_{Ic} curve. The ASME K_{Ic} curve was constructed as a lower bound to its respective linear-elastic K_{Ic} database for reactor pressure vessel steels [4] plotted as a function of test temperature (T) normalized to a reference nil-ductility temperature, RT_{NDT}, namely, $T - RT_{NDT}$. The RT_{NDT} is derived from either drop-weight or CVN impact test results. The majority of the ASME database is represented by the HSST Plate 02. Obviously none of the K_{Jc} values from PCVN specimens reported in Table 1 could satisfy the validity requirements for linear-elastic K_{Ic} stated in ASTM E 399-90. Valid K_{Ic} data have for many years been regarded as necessary to define the lower bound of fracture toughness. Nevertheless, it was recently shown [7] that the Weibull distribution function models the scatter in the ASME K_{Ic} data very well, while the temperature dependence is described by the master curve. Thus, the master curve evaluated by testing PCVN specimens will be compared to the linear-elastic K_{Ic} data of HSST Plate 02 and then to all of the ASME K_{Ic} database.

Figure 1 shows the fracture toughness K_{Ic} data for HSST Plate 02 derived by testing 70 specimens of different sizes up to 11T thickness [4]. The statistical size adjustment by Eq. (5) is applied to convert the data to 1T size equivalence. Finally, the master curve and lower 5% tolerance bound by Eq. (8) evaluated from the testing of PCVN specimens (T_{100} = −25°C) are compared to these size-adjusted K_{Ic} data on the same plot. To cover uncertainty in T_{100} due to testing only a few PCVN specimens, a margin, ΔT_{100} = 7°C, is added to the tolerance bound. The procedure and details of the margin calculation are presented in Refs. [3] and [6]. Figure 2 shows that the master curve and the 5% margin-adjusted tolerance bound derived from testing several PCVN specimens represent very well the large K_{Ic} database accumulated by testing of massive specimens.

Having success in describing the K_{Ic} database by the master curve from PCVN specimens of the same material, the next step is to make a direct comparison between the

Table 1. Results of three-point slow-bend specimen data analysis of HSST Plate 02

Specimen size (mm)	T_{test} (°C)	Number of data points (N)	Valid data points (r)	K_o (MPa√m)	$K_{Jc(med)}$ (MPa√m)	T_{100} (°C)
10 × 10 × 55	-50	7	7	91.9	85.42	-23
4.8 × 10 × 55	-50	8	8	81.1	75.8	1
4.8 × 4.8 × 27	-50	12	8	103.7	96.4	-21
10 × 10 × 55	-30	8	7	122.9	114.6	-26
4.8 × 10 × 55	-30	10	8	124.9	115.7	-15

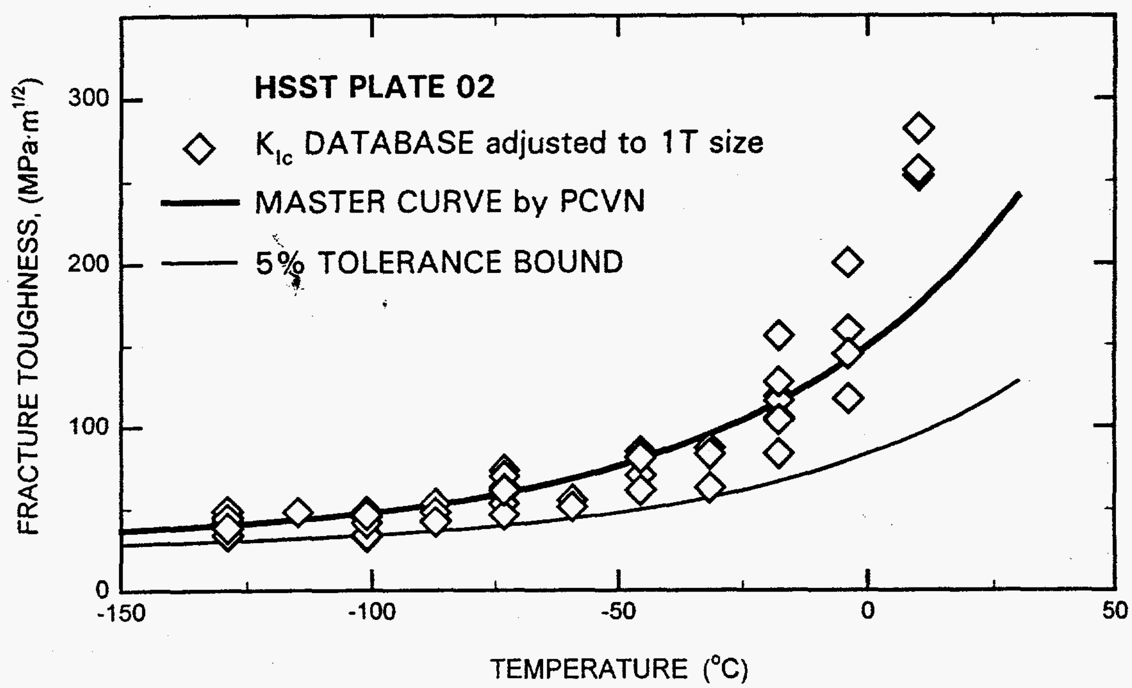

FIG. 1--Comparison of the HSST Plate 02 linear-elastic K_{Ic} database relative to the master curve with 5 % margin-adjusted tolerance bound curve derived by testing of several PCVN specimens.

ASME lower bound curve and the 5% margin-adjusted tolerance bound curve, see Fig. 2. All 174 K_{Ic} data from the EPRI database have been reexamined and checked for accuracy in Ref. [8]; these data are also plotted in this figure. The top and right axes are in English units which is usual when relative temperature, $T - RT_{NDT}$, is expressed in °F. The first ASME curve was manually constructed as the lower boundary to K_{Ic} values only in the normalized temperature range of $T - RT_{NDT}$ from −100 to +100°F. More recently, the manually constructed representation has been replaced by the so-called EPRI equation (expressed in SI units):

$$K_{Ic} = 36.5 + 3.083 \exp\,[0.036(T - RT_{NDT} + 55.6)]\ .\ \mathrm{MPa}\sqrt{\mathrm{m}}\ . \qquad \textbf{(9)}$$

For comparison, the 5% margin-adjusted tolerance bound curve derived from testing of PCVN specimens of HSST Plate 02 in the temperature coordinate normalized to RT_{NDT}, including the effect of ΔT_{100},[3] is equal to:

$$K_{Jc(0.05)} = 25.4 + 37.8 \exp\,[0.019(T - RT_{NDT})],\ \mathrm{MPa}\sqrt{\mathrm{m}}\ . \qquad \textbf{(10)}$$

In Fig. 2, Eqs. (9) and (10) are both plotted over the full temperature range of the K_{Ic} data. The first observation is that Eq. (9) is only a fitting function for the data in the temperature range −100 to +100°F, hence it is not a true lower bound to all of the data. In the transition region, the ASME K_{Ic} curve rises more rapidly than the tolerance bound to the master curve. The deviation starts at $T - RT_{NDT}$ above 25°C. On the other hand, this is the region where almost no K_{Ic} data were available to justify the curve shape. Thus, the shape of the ASME curve at $T - RT_{NDT}$ above 25°C reflects a postulated shape, while the master curve concept has been experimentally proven to describe an unsubjective scatter of elastic-plastic-based fracture toughness values in the transition region. In this discussion however, the caution regarding the necessity for using only valid K_{Ic} data is relaxed by applying the master curve based on K_{Jc} data to describe the scatter of K_{Ic} data of the same material and also the total K_{Ic} database. The specific advantage of the present results is that the master curve was developed from PCVN specimens.

SUBSIZE PRECRACKED CHARPY DATA

The fracture toughness tests with 4.8-mm-thick specimens of HSST Plate 02 at −50°C exhibit some disparities in results (Table 1). The median of twelve K_{Jc} data of 4.8 × 4.8 × 27 mm specimens is 96.4 MPa√m, which yields $T_{100} = -21$°C. The median of eight K_{Jc} data of 4.8 × 10 ×55 mm specimens is 75.8 MPa√m, which yields $T_{100} = +1$°C. Figure 3 compares the median K_{Jc} values of different specimens tested at −50°C. The $K_{Jc(med)}$ values are plotted against thickness of specimens, $B_{(xT)}$, relative to 1T compact specimen thickness, $B_{(1T)}$. The median K_{Jc} value of 71.9 MPa√m derived from analysis of 1T specimens [6] is used as a reference point to plot as a solid line the median K_{Jc} trend

[3] In this case, $T_{100} = -25$°C, $RT_{NDT} = -18$°C(0°F), and $\Delta T_{100} = 7$°C.

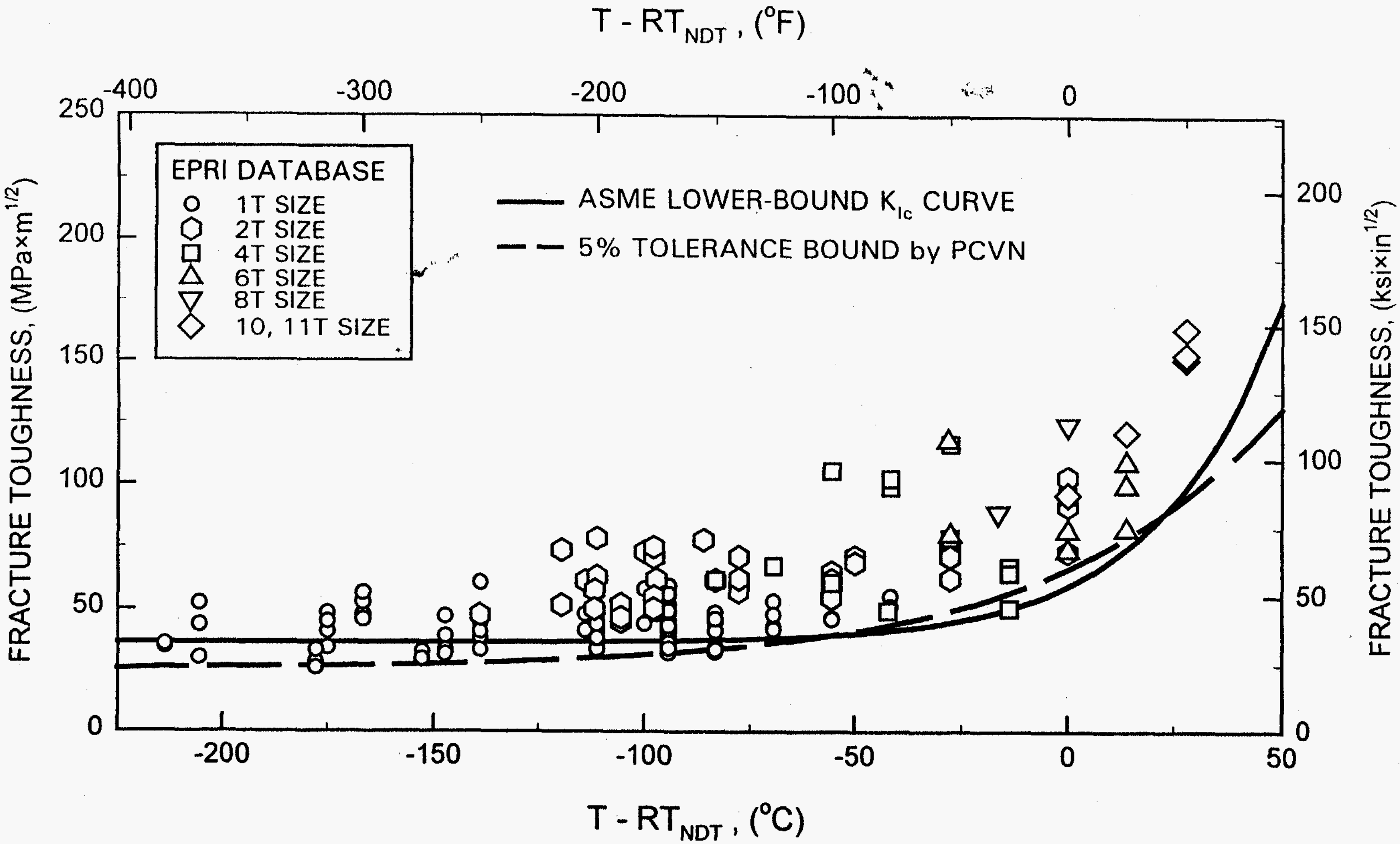

FIG. 2--Comparison of the K_{Ic} EPRI database and ASME lower-bound curve relative to the 5% margin-adjusted tolerance bound curve derived by testing of several PCVN specimens of HSST Plate 02.

prediction according to the weakest-link size adjustment model by Eq. (5) covering the range of thicknesses studied. In addition to the specimens of the present study, the median fracture toughness of 2T compact specimens tested by Westinghouse [4] at −46°C and 0.2T compact specimens tested by ORNL [9] at −50°C are also presented on Fig. 3. As discussed earlier, PCVN data and 2T compact specimen data follow the size adjustment model. The 4.8 × 4.8 × 27 mm specimen data also show good agreement with the weakest-link size adjustment model of Eq. 5.

However, the median data point from 4.8 × 10 × 55 mm specimens fell below this model trend. The median of eight K_{Jc} data of 4.8 × 10 × 55 mm specimens is 75.8 MPa√m, which yields $T_{100} = +1$°C. Results of six 0.2T compact specimens (5 mm thick) tested at the same temperature [9] almost reproduce data of 4.8 × 10 × 55 mm three-point bend specimens. The median K_{Jc} of 0.2T C(T) is 73.8 MPa√m, which yields $T_{100} = +2$°C. These two types of specimens have one common parameter − the ratio of width (W) to the thickness (B) is equal to 2, while the PCVN and its smaller equivalent 4.8 × 4.8 × 27 mm specimens have W/B equal to 1.

The disparity in results for the three different specimens sizes is not evident from the Weibull probability plots of Fig. 4. For all three specimen sizes, the scatter of data follows the same Weibull slope of 4, denoted by the solid lines in Fig. 4. Square points in Fig. 4a are the data which exceeded the constraint limit set by Eq. (3). Load-displacement curves of three-point bend specimens were normalized into so-called "key curves" using limit load expressions described in Ref. [10] and these key curves are compared in Fig. 5. In addition, the key curves from 1T compact specimens tested at −40°C [5] are also presented in Fig. 5. Each type of specimen had exhibited different levels of plastic deformation prior to cleavage; however, all three specimen designs tend to have the same deformation characteristics as indicated by the key curve data of Fig. 5. As stated, this suggests that stress-strain conditions in the plane of the crack are comparable for all three-point bend specimens. The key curves of 1T compact specimens also followed the same trend, but cleavage in these considerably larger specimens occurred at significantly lower plastic deformation.

Additional tests of ten 4.8 × 10 × 55 mm specimens were performed at −30°C; from analysis of these data, the reference fracture toughness temperature, T_{100}, was determined as −15°C (Table 1), confirming that the $K_{Jc(med)}$ value is below the size-adjustment value predicted by Eq. (5) from 1T compact specimen data.

Analysis of 4.8-mm-thick specimens studied here suggests that the mathematical expression for weakest-link theory size adjustment by Eq. (5) may not apply at small thicknesses. Further investigations need to be performed to develop a unique size adjustment model for such small thicknesses.

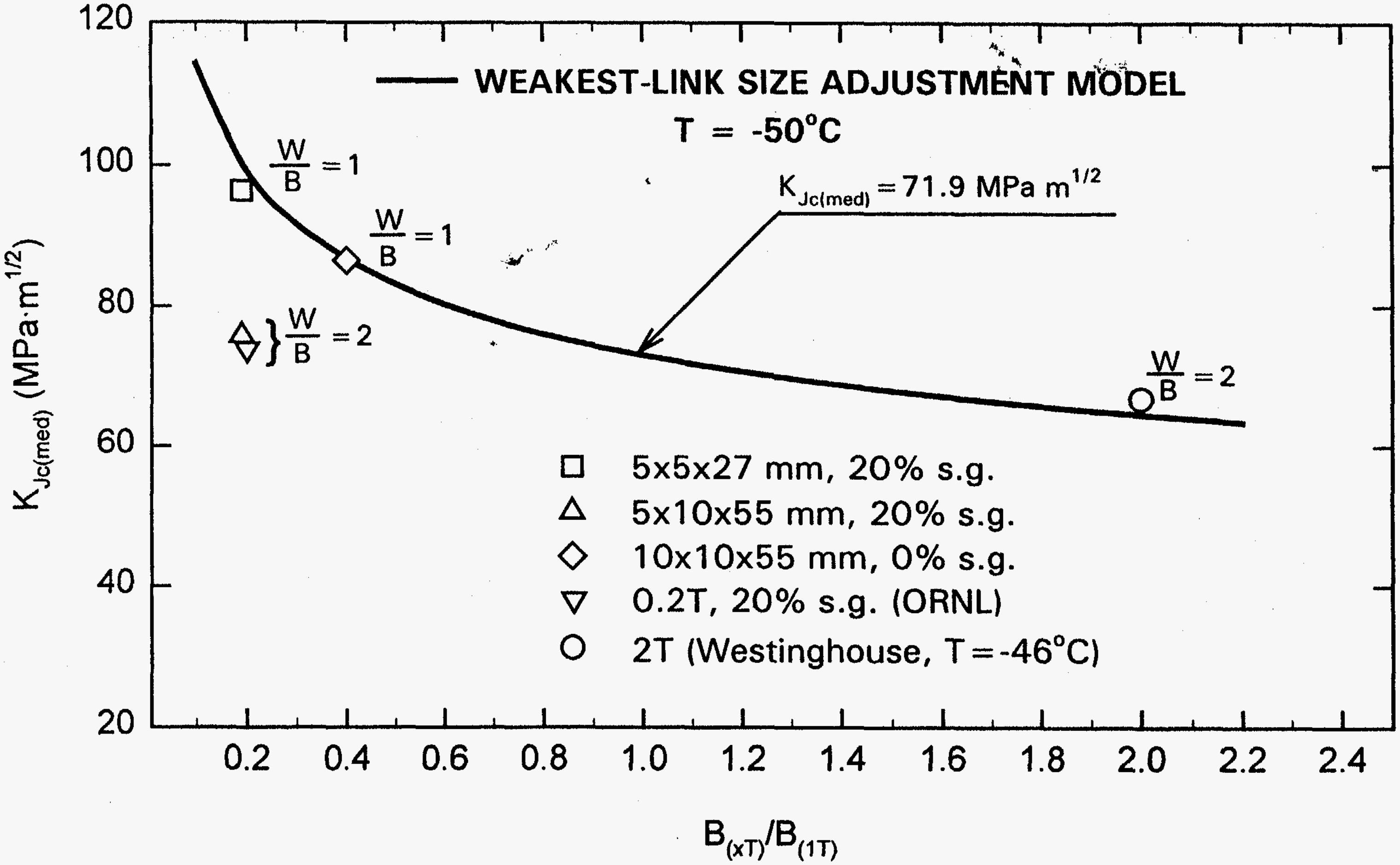

FIG.3--Median fracture toughness values of specimens with different thcikness (B) and width (W) sizes.

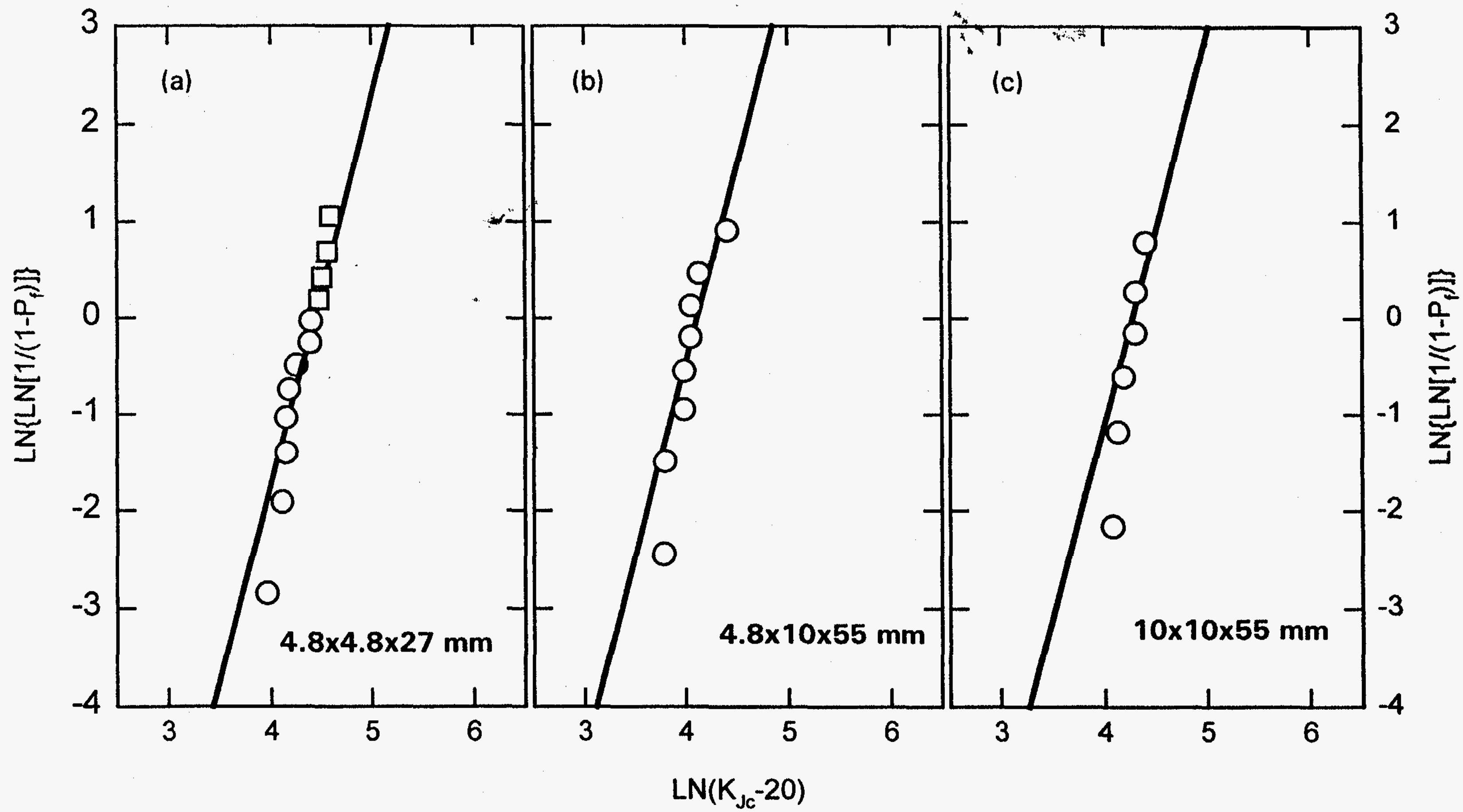

FIG. 4--Weibull probability plots for three-point bend specimens tested at -50°C.

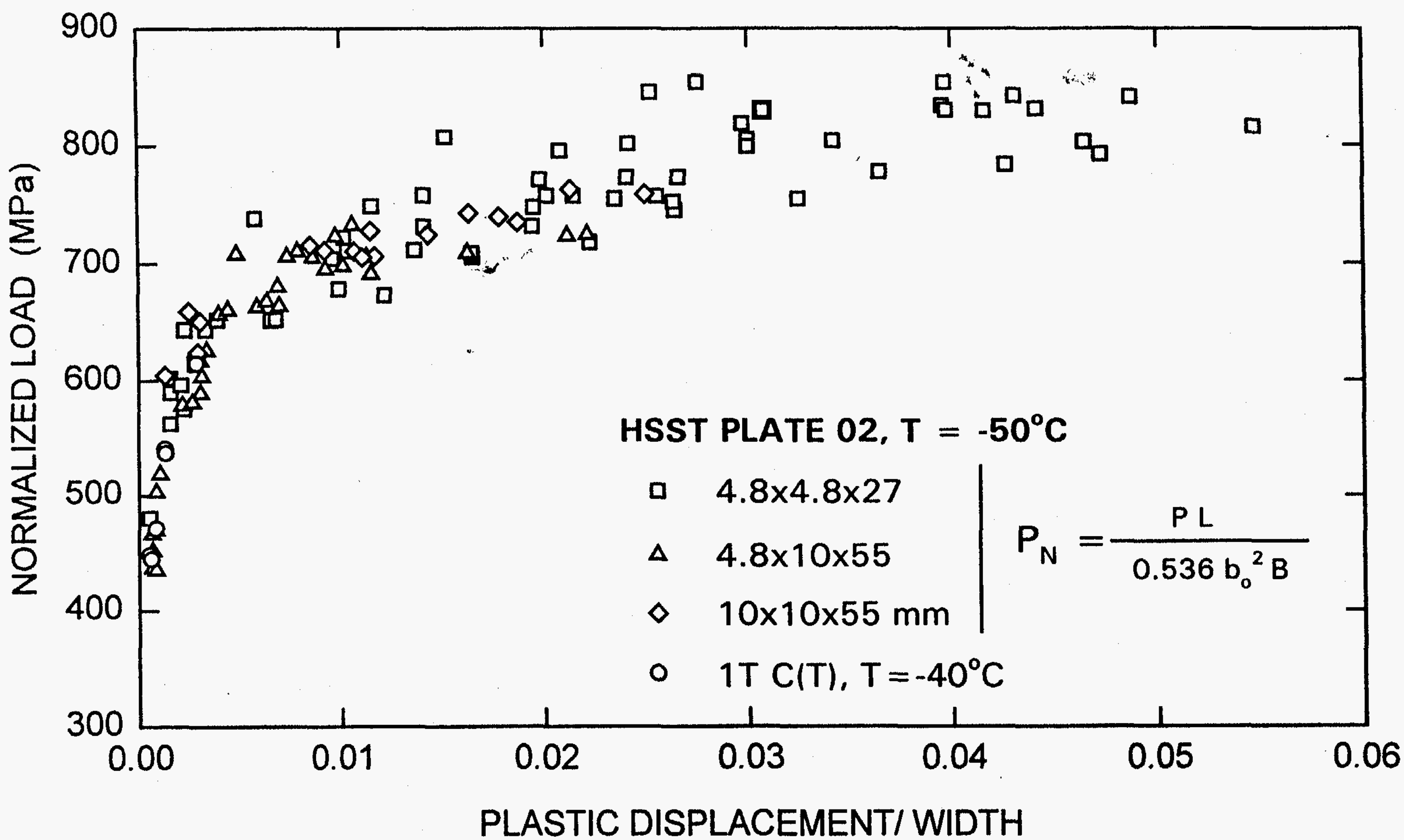

FIG. 5--Key curves of different specimen types.

SUMMARY AND CONCLUSIONS

The applicability of small specimens to characterize the fracture toughness of RPV steels has been examined by three-point slow bend testing of precracked CVN and smaller size specimens. Weibull statistical concepts were applied to analyze K_{Jc} values and the master curve approach was used to describe the temperature dependence of fracture toughness in the transition region.

It is shown that the master curve derived from the testing of several PCVN specimens of HSST Plate 02 represents very well the large linear-elastic K_{Ic} database [adjusted to 1T C(T) size] accumulated by the testing of massive specimens needed for K_{Ic} validity. Also the 5% margin-adjusted tolerance bound of the master curve describes successfully the lower bound of scatter in K_{Ic} of this same material.

The 4.8-mm-thick specimens exhibited some disparities in results relative to the current weakest-link size adjustment predictions, indicating that the current mathematical expression for weakest-link theory size adjustment may need some evaluation for such small thicknesses. The current results suggest that ratio of width to thickness becomes a vital parameter in size adjustment modeling for specimens with small thickness. Further investigation is needed to develop a unique size adjustment model for small thicknesses.

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