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Abstract: Testing of compact tension specimens removed from an unirradiated reactor pressure vessel (RPV) weld has produced data exhibiting a frequency distribution that does not follow that used in the development of the ASTM Transition Range Standard, E1921-97. The data tend to be skewed toward lower toughness values, resulting in calculation of mean toughness and T_o values for individual data sets according to E1921, that are non-conservative with respect to the actual data distributions. Using the principle of linear least squares, a closed form equation has been derived that treats such data sets in a simplified, exact way. Predictions of T_o and 2 percent lower tolerance limits for several data sets using the Master Curve methodology and this linearized equation show the new equation to better predict the median curve and lower bound curves than does the Master Curve procedure for these specific data sets. This report describes development of the governing equations and illustrates the application using data sets from different materials.

1. Introduction

The ASME Task Group on Master Curve has developed and published ASME Code Case N-629 [1] that uses the indexing parameter T_o to establish a new reference temperature for pressure retaining materials for Section III, Division 1, Class 1 vessels. The indexing temperature T_o was developed through the ASTM Committee E08. The procedures for determination of T_o from sets of fracture toughness data are contained in ASTM Standard E-1921 [2] and the companion background document [3]. Development of the mathematical basis for T_o utilizes two observations on fracture toughness behavior of ferritic steels. First, when the data at a single temperature are represented by a three-parameter Weibull distribution, the linearized cumulative frequency distribution of the toughness values can be represented by a straight line with a slope near 4. Second, the temperature dependence of median toughness data for individual ferritic materials is well represented by a single curve when the test temperatures are normalized using the indexing parameter T_o. This has been well demonstrated for a number of different ferritic steels, and the evidence is convincing that the above two observations hold true for most ferritic steels.

Studies have been performed within the HSST Program to investigate the fracture behavior of RPV steels under a variety of flaw depth, flaw tip constraint, and temperature conditions. This required extensive characterization of the test materials in the course of which issues related to indexing of

fracture toughness data using the T_o reference temperature were addressed [4,5]. Data were generated on the fracture toughness properties of longitudinal and circumferential structural welds from an RPV beltline shell segment. Particular attention was given to regions within the welds where shallow, through-surface flaws might exist in an RPV. These studies revealed significant variations of T_o within critical locations of the circumferential weld [5,6]. When these data were treated using the procedures contained in the Transition Range Standard [2], some regions of the circumferential weld exhibited frequency distributions that were not consistent with the Weibull slope of 4 used in the development of T_o [2]. Table 1 summarizes the data from eight specimens taken from a near-inside (clad) surface location of the circumferential weld. Figure 1 shows the histogram for this data set illustrating the skewed distribution behavior observed. Following the ASTM nomenclature for plate products, the flaw orientation was in the T-S (transverse, through-thickness) direction. For welds, the deposition direction was taken as the "rolling" direction. The eight tests were run at a temperature of –30°C (-22°F) at which seven toughness values were valid K_{Jc} results and one required censoring. The histogram shown as Fig. 1 illustrates the skewed character typical of the data for this material. A Weibull plot was prepared and is shown in Fig. 2. The Weibull slope for this set of tests was determined to be 1.84 rather than the value of 4 utilized in the Master Curve development. The differences in slope shown in Fig. 2 is caused, to some extent, by the non-linear character of the data plot, i.e., the initial part of the data set appears to have a slope near 4, but a transition in slope occurs at toughness values greater than 90 MPa√m. Even though these were 1/2T compact tension (CT) specimens, loss of constraint appears not to be

Table 1 Summary of circumferential weld toughness values for CTS Series specimens tested at –30°C.

Rank	Specimen Number	Test Temperature (°C)	K_{Jc} (1/2T) (MPa√m)	K_{Jc} (1T) (MPa√m)
1	CTS15	-30	69.9	62.0
2	CTS13	-30	73.7	65.2
3	CTS23	-30	76.9	67.8
4	CTS16	-30	83.8	73.6
5	CTS20	-30	92.9	81.3
6	CTS11	-30	130.7	113.1
7	CTS14	-30	181.5	155.8
8	CTS22*	-30	218.0	186.5

*Censored per ASTM E1921.

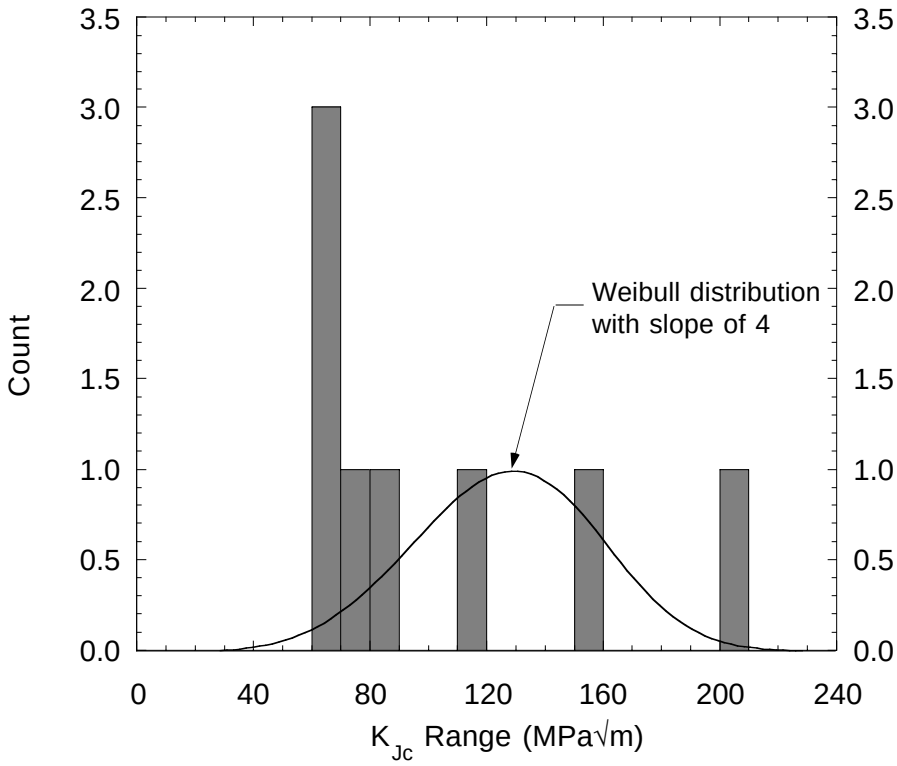

Fig. 1. Histogram of circumferential weld CT data showing skewed distribution relative to Master Curve predicted distribution. Data are from CTS series tested at –30°C.

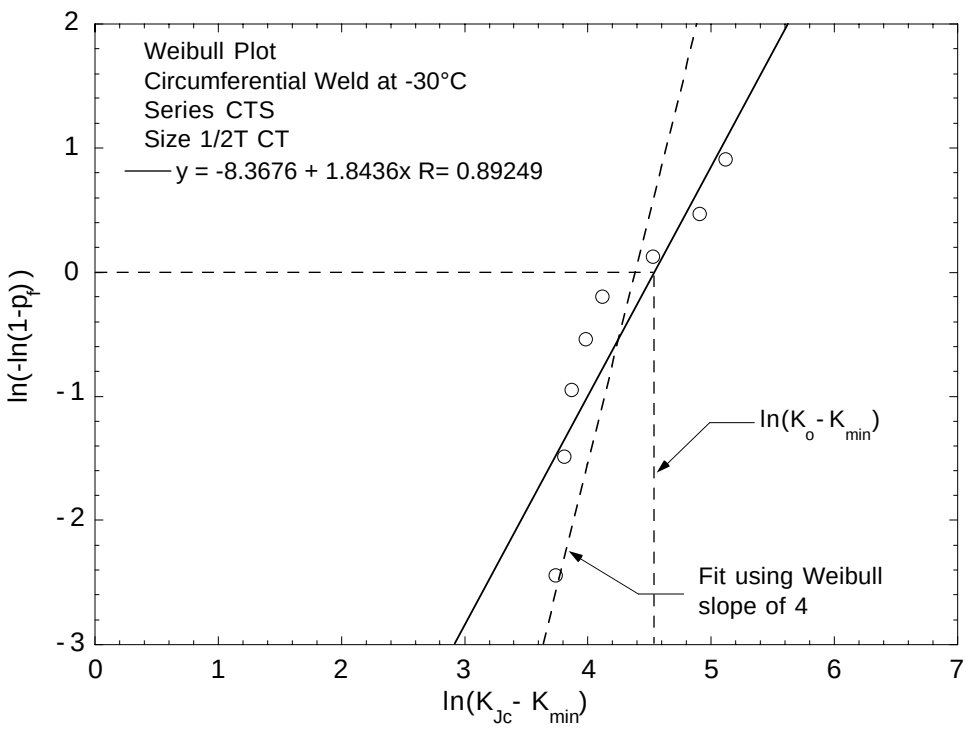

Fig. 2. Weibull plot of data from CTS Series at –30°C showing fitted curves using Weibull slope of 4 and linear least squares.

an issue. Following Ref. 2, the limit on valid K_{Jc} for this specimen size is,

$$K_{Jc(\lim it)} = \left(\frac{E b_o \sigma_{ys}}{M} \right)^{1/2} \quad , \tag{1}$$

where E = material elastic modulus = 206850 MPa,

b_o = initial remaining ligament = 0.0125 m,

σ_{ys} = material yield stress = 551.6 MPa,

and M = factor to establish specimen size requirements = 30.

For this material and these tests performed at –30°C, $K_{Jc(limit)}$ was determined to be 218 MPa√m for a 1/2T CT specimen. Seven of the eight specimens gave toughness values well below this limit such that completely ignoring the highest (censored) value would change the results only marginally.

The failure probability density function is defined as

$$f\left(K_{Jc}, m, K_o, K_{\min}\right) = m \left\{ \frac{\left(K_{Jc} - K_{\min}\right)}{\left(K_o - K_{\min}\right)} \right\}^{(m-1)} \exp\left[-\left\{ \frac{\left(K_{Jc} - K_{\min}\right)}{\left(K_o - K_{\min}\right)} \right\}^{m} \right] \quad . \tag{2}$$

The value of K_o for the actual distribution is detrermined from the straight line fit shown in Fig. 2.

$$\ln\left[-\ln\left(1 - p_f\right)\right] = Y_o + m \ln\left[\left(K_{Jc} - K_{\min}\right)\right] \quad , \tag{3}$$

where Y_o = y-intercept of fitted line = -8.37,

and m = Weibull shape parameter (slope of line) = 1.84.

By definition, when

$$\ln\left[-\ln\left(1 - p_f\right)\right] = 0,$$

$$\ln\left(K_{Jc} - K_{\min}\right) = \ln\left(K_o - K_{\min}\right) \quad .$$

This is shown by the intersecting dashed lines in Fig. 2. Using Eq. (3),

$$\ln\left[-\ln\left(1 - p_f\right)\right] = 0 = Y_o + m \ln\left[\left(K_o - K_{\min}\right)\right],$$

and

$$K_o = K_{\min} + \exp\left[-\left(\frac{Y_o}{m} \right) \right] \quad . \tag{4}$$

Using Eq. (2), Eq. (4), and the Weibull slope of 1.84 and intercept values determined for this data set, the failure probability density function was calculated and is shown in Fig. 3. The predicted distribution using a Weibull slope of 4 is also shown for comparison. This figure clearly demonstrates the skewed behavior of this particular data set.

One set of eight specimens does not provide the level of confidence required to formulate recommendations for consideration by the ASTM E08 Committee responsible for the Transition Range Standard [2]. Since material was limited, and to sample different regions of the weld, additional sets of specimens were prepared and tested. One set of eight 1/2T CT specimens was taken from approximately the 1/2t location (H4 Series) within the circumferential weld, and another from the 1/4t location (H3 Series). Both sets of specimens had an L-S flaw orientation as compared to the T-S orientation of the set discussed above. The data from these specimens are summarized in Tables 2 and 3, respectively. Weibull and probability density plots for both data sets are shown in Figs. 4 through 7.

An obvious question that even the investigators asked is, "Is there something wrong with these results?" Test procedures used in the laboratory have been highly qualified through many years of

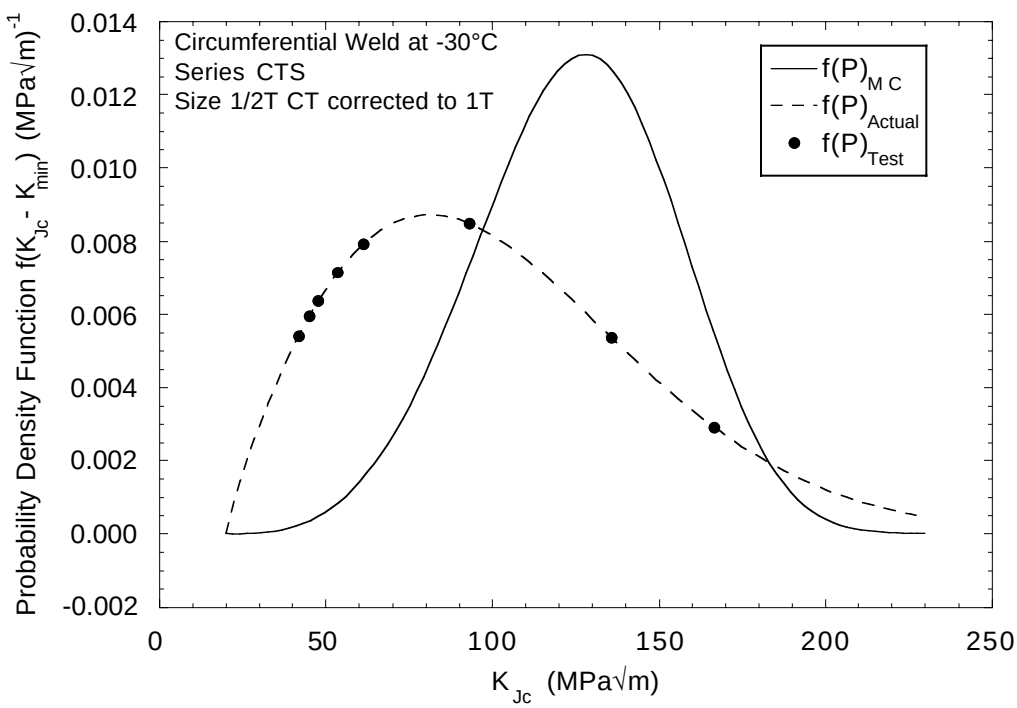

Fig. 3. Failure probability density function for circumferential weld CT specimen data from 1/2T-CTS Series, showing skewed distribution relative to Master Curve predicted distribution.

Table 2 Summary of circumferential weld toughness values for H4 Series specimens tested at –65°C.

Rank	Specimen Number	Test Temperature (°C)	K_{Jc} (1/2T) (MPa√m)	K_{Jc} (1T) (MPa√m)
1	H4-6	-65	45.3	45.3
2	H4-8	-65	46.6	46.6
3	H4-5	-65	51.8	50.0
4	H4-7	-65	58.6	52.5
5	H4-3	-65	94.1	82.3
6	H4-1	-65	118.2	102.6
7	H4-2	-65	134.1	115.9
8	H4-4	-65	152.9	131.8

Table 3 Summary of circumferential weld toughness values for H3 Series specimens tested at –65°C.

Rank	Specimen Number	Test Temperature (°C)	K_{Jc} (1/2T) (MPa√m)	K_{Jc} (1T) (MPa√m)
1	H3-5	-71	59.0	46.1
2	H3-3	-71	65.4	50.4
3	H3-2	-71	81.8	61.3
4	H3-8	-71	89.7	66.6
5	H3-4	-71	96.9	71.4
6	H3-1	-71	111.2	81.0
7	H3-7	-71	145.4	103.9
8	H3-6	-71	155.8	110.8

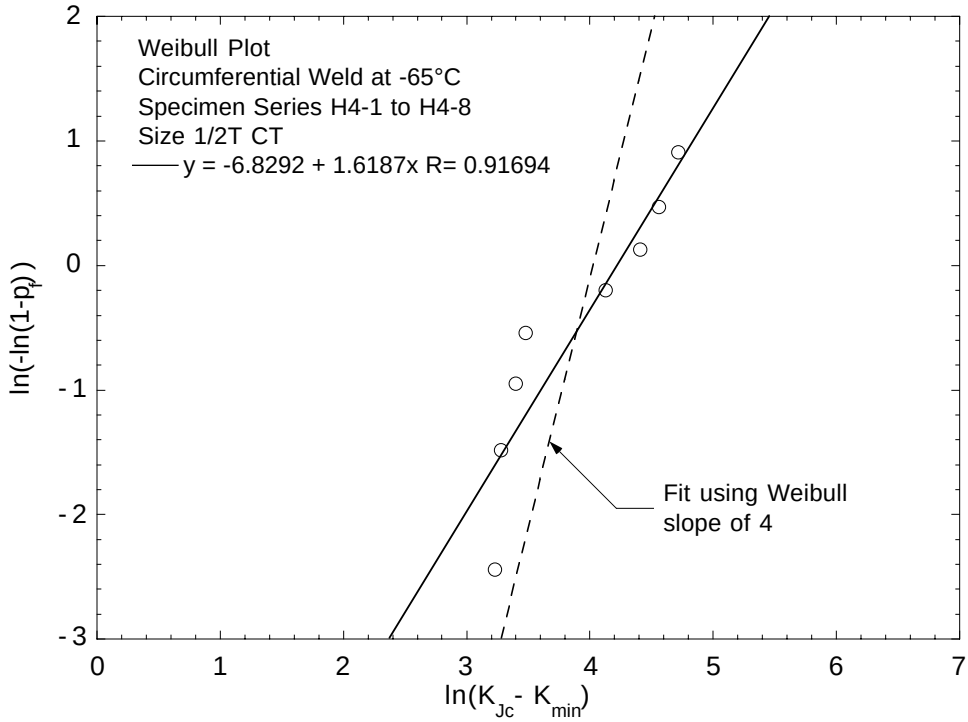

Fig. 4. Weibull plot of data for specimens taken from near weld mid-thickness showing fitted curves using Weibull slope of 4 and linear least squares.

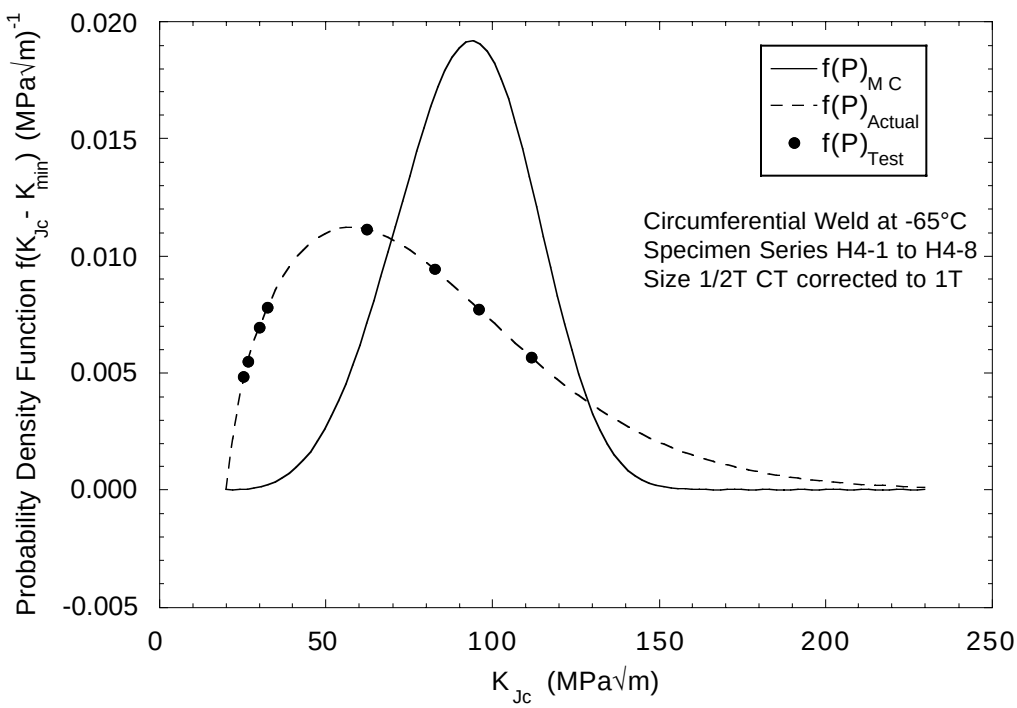

Fig. 5. Failure probability density function for circumferential weld CT data from specimens near weld mid-thickness showing distribution relative to Master Curve predicted distribution.

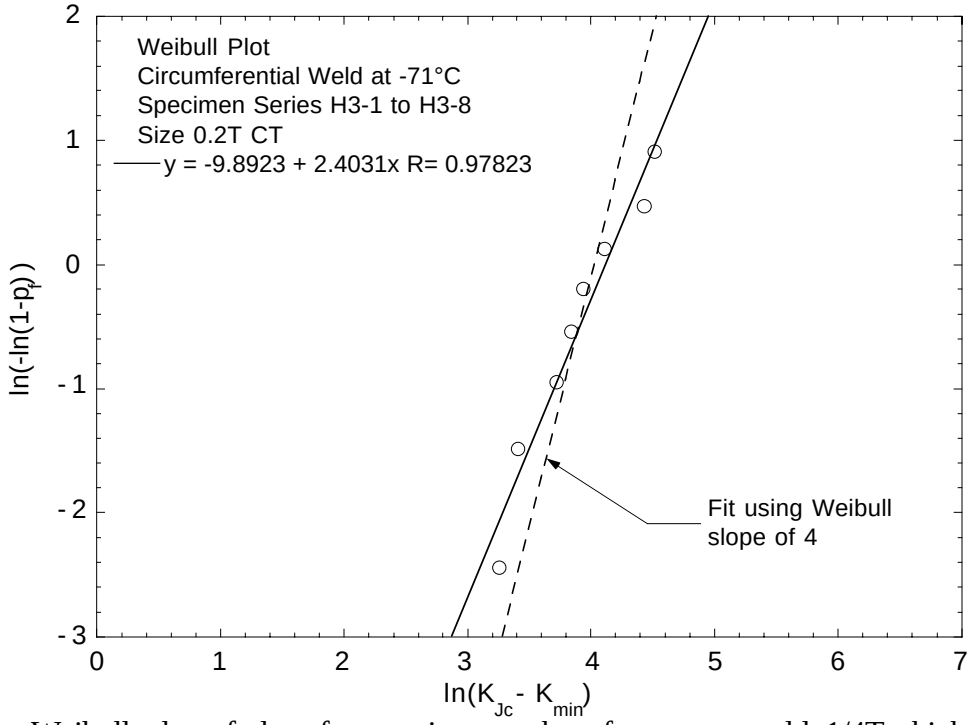

Fig. 6. Weibull plot of data for specimens taken from near weld 1/4T thickness location showing fitted curves using Weibull slope of 4 and linear least squares.

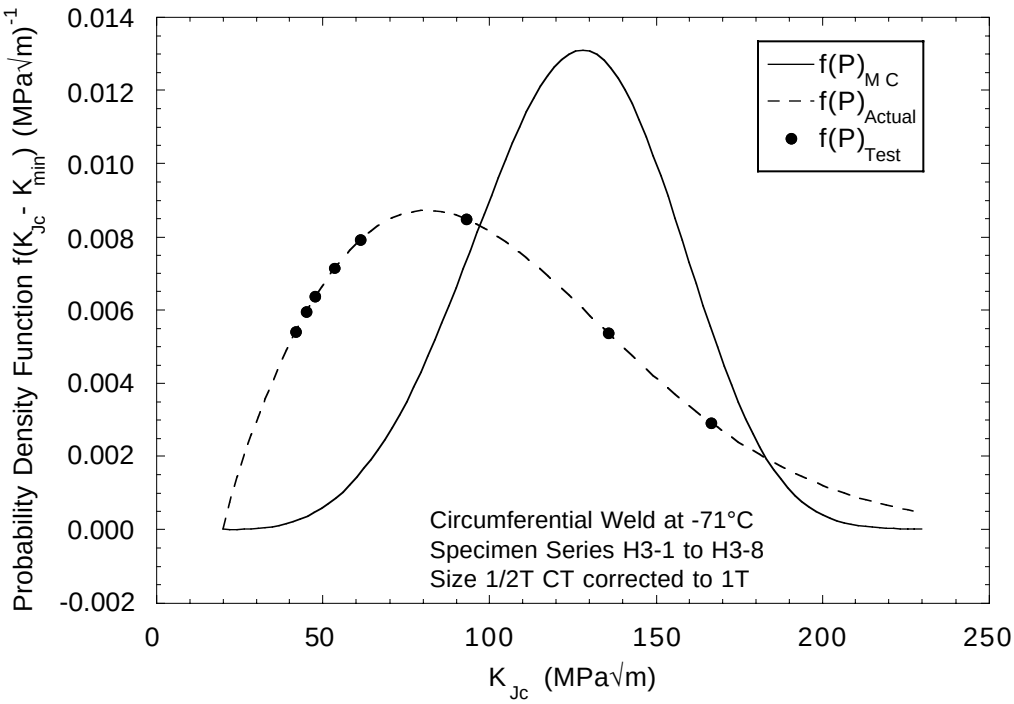

Fig. 7. Failure probability density function for circumferential weld CT data from specimens near weld 1/4t thickness location showing distribution relative to Master Curve predicted distribution.

testing CT specimens with dimensions ranging from smaller than to much larger than those of these specimens. But, to "calibrate" the observations, data from a companion effort on characterization of RPV plate material were evaluated. The specimens were 1/2T CT and were tested under the same conditions as the weld samples, i.e., the same fixture, test set-up, data acquisition and reduction, same personnel, etc. A set of data used, which is typical of the data generated in the plate characterization program, is shown in Table 4. Weibull and probability density plots of these test results are shown in Figs. 8 and 9. The data shown on a Weibull plot, Fig. 8, exhibit a slope of 3.1 which, within the scatter of normal data are, close to the Transition Range Standard value of 4. When the probability density function is determined using Eq. (2), there is good agreement between the calculated distribution and the predicted distribution. Considering that the results shown in Figs. 8 and 9 are typical of several different data sets for the plate material, the conclusion drawn is that the skewed behavior seen in Figs. 5 and 7 is a characteristic of the weld material. Such behavior then might be expected in other RPV welds, although limited data on one longitudinal weld were more in agreement with that of the base material.

Table 4 Summary of heat-treated Plate 14 toughness values for Block P10B specimens tested at –55°C.

Rank	Specimen Number	Test Temperature (°C)	K_{Jc} (1/2T) (MPa√m)	K_{Jc} (1T) (MPa√m)
1	56	-55	67.5	59.9
2	55	-55	69.5	61.6
3	53	-55	70.0	62.0
4	52	-55	81.0	71.3
5	49	-55	96.8	84.6
6	51	-55	107.4	93.5
7	50	-55	114.5	99.5
8	54	-55	131.8	114.0

The implications for the behavior of the circumferential weld material are shown in Figs. 10 and11, which are for the circumferential weld data sets discussed above. Values of T_o were determined, and the mean and 2 and 98 percent tolerance bound curves were calculated. First, the data sets are

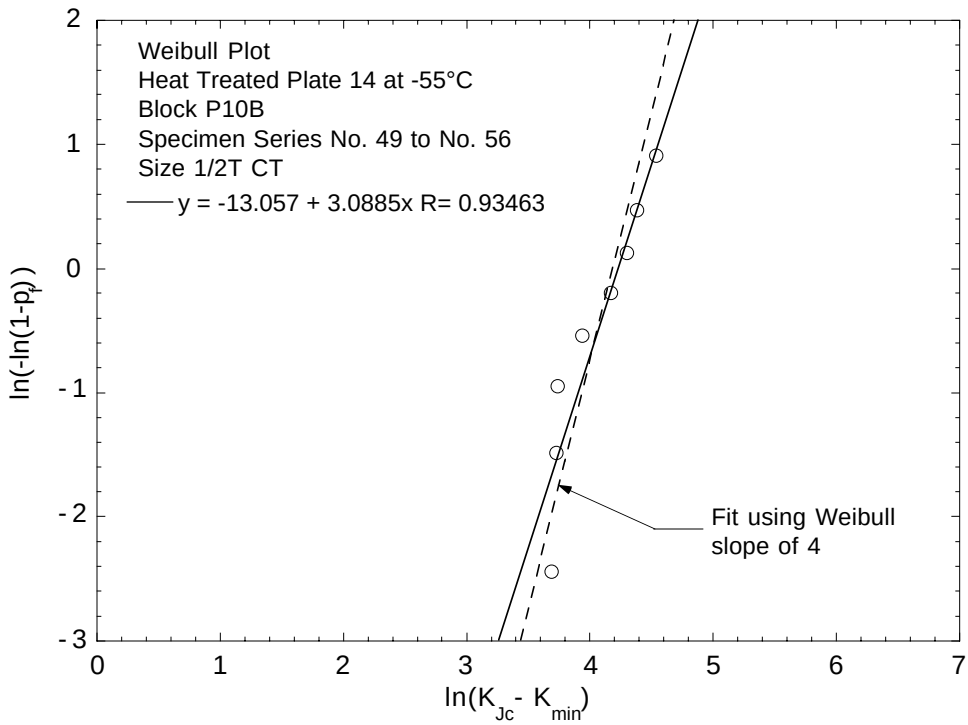

Fig. 8. Weibull plot of data for specimens taken from near mid-thickness of Plate 14 showing fitted curves using Weibull slope of 4 and linear least squares.

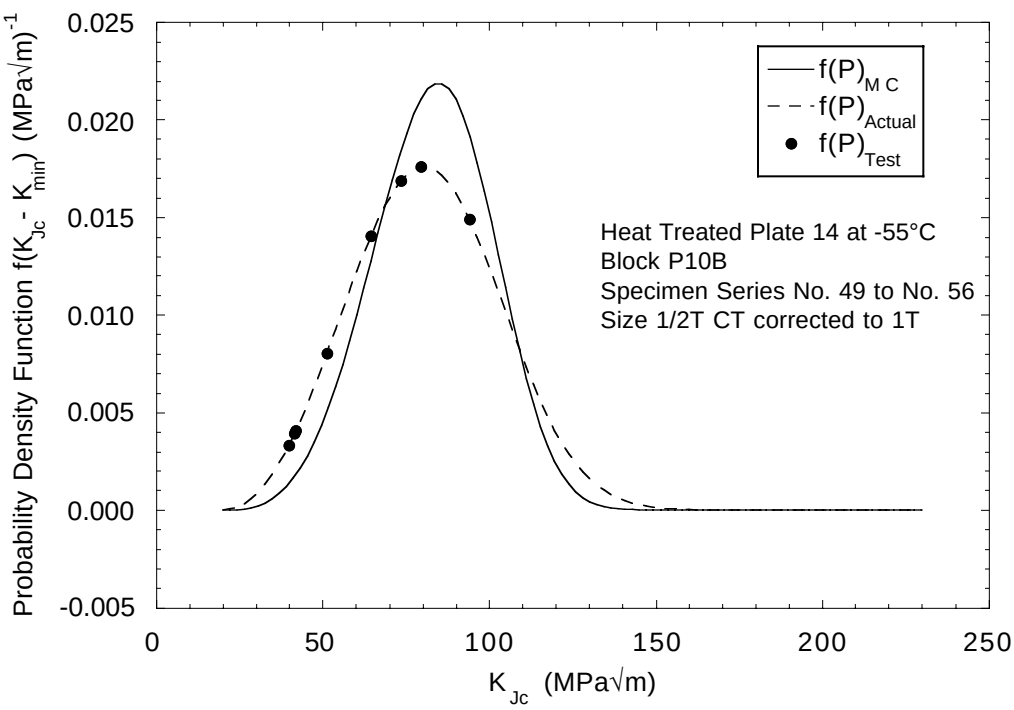

Fig. 9. Failure probability density function for CT data for specimens taken from near mid-thickness of Plate 14 showing distribution relative to Master Curve predicted distribution.

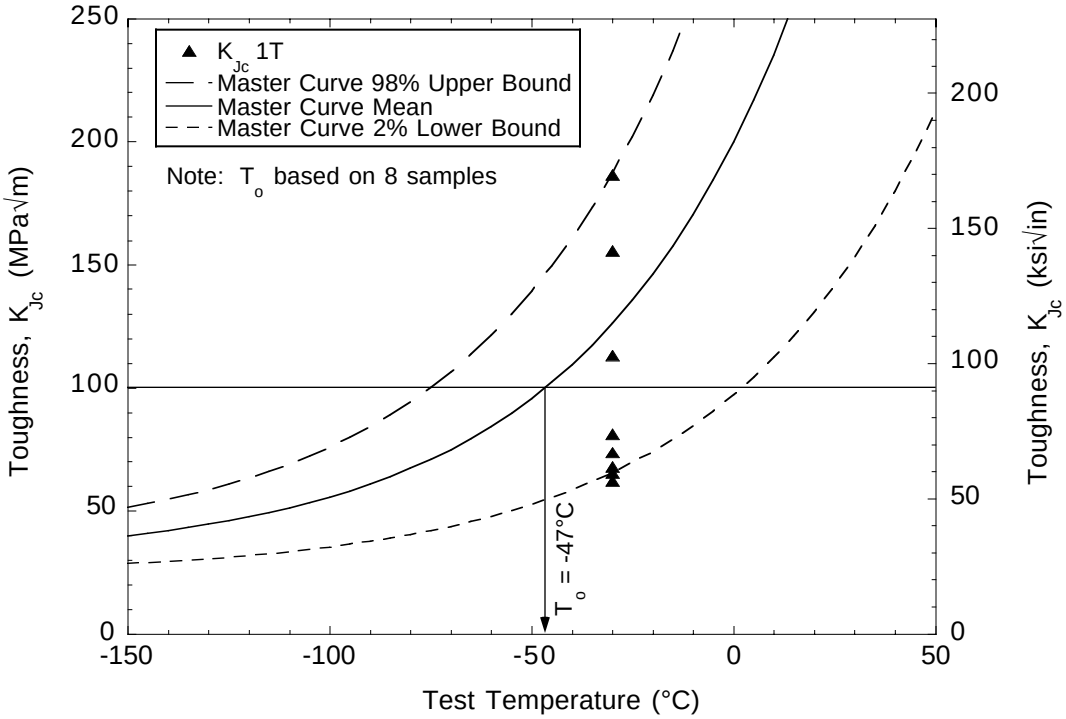

Fig. 10. Mean, 98 percent upper bound and 2 percent lower bound using Master Curve for CTS Series data at –30°C (see Fig. 3). Data are size-adjusted to 1T from original 1/2T size.

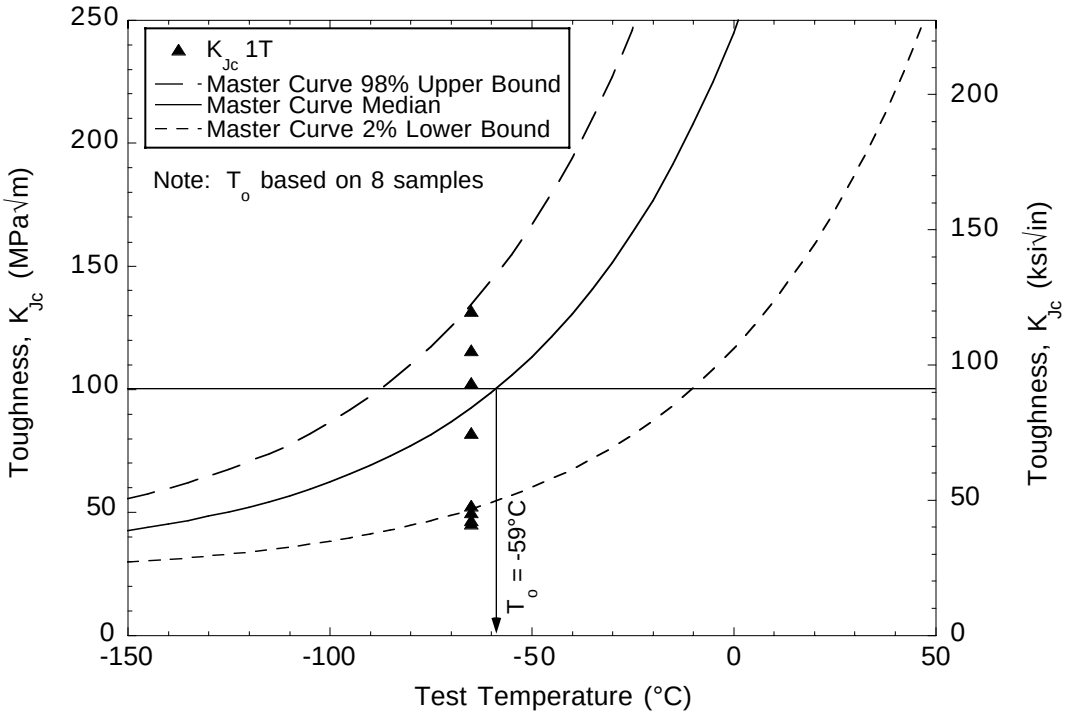

Fig. 11. Mean, 98 percent upper bound and 2 percent lower bound using Master Curve for Series H4-1 to H4-8 data at –65°C (see Fig. 4). Data are size-adjusted to 1T from original 1/2T size.

quite un-symmetric with respect to the mean curve, which is the implication contained within Figs. 3 and 5. Second, the data are not lower bounded by the 2 percent curve, which should be a very conservative lower bound. This alone would not be of concern except for the first observation. The end result is that the predictions developed using the Master Curve are non-conservative for these data sets.

Once again, for comparison, the same procedures were applied to the plate material data set shown in Figs. 8 and 9. The results are provided in Fig. 12. Visually, the Master Curve bisects the data set, and the 98 percent and 2 percent tolerance bound curves do an excellent job of bounding the data.

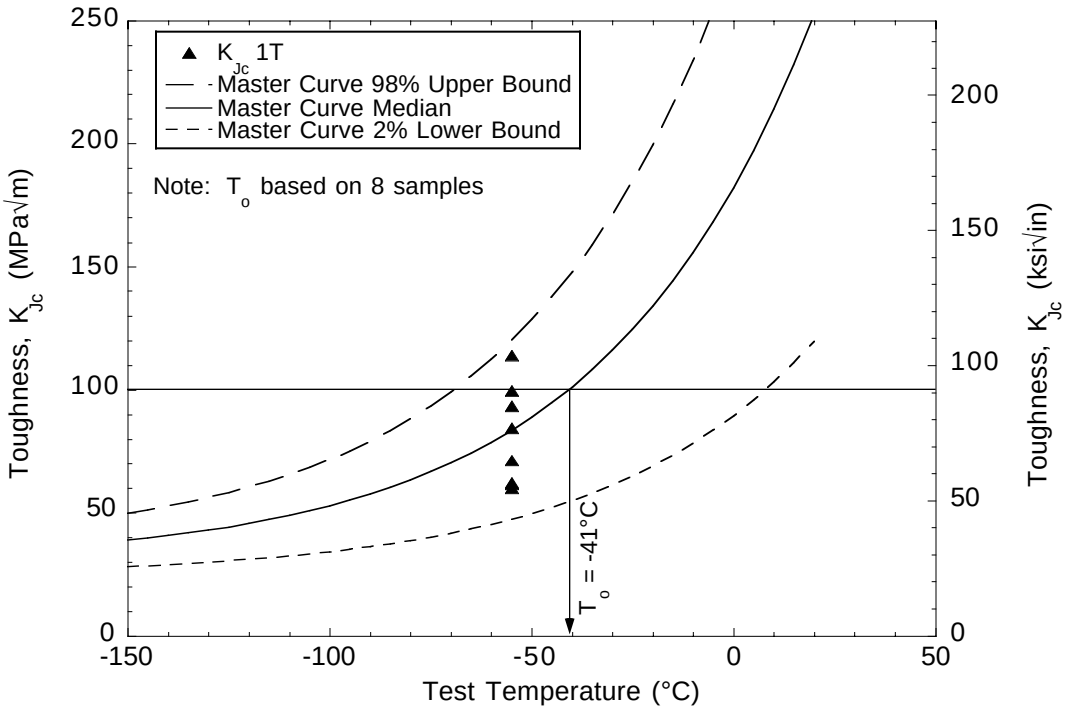

Fig. 12. Mean, 98 percent upper bound and 2 percent lower bound using Master Curve for heat-treated Plate 14 Specimen Series No. 49 to No. 56 data at –55°C (see Fig. 9). Data are size-adjusted to 1T from original 1/2T size.

These results indicated the need for additional consideration for cases where materials do not follow the trends utilized in development of the Transition Range Standard. This is particularly true for surveillance data since these are relatively small data sets for a given material tested at a single irradiation level. A means of addressing this need is discussed in the following sections.

2. Development of Governing Equation

Merkle [7] proposed a method to address the situation of skewed data sets not well described by Transition Range Standard procedures. He derived a simple closed-form equation for estimating T_o using the method of linear least squares as a basis. This derivation is repeated here and applied to several data sets in the next section of this report.

The derivation begins with the Master Curve equation.

$$K_{Jc(med)} = 30 + 70\exp^{[0.019(T_i - T_o)]} \quad , \tag{5}$$

where $K_{Jc(med)}$ = fracture toughness, MPa√m,

T_i = test temperature for the ith specimen, °C,

and T_o = Master Curve temperature indexing parameter, °C.

By rearranging Eq. (5) and then taking logarithms, a toughness estimating parameter, $\hat{y}_i$, at temperature T_i can be defined as,

$$\hat{y}_i = \ln\left[\frac{K_{Jc(med)} - 30}{70}\right] = 0.019T_i - b \quad , \tag{6}$$

where $b = 0.019T_o$. (7)

The corresponding parameter for a measured value of toughness at temperature T_i

$$y_i = \ln\left[\frac{K_{Jc(i)} - 30}{70}\right]. \tag{8}$$

Using the method of least squares, let

$$\frac{\partial}{\partial b}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 = 0, \tag{9}$$

which leads to

$$\sum_{i=1}^{n}(y_i - \hat{y}_i)\left(-\frac{\partial \hat{y}_i}{\partial b}\right) = 0 \ . \tag{10}$$

Since

$$\left(-\frac{\partial \hat{y}_i}{\partial b}\right) = 1, \tag{11}$$

it follows that

$$\sum_{i=1}^{n} y_i - \sum_{i=1}^{n} \hat{y}_i = 0 \quad . \tag{12}$$

Using Eqs. (6), (7), and (8), Eq. (12) becomes

$$\sum_{i=1}^{n} \ln\left[\frac{K_{Jc(i)} - 30}{70}\right] - 0.019\sum_{i=1}^{n} T_i + n(0.019T_o) = 0 \quad . \tag{13}$$

Solving Eq. (13) for T_o yields

$$T_o = \frac{\sum_{i=1}^{n} T_i - \left\{52.63\sum_{i=1}^{n} \ln\left[\frac{K_{Jc(i)} - 30}{70}\right]\right\}}{n} \quad , \tag{14}$$

and n = the number of specimens tested.

Note that Eq. (14) does not depend on a Weibull slope of 4, and can be used to estimate T_o for data obtained at either one or multiple temperatures. Application of this equation is discussed below.

3. Application of Governing Equation

When Eq. (14) is applied to the CTS data set shown in Table 1, a value of T_o = -24°C is determined. For this particular data set, since the highest toughness value was censored, a value of n = 7 was used (8 specimens tested). The failure probability density function associated with this new value of T_o was shown in Fig. 3. A comparison of the median and 2 percent lower bound curves calculated using the Master Curve T_o and this linearized T_o are shown in Fig. 13 superimposed on the data set. Figure 13 shows the median curve to be near the centroid of the data set with the 2 percent lower bound curve providing an envelope to all the data.

Two additional applications of this procedure were investigated. The first of these comprised two sets of specimens taken from the circumferential weld. There were 18 CTS Series specimens, 8 of which had been tested at –30°C, as discussed above. All these specimens were 1/2T CTs with T-S

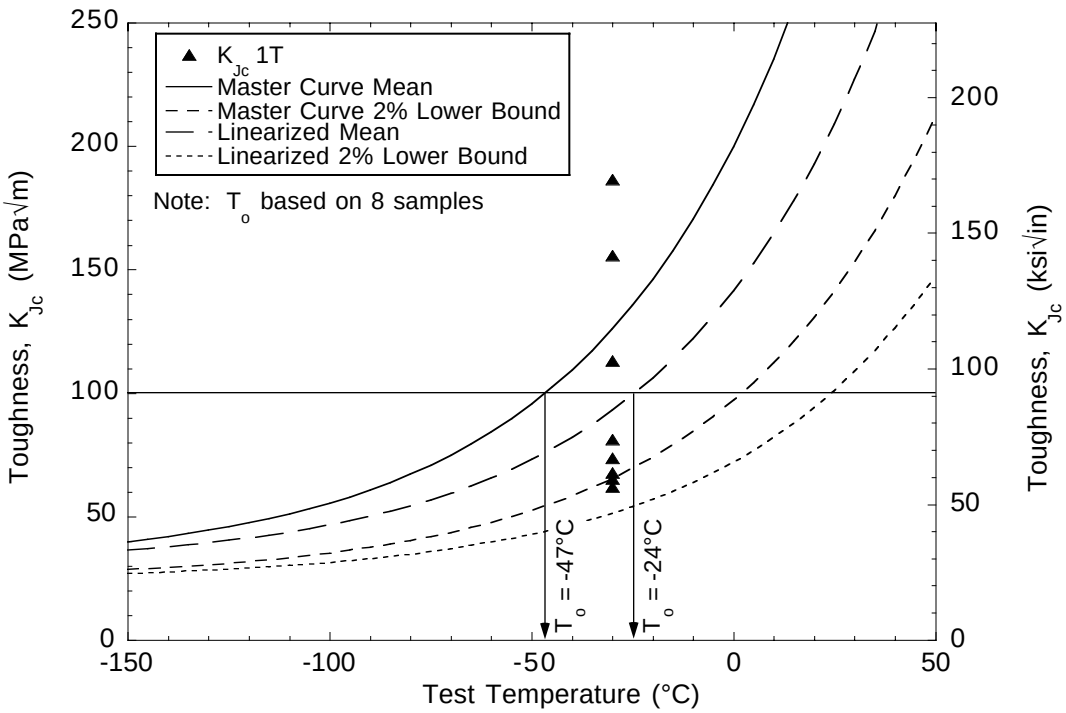

Fig. 13. Comparison of mean and 2 percent lower bounds using Master Curve and Linearized procedured for for CTS Series data at –30°C.

flaw orientation and were removed from a volume of weld metal approximately 150 mm long (circumferential direction) and 75 mm thick (through thickness direction). Thus all the specimens came from a contigious volume of material. These specimens were tested over the temperature range –150°C ≤ T ≤ 0°C. Added to the CTS Series was the set of H4 Series specimens which were also 1/2T CTs but had an L-S flaw orientation. Using the Method of Maximum Likelihood (MML), T_o for this combined data set was calculated to be –52°C. A plot of the Master Curve and the 2 percent lower bound are shown in Fig. 14. The 2 percent curve does not provide a lower bound to the data; 5 of the 26 data points fall below the 2 percent curve. Equation (14) was also used to calculate T_o from which a value of –40°C was determined. The 2 percent lower bound curve for T_o = -40°C bounds all the data, as shown in Fig. 14.

The second example consisted of 50 1/2T CT specimens from the HSST heat treated Plate 14. All these specimens were taken from near the mid-plane of the plate, were machined with an L-S flaw orientation, and were tested over the temperature range –150°C ≤ T ≤ 23°C. A total of 63 specimens yielded 61 valid K_{Jc} values and two that required censoring. Both the MML and the Linearized Least Squares (LLS) developed here were used to calculate values of T_o, as is shown in Fig. 15. The Master Curve gives a value of T_o of –51°C from which a 2 percent lower limit was

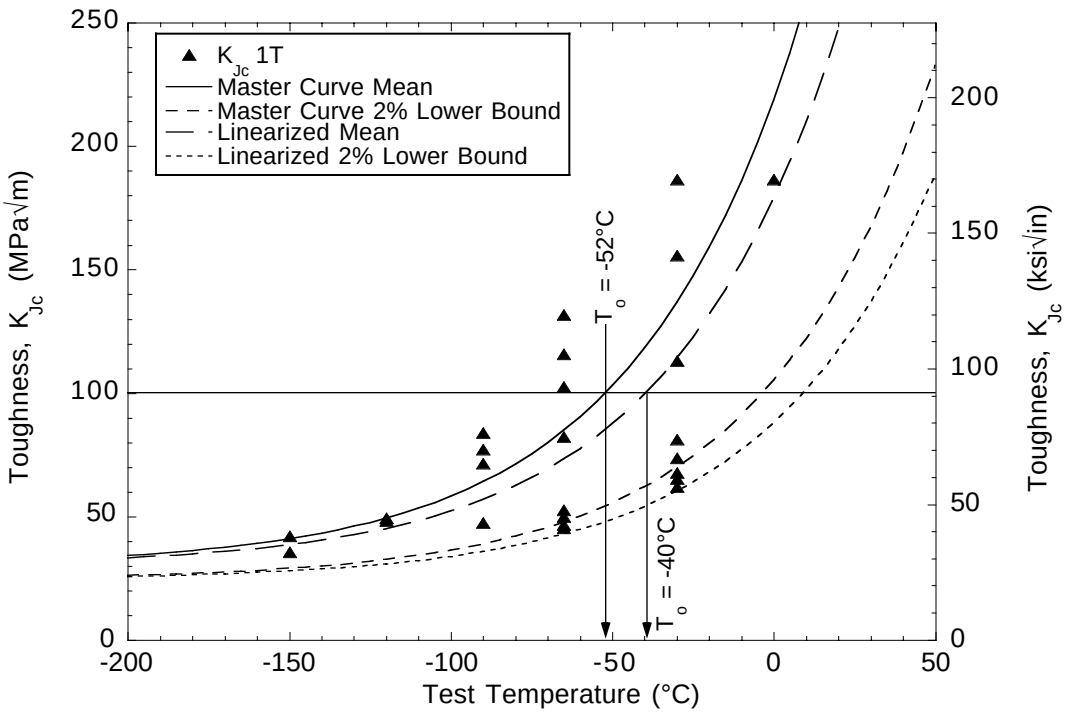

Fig. 14. Comparison of mean and 2 percent lower bounds for circumferential weld data using Master Curve and Linearized procedured. All specimens were 1/2T adjusted to 1T.

calculated. From a visual standpoint, the Master Curve does not provide a good mean curve to the data set. This is substantiated from a statistical standpoint by the fact that the 2 percent lower limit curve does not lower bound the data. One cause for this lack of fit is probably due to 32 of the 63 points all being at a single temperature, -55°C. This cluster of data tends to dominate the overall fit. The LLS equation was used to calculate at T_o value of –41°C. The resulting mean and 2 percent lower limit curves are also shown in Fig. 15. The mean curve appears to give a better representation to the data set, and the 2 percent curve provides a lower bound to all the data.

4. Discussion and Conclusions

The Master Curve methodology has been developed into a Standard by ASTM Subcommittee E08.08 and has been adopted for use by ASME Section XI. While the development of the Transition Range Standard has a rigorous mathematical basis and an extensive supporting material properties database, there appear to be cases of RPV ferritic materials whose fracture behavior deviates from the Weibull slope of 4 assumption. This is particularly the case when small numbers of data points are involved, such as would be the encountered in the testing of surveillance specimens. For the sets of data considered here, the Weibull slope of 4 appeared to be an upper bound in determination of T_o, resulting in predictions of mean and lower limit curves that were non-conservative relative to the data sets.

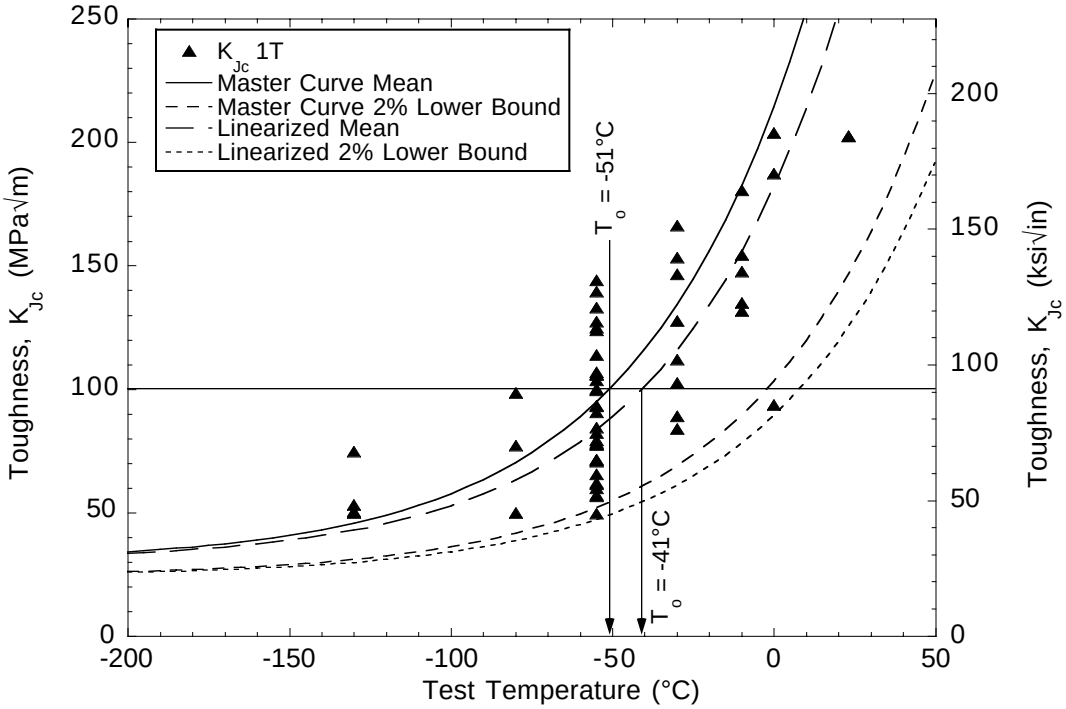

Fig. 15. Comparison of mean and 2 percent lower bounds for heat treated Plate 14 data using Master Curve and Linearized procedured. All specimens were 1/2T adjusted to 1T.

An alternate, simplified formulation has been proposed for use only in those cases where the basic assumption of large-scale uniformity of properties used in development of the Master Curve appears not to be supported, i.e., a Weibull slope of 4 does not fit the data or the resulting mean curve for T_o calculated using the MML procedure appears not to represent the mean of the data set. This latter occurrence may seem very subjective since it requires, to some extent, a visual interpretation of the fit to the data set. However, this may lead to data falling below the selected lower bound. The equation developed provided good agreement with the data sets analyzed. A 2 percent lower tolerance limit curve bounded the data without introduction of undue conservatism.

While these results are based on only a few data sets, these data represent actual RPV materials, and, as such, comparable behavior would be expected in other similar materials. This behavior may be limited to RPV circumferential welds where a back-fill weld is used at the inside surface. The reasons for the observed behavior is not known, just that it existed in one RPV circumferential weld. It is recommended that other RPV circumferential welds be investigated if material can be obtained. The additional data sets can then be used to further refine the LLS analytical model presented here.

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