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A Comparison of Weibull and β_{Ic} Analysis of Transition Range Fracture Toughness Data

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Abstract

Characteristics of extremal statistics that are used to predict size effects on cleavage fracture toughness in the transition range were explored. A 533 grade B steel base and weld metals were tested using compact specimens ranging in size from 1/2TC(T) to 8TC(T) and with sufficient replication in some cases to provide good fits to Weibull distributions. The classical specimen size effect on data scatter and median K_{Jc} toughness at a given test temperature was observed in the low- to mid-transition range. These effects were well predicted with extremal statistics. However, the same model is not applicable on the lower shelf, and it also becomes extremely weak and unreliable in the mid- to high-transition range. The Irwin β_c-β_{Ic} relationship was also explored as a model and was found to predict similar size effects. The predictive characteristics of the latter seemed better suited to deal with the diminution of size effects in the near- to low-shelf toughness range. In the rising toughness part of the transition, the predictive characteristics were about the same as the statistical model up to where β_c (β_{Jc} in this study) of the baseline (small specimen) data were π or less. This work could be used in the establishment of a framework for transition temperature test criteria. Upper- and lower-bound β_{Jc} criteria could be used to define optimum conditions for the application of either of the aforementioned models. For surveillance programs, sensible rules should be specified as to specimen size requirements and numbers of specimens to be tested in order to apply these analytical models. Another need would be the definition of a procedure for the Weibull distribution fitting. The present report suggests items to be considered for requirements in application of these predictive techniques.

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Acknowledgments

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Nomenclature

1/2TC(T)	Compact specimen of 1/2-in. thickness
1TC(T)	Compact specimen of 1-in. thickness
2TC(T)	Compact specimen of 2-in. thickness
4TC(T)	Compact specimen of 4-in. thickness
8TC(T)	Compact specimen of 8-in. thickness
P_f	Probability of failure for an arbitrarily chosen specimen at a chosen J or K level of loading
Θ	Scale parameter
b	Weibull slope
K_{min}	Lower bound toughness level
N	Size ratio
γ	Dimensionless constraint parameter
σ_{ys}	Material yield strength
σ_{uts}	Material ultimate strength

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D. E. McCabe

Introduction

The fact that section size has an effect on the transition temperature of ferritic steels has been known for several decades, but aside from empirical observations of constraint effects (Pellini and Puzak, 1963; Rolfe and Barsom, 1977) no rationale in the form of analytically based models were forthcoming until recently. Early application of statistical practices lacked a physical concept that could serve as the basis for an improved understanding of what was already known empirically. Recently, the principle of extreme value statistics has been shown to provide the needed model, and Weibull analysis has been applied to the model to characterize data distributions. Good accuracy of determination requires considerable replication of tests, however. In the current project, over 120 compact specimens of A 533 grade B, class 1, base metal in sizes ranging from 1/2T to 4T and A 533 grade B, weld metal ranging from 1T to 8T have been tested in the transition range with sufficient replication at some of the test temperatures for viable statistical analysis. Hence, the methods that have recently been proposed to predict trends in mean toughness values due to specimen size can be accurately evaluated. The test specimen matrix, steel chemistries, and tensile properties for the materials tested are given in Tables 1 through 3, respectively. The toughness parameter to be used herein is K_{Jc}, which is defined as K_J at onset of cleavage and is derived by conversion from J_c. This report will evaluate Weibull data fitting methods and extremal (weakest link) statistics that are used to predict specimen size effects. Also, limited data are available for studying the effect that slow-stable crack growth can have on the two and/or three parameter Weibull models. An alternative predictive model, the β_{Ic} fracture toughness adjustment to measured values of K_{Jc}, that is deterministic in general use and uses a constraint based argument, will also be discussed.

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Weibull Analysis

The rationale to apply extremal statistics to transition temperature behavior was developed by Landes and Shaffer (1980). Using a two-parameter Weibull model, they demonstrated how data from small specimens (1T compact) could be used to characterize the fracture toughness distribution of larger specimens (4T compact specimens). The scatter between replicate specimens was proposed to be governed by occasional weak points or sources for brittle cleavage crack initiation distributed randomly throughout the microstructure. Small specimens have less crack front in direct proportion to the compact specimen thickness, and hence contain proportionately fewer inclusions of critical size. Larger specimens are more likely to have lower overall toughness and narrower scatter bands because of the greater opportunity for having critical imperfections. The fracture toughness was expressed in terms of J_c and the distribution for small

Table 1. Test materials and number of replicate specimens used in statistical analysis

Material	Test temperature (°C)	Number of specimens					
		1/2TC(T)	1TC(T)	2TC(T)	4TC(T)	6TC(T)	8TC(T)
A 533 grade B class 1, Plate 13A	−150	18	17	12			
	−75	20	26	12	6		
	−18		6	2			
	24		5				
A 533 grade B welds							
72W	10			4	2	2	2
73W	−5			4	2	2	2

Table 2. Nominal chemical compositions for A 533 grade B class 1 base plate and two welds

Material[a]	Composition (wt %)									
	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	V
A 533 grade B class 1, Plate 13A	0.25	1.34	0.35[b]	0.40[b]	0.29		0.55	0.52		
A 533 grade B welds										
72W	0.093	1.66	0.006	0.006	0.044	0.27	0.60	0.58	0.23	0.003
73W	0.098	1.56	0.005	0.005	0.045	0.25	0.60	0.58	0.21	0.003

[a]ASTM specifications for A 533 grade B class 1.

[b]Maximum.

Table 3. Room temperature yield and tensile strengths of test materials

Material	Room temperature[a] Strength, MPa (ksi) Yield	Ultimate
A 533 grade B class 1, Plate 13A	444 (64.4)	600 (87.0)
A 533 grade B welds		
72W	499 (72.4)	608 (88.2)
73W	490 (71.1)	600 (87.0)

[a]For temperatures other than room, use the following: $\sigma_y = 374.9 + 59.9 \exp(-0.0079328T)$ MPa T (degrees Celsius).

specimens was fit by the following Weibull model:

$$P_{f1} = 1 - \exp[-(J/\Theta_1)^b] , \quad (1)$$

where

P_{f1} = the probability that an arbitrarily chosen 1T specimen will have $J_c < J$,
Θ_1 = scale parameter ($J_c = \Theta_1$ when $P_{f1} = 0.632$), and
b = Weibull slope.

The data fitting constants are Θ_1 and b. It was assumed that the Weibull slope would be independent of specimen size and perhaps independent of test temperature. It also was assumed that constraint does not vary significantly among specimen sizes so long as the testing is performed in the lower part of the transition range. Then, if one were to test 4T specimens, the probability for J_c instability prior to reaching toughness level J, must be given by:

$$P_{f4} = 1 - \exp[-(J/\Theta_4)^b] . \quad (2)$$

For a 4TC(T) specimen, $\Theta_4 = \Theta_1/(N)^{1/b}$, where N is size ratio (4/1).

The above model had predicted mean J_c values for 4T specimens of ASTM A 471 steel quite accurately at two of three temperatures in the transition range. The Weibull slope (on J_c) was 5. A weakness with the two-parameter Weibull model not discussed (Landes and Shaffer, 1980) was that the lower bound of predicted fracture toughness approached zero as specimen size tended to infinity. Therefore, in a later publication, the three-parameter model with a lower-bound value, J_{min}, was proposed (Landes and McCabe, 1984). The lower-bound value can be determined when and if the data show nonlinear characteristics when plotted as two-parameter data on Weibull graph paper. The procedure for determining J_{min} is trial and error, based on the replacement of J_c with ($J_c - J_{min}$) on the abscissa, looking for the J_{min} value to establish optimum linearity.

$$P_f = 1 - \exp\{-[(J - J_{min})/(\Theta - J_{min})]^b\} , \quad (3)$$

where J is the independent variable, and P_f is the dependent variable.

Figure 1 was used to illustrate the principle as applied to 1/2T compact specimen data of A 508 steel published by Landes and McCabe (1984). In

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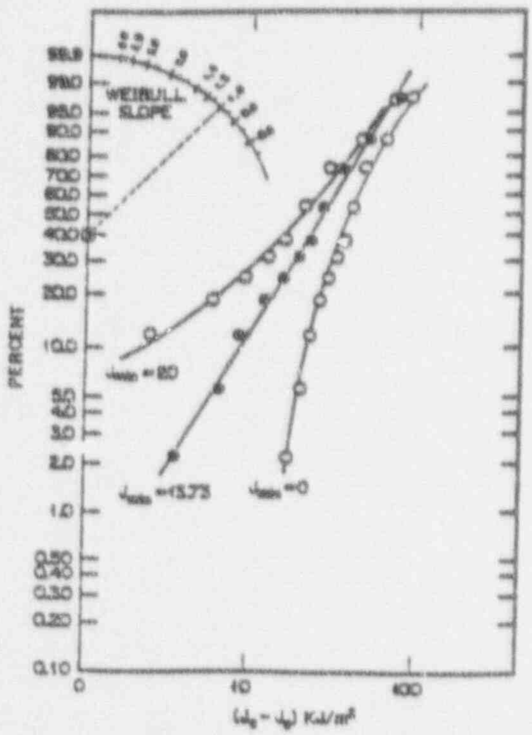

Figure 1. Cumulative distribution function versus $(J_c - J_o)$ for A508 class 3 steel at -59°C.

this context, $(J_c - J_{min})$ is the independent variable, and constants $\Theta_{1/2}$ and b become the dependent variables. Seven examples of three-parameter determinations (Landes and McCabe, 1984) gave four apparently reasonable J_{min} results for lower-bound toughness predictions. The three doubtful predictions were from small data sets containing only four to seven values, and these were far too few to expect a good measure for nonlinearity of a data population. The general form expressed in terms of K is:

$$P_f = 1 - \exp\{-[(K - K_{min})/(K_0 - K_{min})]^b\} \qquad (4)$$

and $(K_o - K_{min})$ is the scale parameter.

Wallin (1984) has performed Weibull analysis on numerous data sets (large and small). He has concluded that toughness data expressed in terms of K should have a fixed Weibull slope of b = 4 and that K_{min} should be about 20 MPa√m. Implicit in this argument is that all J_c distributions should have a Weibull slope of b = 2. This conclusion has been generally supported by others (Mudry 1987; Anderson, 1989). Accepting a fixed Weibull slope of 4, it follows that when $P_{fs} = 0.632$, $(K_J - K_{min})$ is equal to the scale parameter $(K_0 - K_{min})$. Knowing this, the following equation can be established to transform K_{Jc} data from one specimen size, B_o, to another size, B_x:

$$K_{Bx} = K_{min} + (K_{B1} - K_{min})(B_o/B_x)^{1/4}, \qquad (5)$$

where

K_{min} = lower bound fracture toughness,
B = thickness of the specimen, and
K_{Bx} = K_{Jc} for a specimen of thickness B_x.

Wallin has used the above relationship to collapse K_{Jc} data from several specimen sizes to one specimen size to enlarge data replication. Obviously, the accuracy of this normalization depends on the postulate that there is a single Weibull slope for all ferritic materials that is invariant over all specimen sizes and test temperatures, and that K_{min} is also invariant over all thicknesses and temperatures.

The fitting of Equation 4 to test data became inaccurate at the high end of the transition range because of the two competing fracture mechanisms of brittle cleavage fracture and ductile slow-stable tearing. Stable crack growth produces multiple effects, some of which retard cleavage and some of which promote it. Stable crack growth leads to reduced constraint (McCabe, Ernst, and Landes, 1985) by causing crack tip blunting, which weakens the stress concentration that promotes cleavage. Stable crack growth also increases the volume of material subjected to high stress, as well as causing elevated crack tip strain rates, both of which promote cleavage. The Weibull distribution fit to data is hampered by this competition, with the result being a slope change above a certain toughness level (see Figure 2). Onset of slow-stable crack growth effectively develops at or near J_{Ic} and this has been identified as a possible cause of the bilinear trend (Anderson, 1989). An explanation is that with crack

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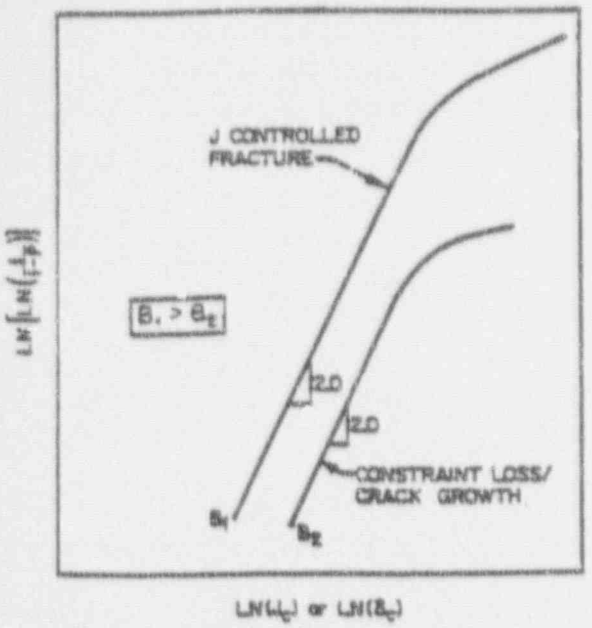

Figure 2. **Schematic of slope change in Weibull trends due to crack growth and constraint relaxation.**

growth the volume of material exposed to the intensified crack tip stress is increased out of proportion to the crack front dimension, B. This increases the opportunity of exposing cleavage-crack activation sources, and K_{Jc} distributions will no longer scale in the same way with specimen size. Some analytical models have been developed to modify K_{Jc} toughness numbers to account for crack growth (Bruckner and Munz, 1984; Wallin, 1989). Interestingly, these models estimate higher fracture toughnesses and lower cleavage probability due to stable crack growth. Of the two options cited (Bruckner and Munz, 1984; Wallin, 1989), we will examine the "simplified one" proposed by Wallin. This one gives corrections that are comparable to the more complex models and has the advantage of not having to characterize the R-curve. Crack growth is normalized by a plastic zone size related parameter according to the following equation:

$$K_{Jc}' = K_{Jc}[1 + \Delta a/(\gamma/2)(K/\sigma_{flow})^2]^{1/4} , \qquad (6)$$

where γ is a dimensionless constraint parameter of magnitude defined by the distance from the crack-tip to the point of maximum local crack tip stress. Values of the distance to the point of maximum stress, are a function of the material flow strength [$\sigma_{flow} = (\sigma_{ys} + \sigma_{uts})/2$], and this has been defined analytically by McMeeking (1977). A few of the specimens in the present series were tested at relatively high temperatures (−18 and 24°C) and showed slow-stable crack growth before the onset of cleavage. The impact of Equation 6 on correcting these data will be reported here.

β_{Ic} Analysis

Another perspective on the K_{Jc} data scatter and specimen size effect phenomena is to consider that the increase in scatter along the rising part of the transition curve for small specimens is due to a decrease in the hydrostatic component of stress (reduction in constraint). This viewpoint is supported by Figure 3, taken from Landes and McCabe (1984). Specimens of A 533 grade B steel with thicknesses of 0.4, 1, 2, and 4 in. were tested through a transition range, and data scatter, presented in bar graph format, was shown to be a definable function of specimen size and test temperature. The thinner specimens tend to lose constraint and develop data scatter at the temperature where plastic deformation in the form of cross slip first develops. Thicker specimens require greater ductility for proportional cross slip, and essentially similar data scatter characteristics are delayed to higher temperatures. To relate high- and low-constraint toughness, Irwin (1960) developed a semiempirical relationship using test data on high strength materials. Merkle (1984) investigated the potential of this expression for use on structural materials:

$$\beta_{Jc} = \beta_{Ic} + 1.4\ \beta_{Ic}^3 , \qquad (7)$$

where

$\beta_{Ic} = (1/B_s)(K_{Ic}/\sigma_{ys})^2$,
$\beta_{Jc} = (1/B)(K_{Jc}/\sigma_{ys})^2$, and
B_s = thickness required for plane-strain constraint.

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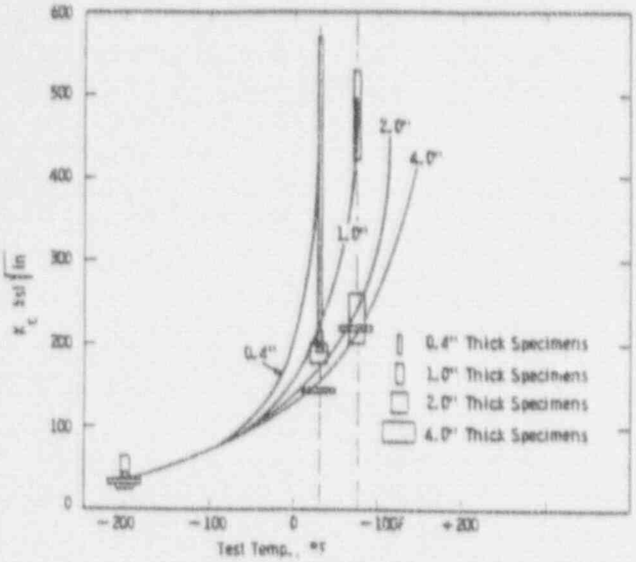

Figure 3. K_{Jc} instability versus test temperature separated by thicknesses scatter band of K_{Jc} instabilities.

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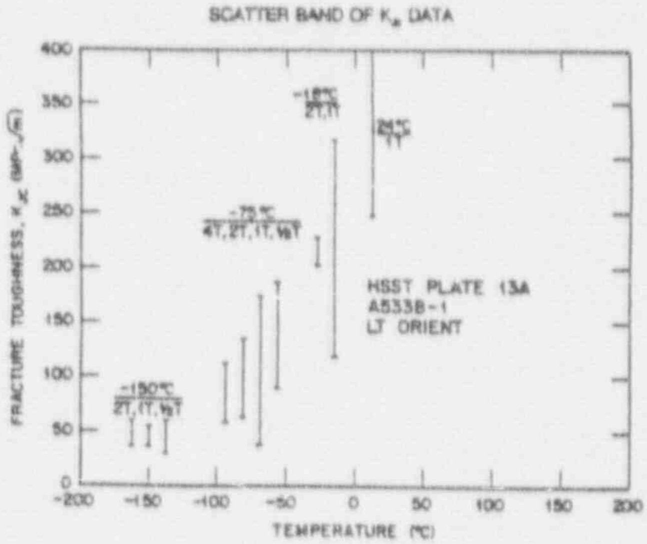

Figure 4. Scatter bands of K_{Jc} data on A 533 grade B, class 1.

This model also predicts a change in data scatter due to specimen size effects as will be demonstrated in a subsequent section. The β_{Jc} value is determined on each K_{Jc} datum and is then used to estimate a full constraint value of K_{Jc}, intended to be an estimate of K_{Ic}. Either an iterative technique or a preformulated solution for the cubic equation can be used. Scattered K_{Jc} values due to constraint loss will not collapse to a single plane-strain toughness value, but instead will generate a new toughness distribution for high constraint. This suggests that the micromechanics mechanisms that serve as the rationale for extremal statistics could be argued as the basis for a constraint based model as well.

Program Scope

The numbers of specimens, specimen sizes, and test temperatures are given in Table 1. All specimens were proportionally dimensioned compacts with relative initial crack size a/W nominally at 0.5. Data scatter observed here is shown in Figure 4. The dependence of data scatter on specimen size previously pointed out is most evident at −75°C. It can be noted that specimen size effects tend to vanish on the lower shelf and perhaps become highly obscured at high toughness levels of the transition curve. To add further instructional evidence to these observations, data from the ORNL Heavy-Section Steel Irradiation (HSSI) Program Fifth Irradiation Series were analyzed (Nanstad et al., 1990). Extremal statistics were applied where there was sufficient replication to develop Weibull-related implications. The materials were two A 533 grade B submerged-arc weld metals of identical chemical composition except for copper content (Table 2).

Extremal Statistics

Three-Parameter Weibull Fitting

Except for the initial two-parameter work of Landes and Shaffer (1980), cleavage instability data have been fitted principally using the three-parameter Weibull model. Considerable latitude has been employed in setting either one or two of the three parameters to fixed values while still achieving what seems to be suitable results. Usually J_c is calculated experimentally, and the corresponding elastic-plastic stress intensity value at onset of cleavage fracture is obtained from J_c using the following:

$$K_{Jc} = \sqrt{J_c E} \,. \qquad (8)$$

Wallin (1989) and others have shown, both through fundamental microstructural statistical modeling and Weibull fitting of sufficiently replicated test data, that the slope parameter on K_{Jc} data for all intents and purposes is invariant at four. This suggests that the basic shape of data distributions is independent of test temperature and specimen size, and because Gaussian slope is about 3.2, the shape is very close to that of the normal Gaussian distribution. This assertion is tested on the A 533 grade B base metal data in Figures 5 through 13 using three adjustable parameters; the scale parameter K_o, K_{min}, and the Weibull slope, b, or two adjustable parameters with a fixed Weibull slope. These data cover four specimen sizes and four test temperatures. Individual datum is presented in Appendix A. Weibull fitting to the data for the highest test temperature (24°C) should be discounted as a viable example for lack of sufficient replication. Table 4 lists the two adjustable parameters, K_o and K_{min} from the fixed slope model and the correlation coefficients from the linear regression determinations. In this program, K_{min} cannot be set to negative values so that when the best fit is zero, the result is, in effect, a two-parameter Weibull fit, for which there were two cases. From these plots and tabulations, it appears that the fixed Weibull slope of 4 can be fitted quite well to almost all of the data throughout the transition temperature range of K_{Jc} behavior. However, K_{min} is used principally as the distribution

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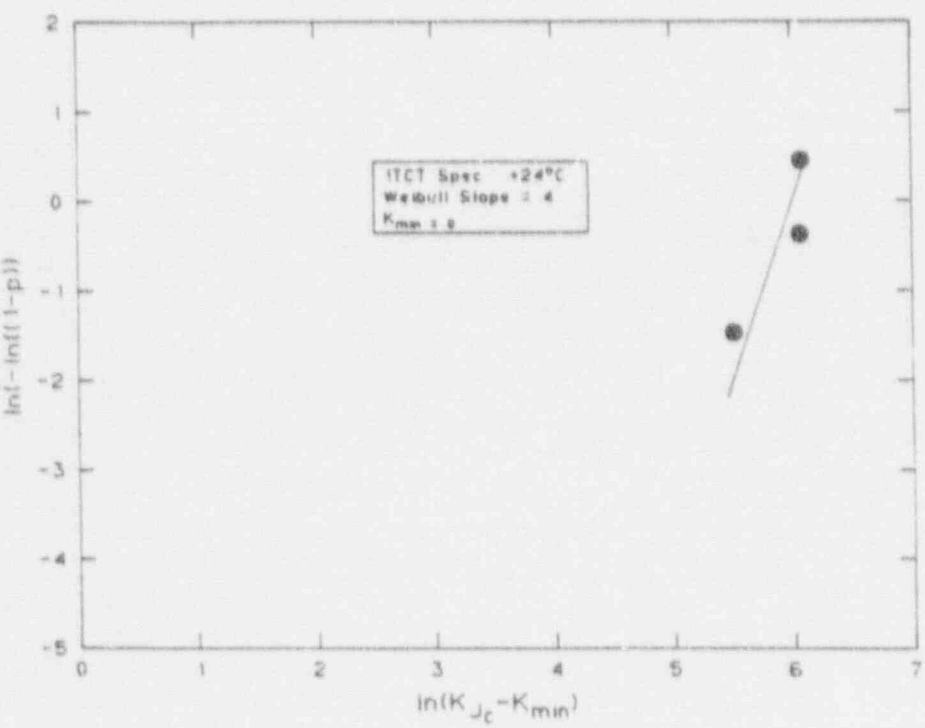

Figure 5. Weibull fit to K_{Jc} values determined at 24°C.

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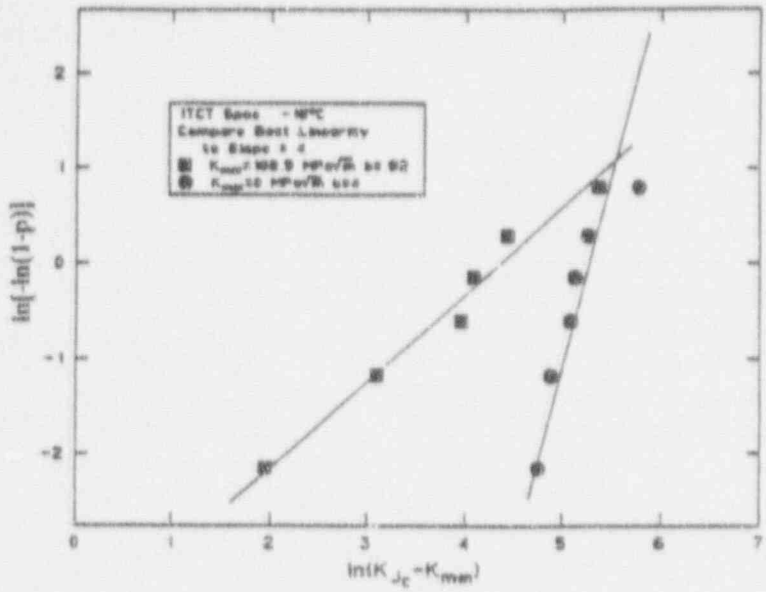

Figure 6. Weibull fits comparing best linearity to fixed slope of 4, 1TC(T) at -18° C.

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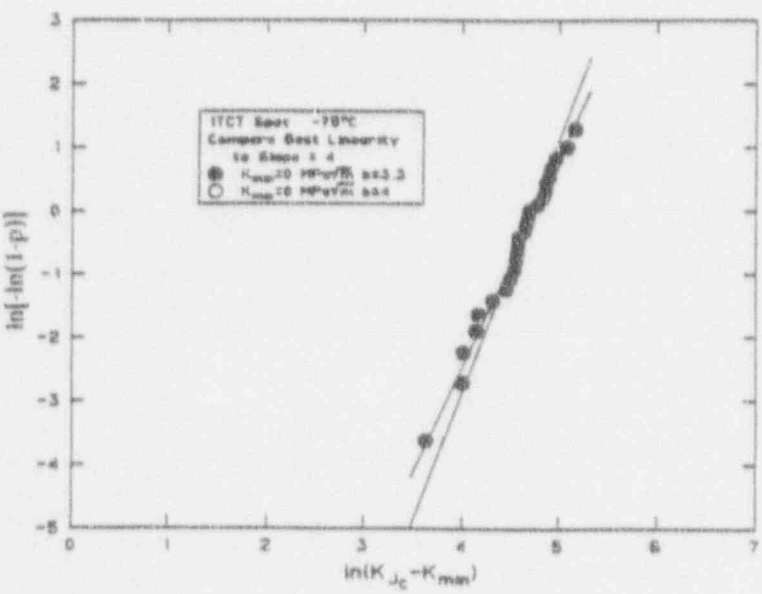

Figure 7. Weibull fits comparing best linearity to fixed slope of 4, 1TC(T) at -75° C.

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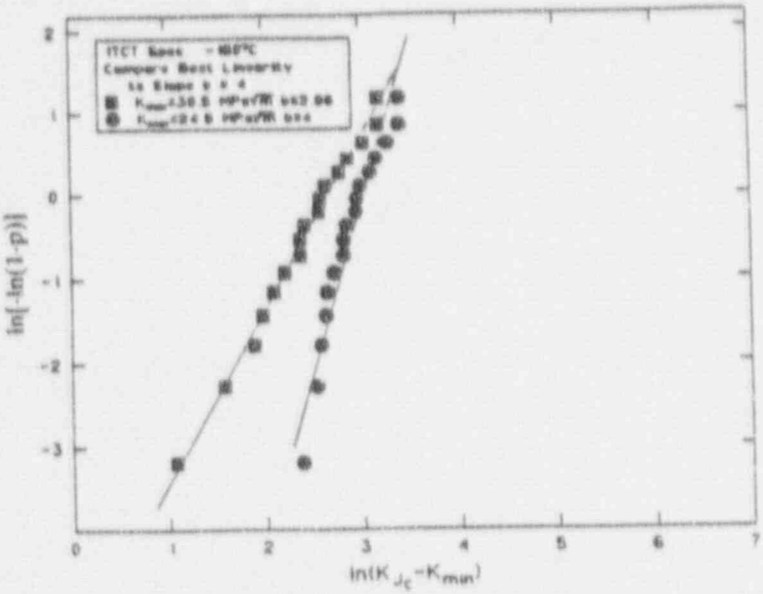

Figure 8. Weibull fits comparing best linearity to fixed slope of 4, 1TC(T) at -150°C.

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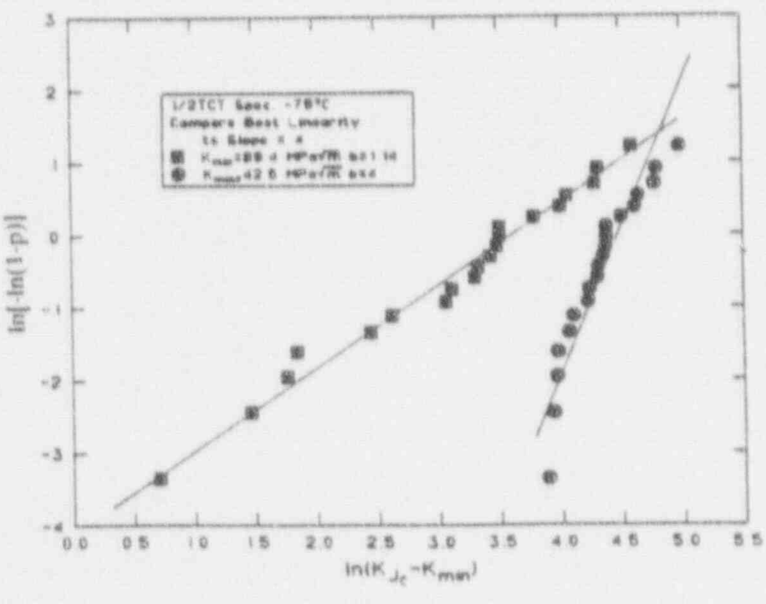

Figure 9. Weibull fits comparing best linearity to fixed slope of 4, 1/2TC(T) at -75°C.

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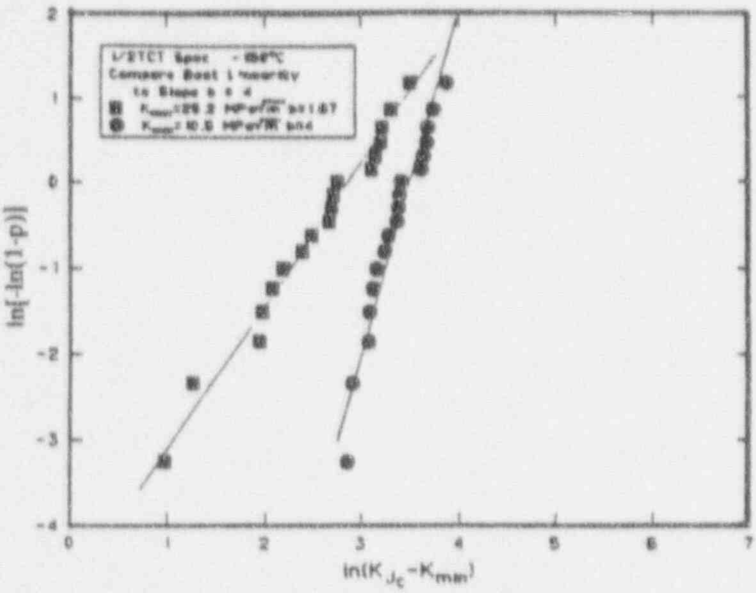

Figure 10. Weibull fits comparing best linearity to fixed slope of 4, 1/2TC(T) data at −150° C.

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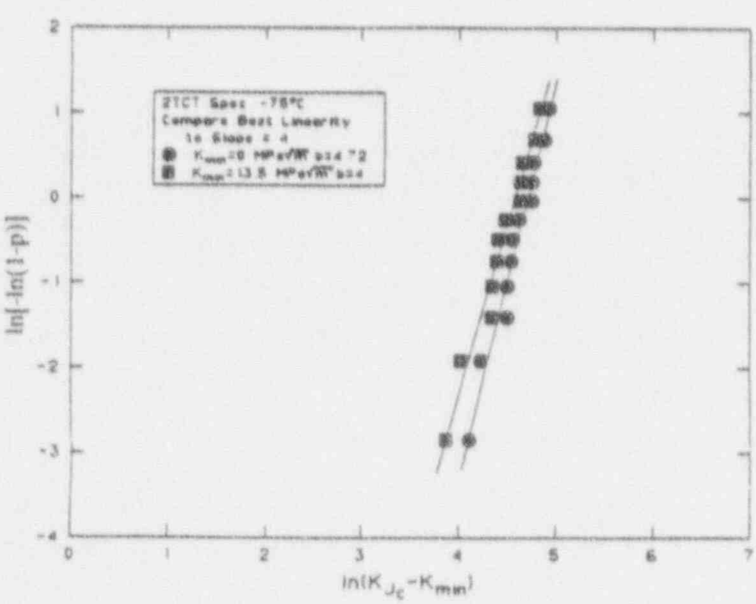

Figure 11. Weibull fits comparing best linearity to fixed slope of 4, 2TC(T) data at −75° C.

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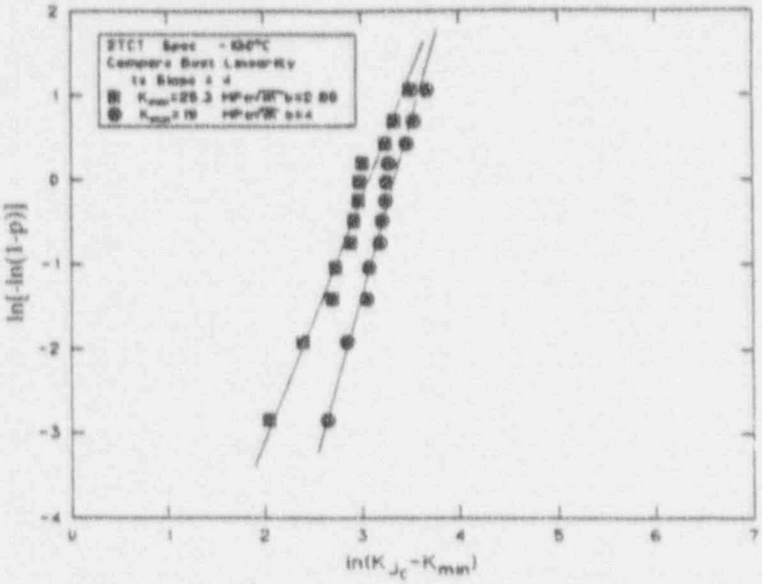

Figure 12. Weibull fits comparing best linearity to fixed slope of 4, 2TC(T) data at −150° C.

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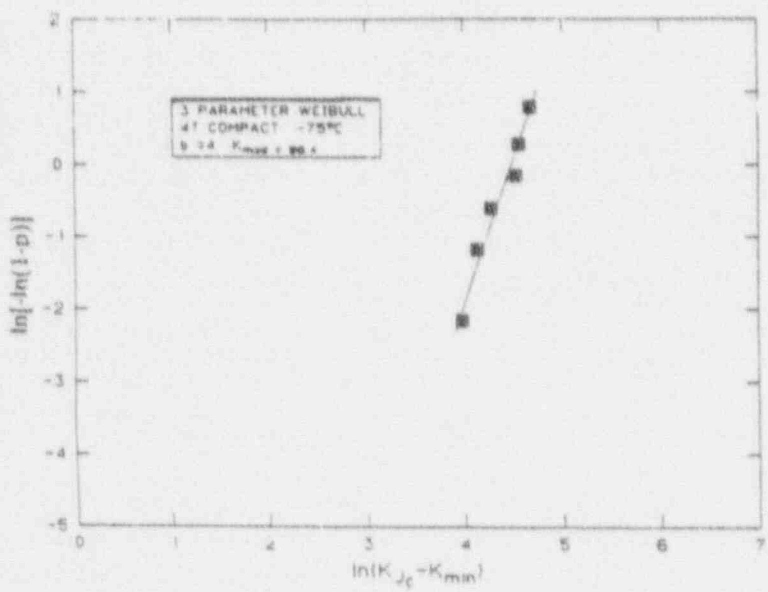

Figure 13. Weibull fits comparing best linearity to fixed slope of 4, 4TC(T) data at −75° C.

Table 4. Weibull fitting parameters for A 533 grade B Plate 13A (Weibull slope fixed at b = 4)

Test temperature (°C)	Specimens		K_o[a]	K_{med}[b]	K_{min}[c]	Correlation coefficient
	Size	Number				
-150	1/2TC(T)	18	43.5	40.6	10.5	0.971
	1TC(T)	17	45.2	43.0	24.5	0.978
	2TC(T)	12	47.2	44.8	19.0	0.981
-75	1/2TC(T)	20	130.0	122.4	42.5	0.938
	1TC(T)	26	111.8	101.8	0	0.993
	2TC(T)	12	111.1	102.6	13.5	0.983
	4TC(T)	6	94.1	86.4	6.0	0.982
-18	1TC(T)	6	194.3	177.3	0	--

[a]K_0 is the three-parameter scale factor.

[b]K_{med} is the value of K_{Jc} at $P_f = 0.5$.

[c]K_{min} is the fitting parameter.

fitting parameter that is needed specifically to improve the data fit to the fixed Weibull slope. There were only two cases where an excellent fit could not be established, and these were for 1/2TC(T) specimens tested in a moderately increased toughness range at -75°C (see Figure 9) and 1TC(T) specimens with high toughness, tested at -18°C (see Figure 6). In the latter case, only one of the 1TC(T) data points did not fit the slope of 4 and this one also showed significant slow-stable crack growth prior to instability. The curvature in the data trend in the case of the 1/2TC(T) specimens at -75°C (Figure 9) does not fit very well to the Weibull slope of 4, primarily because there was a sharp break in slope at about $K_{Jc} = 125$ MPa$\sqrt{m}$.

Crack Growth Correction

Five of the six 1TC(T) specimens tested at -18°C fit a Weibull slope of 4, as shown in Figure 6. All but one of the specimens had essentially negligible stable-crack growth, and the one that deviated was for the highest toughness with about 1 mm of stable-crack growth prior to cleavage. Three of the five specimens tested at 24°C had significant slow-stable growth prior to cleavage instability. Two others (not shown) did not cleave and full R-curves were obtained. Equation 6 was then used to develop a no-growth equivalent toughness (Table 5). Also, included in the next to the last column of Table 5 are the fracture toughness, K_R, values obtained from R-curves corresponding to the point on the R-curve that has the same amount of prior slow-stable crack growth. Nearly equal comparison was not possible because the K_{Jc} test specimens had smooth sides and the R-curve specimens were 20% side-grooved. Nevertheless, a point can be made that the plastic deformation properties, as observed by macroscale R-curve data measurements, were not significantly reduced by local crack-tip, strain-rate effects. Figure 14 shows the extent of fracture toughness adjustment calculated for all 1TC(T) specimens tested at -18°C. The one specimen that had significant growth (4%), had a 13% increase in K_{Jc}, whereas about a 65% toughness reduction was needed to bring that point into line with the other data having negligible crack growth. The adjustments are not a monotonic function of crack growth only, because both R-curve shape and the

Table 5. Adjustments to K_{Jc} data for slow-stable crack growth, 1TC(T) specimens

Test temperature (°C)	Δa (mm)	K_{Jc} (MPa√m) Measured	K_{Jc} (MPa√m) Adjusted	Difference (%)	K_R from R-curve[a]	σ_f[b] (MPa)
24	0.88	247.7	296.8	19.8	288	516
−18	1.05	321.9	369.4	14.8	305	544
24	2.66	437.5	522.1	19.3	398	516
24	3.18	431.9	529.6	22.6	413	516

[a]20% side-grooved specimens.

[b]Flow strength, $\sigma_f = (\sigma_y + \sigma_u)/2$.

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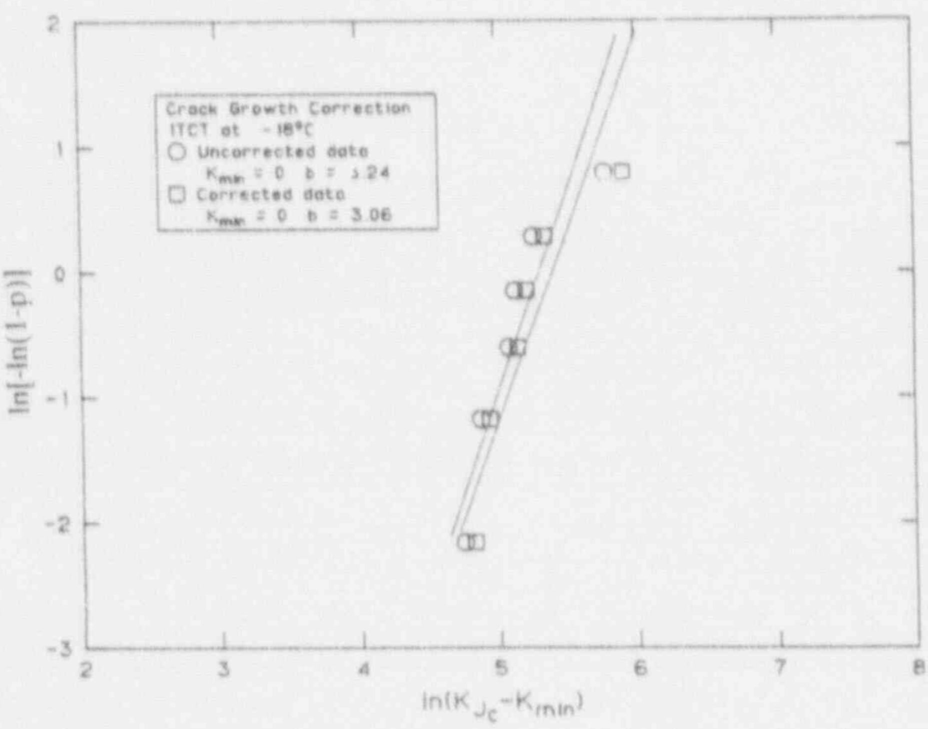

Figure 14. Effect of Equation 6 crack growth correlation on data obtained at −18°C.

rate of plastic zone development exert a significant influence on the magnitude of the adjustment. Equation 6 did not resolve the curve fitting problem of Figure 6, apparently because the reason for the break in the curve has not been successfully modeled. The micromechanics basis for Equation 6 is that crack growth should act to increase the probability for fracture, and if this were so, one would expect to see a concentration of specimens that fail by cleavage at K_{Jc} corresponding to near the J_{Ic} level of fracture toughness. Instead, there is no concentration of toughness values near J_{Ic} nor at any other level of toughness, and there is no obvious evidence of alteration in the R-curve behavior, as seen by comparing K_{Jc}-Δa_p to K_R-Δa_p data pairs. Hence, it would seem more likely that the sharp break in Weibull plots is due to a change in the constraint. For typical A 533 grade B steel tested as 1T compact specimens, that sharp break point will be coincident with J_{Ic} for the onset of R-curve controlled slow-stable crack growth. The extremal model for prediction of failure probability depends upon equal constraint at all levels of fracture toughness. To illustrate, Figure 15 recasts the 1/2TC(T) data at -75°C, shown in Figure 9, as a bilinear distribution. The slope of the low-toughness part is 4 and the slope of the higher-toughness part is 1.5. Since none of the specimens in Figure 9 had fractured at toughness above the J_{Ic} level of toughness for the A 533 grade B steel, slow stable-crack growth did not cause the bilinearity.

Evaluation of Extremal Statistics for Size Effect Predictions

The rationale behind extremal statistics requires that certain conditions be controlled. Constraint, the Weibull slope, and K_{min} must be reasonably comparable over the various specimen sizes. Also, the slope must be invariant over temperature for Equation 5 to be useful. Having accepted that a fixed Weibull slope of 4 is defensible for these data, with the possible exception of the 1/2TC(T) data, data for four specimen sizes were fitted using K_{min} as an adjustable parameter. It was expected that the tests with extensive replication at -75°C would have

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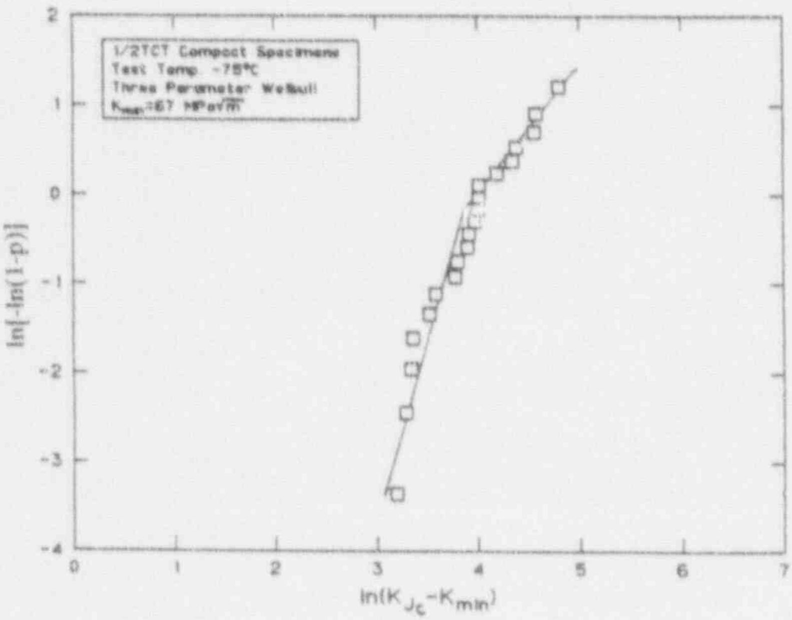

Figure 15. Data of 1/2TC(T) specimens segmented into two slopes.

provided a specimen size independent lower-bound value for K_{min} at that test temperature. The results indicated, however, that this was not the case, and K_{min} was found to be useful only as a convenient fitting parameter for each set of data using the Weibull slope of 4. To develop Table 6, the density function for the 1/2TC(T) compact specimens was used to predict the density functions for 1TC(T), 2TC(T), and 4TC(T) compact specimens. These are compared to the results of density function fits to actual data. Predicted median K values from the density functions are listed. The magnitude of shift of K (median) values due to specimen size was reasonably predicted for the -75°C data, but the K_{min} value of 43.5 that resulted from the high-toughness distribution of the 1/2TC(T) data was high when compared to K_{min} for the actual toughness distribution of other specimen sizes.

A comparison similar to the above, for a test temperature of -150°C, is also given in Table 6 and in Figure 16, but in this case, the largest specimen was only 2TC(T). The Weibull distributions fit to the actual data shown in Figure 16 indicate that, if there is a specimen size effect at -150°C it was not shown by this data. The 1/2TC(T) data listed in Appendix A (at -150°C) not only indicate a broad distribution of K_{Jc} data, they also show that the highest and the lowest toughness values obtained at that temperature (see Figure 4 at -150°C) were measured from the 1/2TC(T) specimens. Therefore, extremal statistics applied to the -150°C data predicts a size effect, as shown in Figure 17 that does not exist. Evidently, the problem is that particles large enough to be critical for cleavage initiation at this temperature are small enough and frequent enough that they always occur in the characteristic

Table 6. Results of using extremal statistics based on 1/2TC(T) data of A 533 grade B tested at -150 and -75°C to predict median K_{Jc} for larger specimens; Weibull slope fixed at 4

Test temperature (°C)	Specimen size	K_{Jc} (MPa$\sqrt{m}$)		
		Predicted median	Actual data fit	
			Median	K_{min}
-75	1/2TC(T)	122.4	122.4	43.5
-75	1TC(T)	109.9	102.0	0
-75	2TC(T)	99.3	102.6	13.5
-75	4TC(T)	90.4	86.4	6
-150	1/2TC(T)	40.6	40.6	10.5
-150	1TC(T)	33.9	43.4	24.5
-150	2TC(T)	31.9	44.8	19.0
-150	4TC(T)	28.5	--	--

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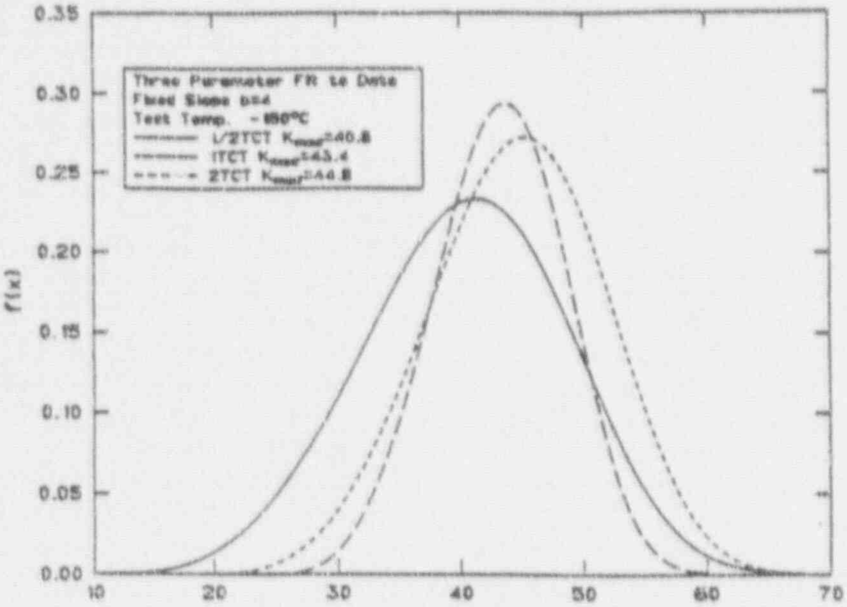

Figure 16. Raw data from tests at −150°C fitted to Weibull slope of 4.

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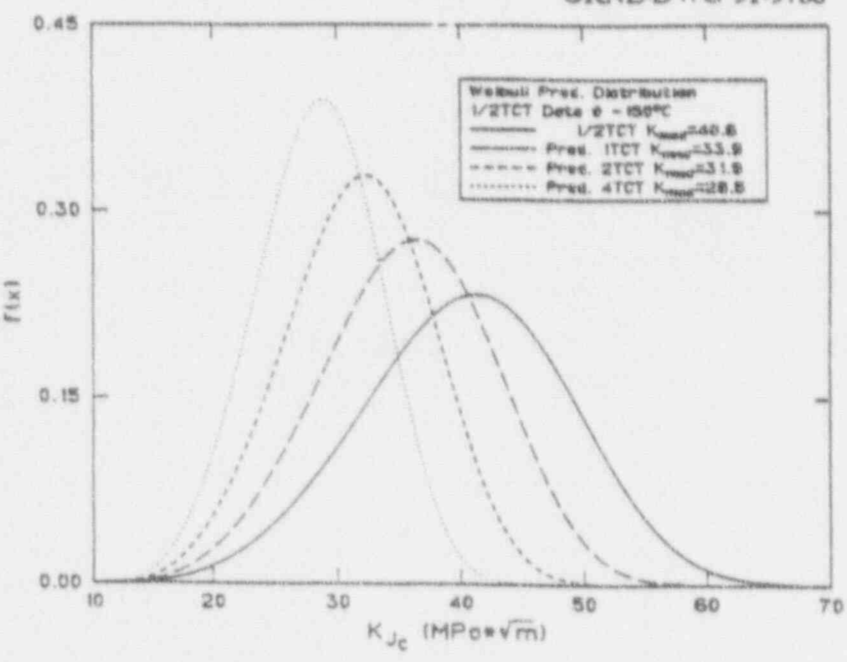

Figure 17. Extremal statistics used on 1/2TC(T) data to predict K_{Jc} populations for larger specimens.

unit volume assumed for the statistical model. Hence, there is a need to identify a lower toughness limit for data that can be analyzed with extremal statistics.

There also can be some difficulty with the application of extremal statistics in the mid- to high-transition range, and this was experienced in the experiment by Nanstad et al. (1991). The objective of that particular experiment was to establish lower-bound K_{Ic} curve for unirradiated and irradiated high- and medium-copper, A 533 grade B weld metal. Large compact specimens up to 8TC(T) size were made to make it possible to obtain valid K_{Ic} toughness values for the unirradiated material in a fairly high toughness range. The sequence used was to first test 2TC(T) compact specimens to provide a baseline K_{Jc} distribution. The 2TC(T) distribution was then analyzed by extremal analysis to estimate that 150 MPa$\sqrt{m}$ would be the mean valid K_{Ic} toughness level for 8TC(T) specimens at the selected test temperatures for each material (see Figure 18 and Figure 19). The estimated median toughness

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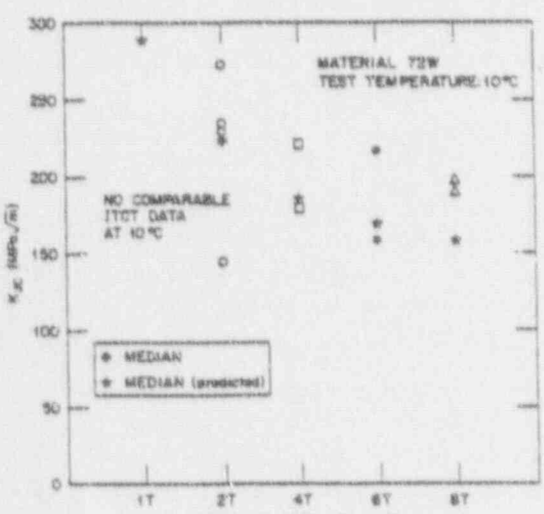

Figure 18. Data from 2TC(T) specimens used to predict median K_{Jc} values for other sizes (A 533 grade B weld metal 72W at 10°C).

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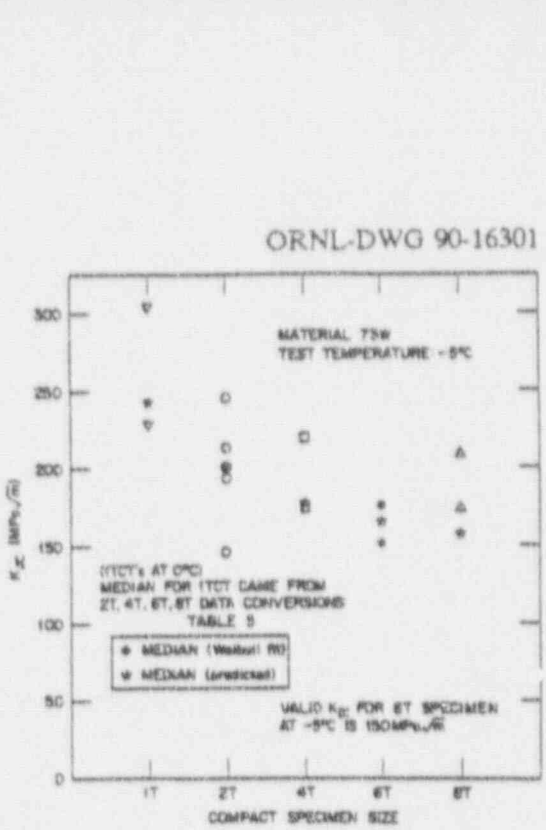

Figure 19. Data from 2TC(T) specimens used to predict median K_{Jc} values for other sizes (A 533 grade B weld metal 73W at -5°C).

values tended to be confirmed with 4TC(T) and 6TC(T) compact specimens. However, even with two chances at what was believed to be a 50% probability each time for obtaining a valid K_{Ic}, no valid value was obtained for either weld metal.

This failure to achieve the objective was perhaps bad luck, but there was an object lesson in the outcome. As had been indicated in Figure 3, for each specimen size there is a test temperature below which the scatter band of K_{Jc} values contracts radically. Weibull analysis works correctly in a certain part of the transition range where large specimens do in fact have lower mean K_{Jc} values and reduced scatter in proportion to specimen size. However, in the high toughness part of the transition range, even specimens of massive dimensions may not be biased toward lower-bound toughness. To demonstrate the reality of the outcome, Equation 5, which is derived from the extremal assumption, was used to adjust K_{Jc} values for welds 72 and 73W from 8TC(T), 4TC(T), and 2TC(T) specimens to 1TC(T) specimen size. Equivalent 1TC(T) K_{Jc} values are calculated and presented in Table 7. Unfortunately, no 1TC(T) specimens of 73W were tested exactly at −5°C, nor 72W exactly at 10°C, so a direct comparison cannot be made. However, two 1TC(T) 73W specimens were tested at 0°C and, as shown in Figure 19, demonstrated that the 8TC(T) data were easily within an extremal statistics projected distribution. Evidently, the results from the 8TC(T) specimens favored the high part of the fracture toughness scatter band. Hence, when constraint is reduced at high toughness levels, the precision of the extremal model diminishes.

Table 7. Use of specimen thickness normalizing equation to predict K_{Jc} distributions for 1TC(T) specimens

Source specimen	Measured (K_{Jc} MPa$\sqrt{m}$)	Normalized 1TC(T)[a] (K_{Jc} MPa$\sqrt{m}$)
	72W K_{Jc} values (10°C)[b]	
8T	191.1	321
8T	197.9	332
6T	217.5	340
6T	159.5	250
4T	178.9	253
4T	221.5	313
2T	145.7	173
2T	230.7	274
2T	235.7	280
2T	278.4	331
	73W K_{Jc} values (−5°C)[c]	
8T	176.1	260.4
8T	211.8	320.4
6T	151.6	207.4
6T	175.9	245.6
4T	174.9	226.6
4T	221.4	312.6
2T	246.5	283.2
2T	214.8	245.5
2T	199.6	227.4
2T	193.2	219.8
2T	147.1	165.0

[a] $K_{IT} = K_{min} + (K_B - K_{min})(B_1/B_0)^{1/4}$.

[b] K_{med} = 287.9 MPa$\sqrt{m}$.

[c] K_{med} = 243.9 MPa$\sqrt{m}$.

β_{Jc}-β_{Ic} Fracture Toughness Correlation

As previously noted, the 1/2TC(T) specimens of A 533 grade B steel tested at -75°C had shown a bilinear Weibull characteristic where there was no significant stable crack growth (Figure 15). The break in slope, therefore, must have been due to onset of reduced constraint and this violates one requirement for valid application of extremal statistics. Onset of reduced constraint apparently is about 125 MPa$\sqrt{m}$ for 1/2TC(T) specimens of A 533 grade B steel, and this also happens to be where $\beta_c = 2\pi$. The β_{Ic} correlation of Equation 6 assumes that variable constraint is the explanation for specimen size effects and, as such, the suggestion deserves fair consideration as an alternate method of analysis. The β_{Jc}-β_{Ic} model predicts specimen size effect trends much like those of the extremal statistics model. Although the β_{Ic} relationship has been used in a deterministic way to estimate K_{Ic}, it can also be used to project K_{Jc} distributions for various specimens sizes. The individual K_{Jc} values that produce a small specimen toughness distribution can each be adjusted to a larger size, using Equation 7, and the adjusted values then fit with a new distribution curve.

The circumstance under which the β_{Ic} constraint model is clearly more correct in characterizing specimen size effects than the extremal statistical model is when toughness is approaching a lower bound. For example, the toughness of A 533 grade B class 1 tested at -150°C is low enough such that even the majority of the 1/2TC(T) specimens behaved the same as the large specimens and gave valid K_{Ic} values. Figure 16 represents direct Weibull fitting to experimental data sets for 1/2TC(T), 1TC(T), and 2TC(T) specimens tested at -150°C, and it is apparent that there is no evidence of reduced toughness with increased specimen size. As was pointed out before, both the highest and the lowest K_{Ic} values measured at -150°C were obtained with the 1/2TC(T) specimens. Figure 17 shows that extremal statistics based on the 1/2TC(T) distribution predicts a considerable size effect that would only be truncated for infinite size at the K_{min} value of 10.5 MPa$\sqrt{m}$. The problem here may be that the unit volume discussed by Wallin (1984), that is assumed to characterize the inhomogeneity of cleavage initiation sites in the statistical model, has become smaller than the smallest volume that displays statistical independence. The statistical independence, of course, is basic to a weak link type mechanism. Figure 20 shows that the constraint-based β_{Ic} model predicts that size effects should be negligible when the median toughness is below 40 MPa$\sqrt{m}$. Median toughness at about 37 MPa$\sqrt{m}$ is in much better agreement with experimental results.

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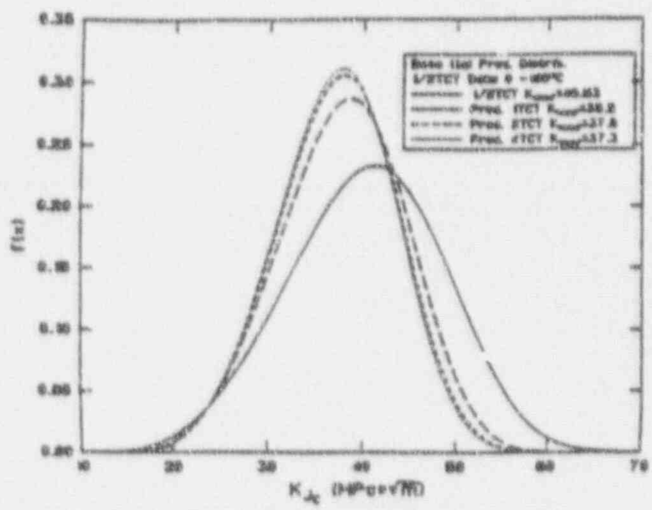

Figure 20. β_{Ic} relationship used on 1/2TC(T) data to predict K_{Jc} populations for larger specimens.

The β_{Jc}-β_{Ic} relationship expressed by Equation 7 was based on empirical observations, and Irwin (1960) cautioned that there are limits at the reduced thickness and/or high-toughness end of the general trend. It was suggested that $\beta_{Jc} = \pi$ might be an upper limit to the use of Equation 7 (Irwin, 1960).

Figure 21 is a plot representing three selected (plane strain) toughness levels, and the toughness trends due to constraint differences defined by Equation 7. Solid data points represent selected K_{Jc} values from

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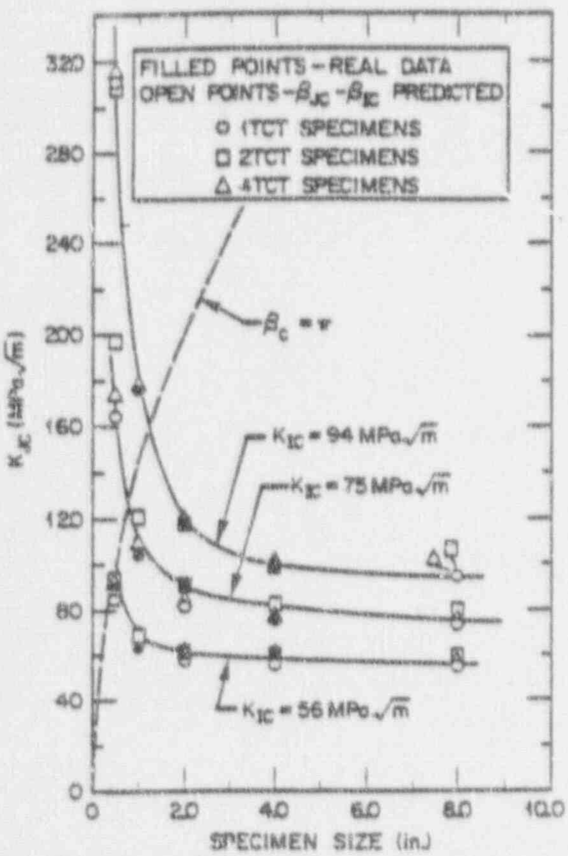

Figure 21. β_{Jc}-β_{Ic} trend lines for three levels of fracture toughness at −75°C (A 533 grade B, class 1, 73-ksi yield strength).

data distributions at −75°C. These data can be found in Appendix A, and open points are predicted K_{Jc} values. The upward asymptotic nature of K_{Jc} toughness at low constraint indicates a region of potential weakness in the method. For the −75°C test temperature shown, β_{Jc} values for many of the 1/2TC(T) specimens were above 2π and the prediction of β_{Ic} would tend to be low for large specimens. On the other hand, the β_{Jc} values for all but two of the 1TC(T) specimens were less than π. Therefore, frequency distribution predictions made for 1/2TC(T), 2TC(T), and 4TC(T) compact specimens were based on the 1TC(T) distribution (Figure 22). These predictions can be compared to the extremal statistical predictions shown in

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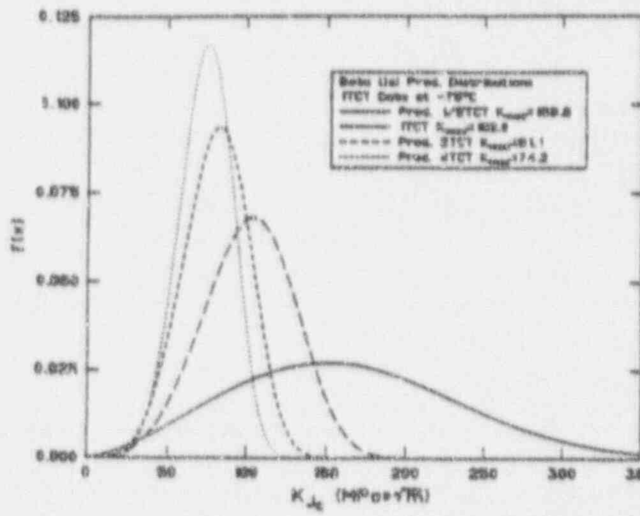

Figure 22. β_{Ic} relationship used on 1TC(T) data to predict distributions for specimens of other sizes (A 533 grade B class 1, plate 13A, tested at −75°C).

Figure 23. Both have used the 1TC(T) distribution as baseline. For 2TC(T) and 4TC(T) specimens, the results are comparable between the two models. For 1/2TC(T) specimens, only the extremal statistics predicted accurately. It would be interesting to know why the statistical model seemed to work with small specimens even when there was a significant bilinear characteristic in the original Weibull data. With the data above 125 MPa$\sqrt{m}$ removed, the 1/2TC(T) data could be easily fitted to a linear slope of 4. However, the new K_{med} value was determined to be 110 MPa$\sqrt{m}$, so that the prediction from the 1TCT(T) data that 1/2TC(T) K_{med} is 121.3 MPa (Figure 23), is less accurate by this criterion.

Discussion

The practical application for this work is the development of information on the relevance of test results obtained from small specimens of the size

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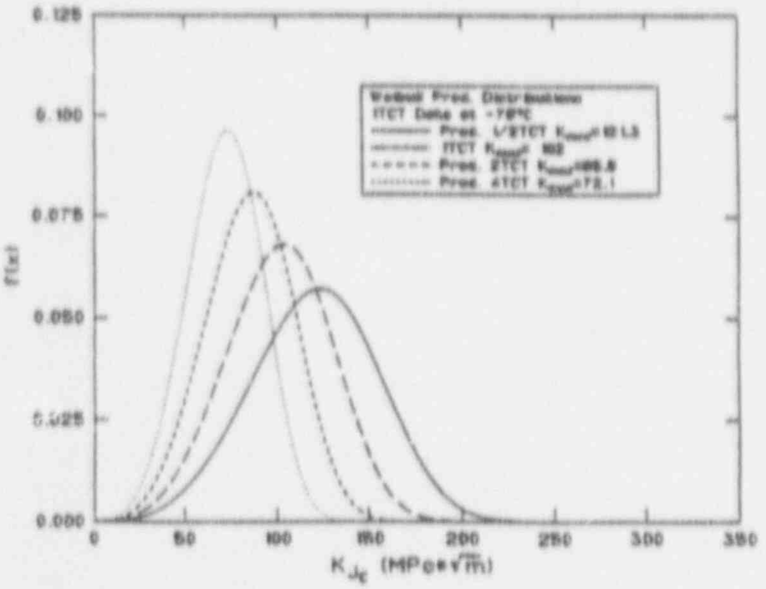

Figure 23. Weibull relationship used on 1TC(T) data to predict distributions for specimens of other sizes (A 533 grade B, class 1, plate 13A, tested at −75° C).

used in surveillance capsules. The question is, are such specimens, when tested in small quantities, capable of indicating the fracture toughness properties of large components. There is a definite advantage in knowing that there is only one possible Weibull slope, which cuts down specimen replication requirements for application of extremal methods, but the number of replicates that would be needed to establish K_{min} values with good confidence is still substantial. The number needed has not been determined here. Safe limits should be put on the acceptability of data for analysis and these limits can be based on allowable levels of β_{Jc}. The general approach that these data suggest is presented in Figure 24. For extremal statistics prediction of size effects, these tests indicate β_{Jc} between 1.5 and 2π should be an upper-toughness limit to avoid excessive loss of constraint and the consequent bilinear Weibull characteristics. Alternatively, if the baseline data show low β_{Jc} values of the order of unity or less, specimen size effects tend to vanish and the β_{Jc} constraint model is the only one that has the appropriate characteristics. When β_{Jc} approaches valid K_{Ic} conditions, i.e., $(0.4 < \beta_{Jc} < 1)$, then the β_{Jc} method tends to be more accurate than the pure statistical model.

In some cases noted in the literature, the third Weibull parameter, K_{min}, has been fixed on the assumption that a reasonably constant lower-bound toughness has already been experimentally proved. However, if the Weibull slope is predetermined, K_{min} cannot be regarded as a lower-bound material toughness property but instead should be considered a fitting parameter.

The experience in working with the present A 533 grade B data suggests that K_{min} should be less

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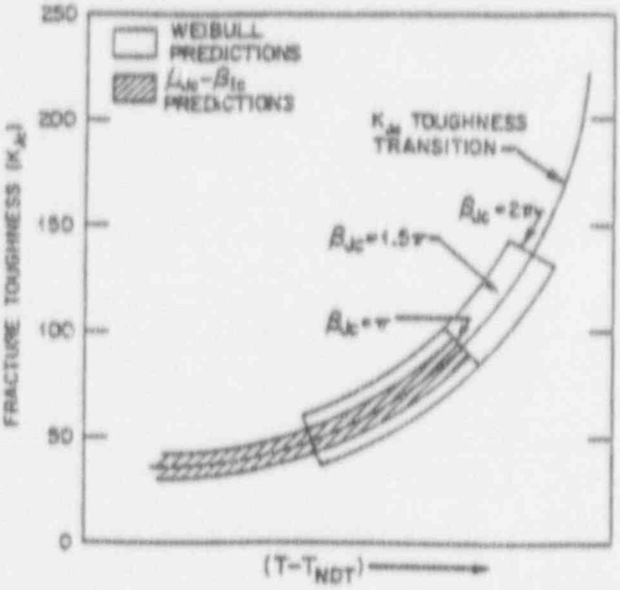

Figure 24. Zones of applicability for 1/2TC(T) specimens of A 533 grade B to make specimen size effect predictions.

than one-half K_{med} for the largest specimen size to be predicted. The Weibull estimate of the real K_{Jc} distribution becomes quite poor when the slope is fixed and K_{min} is higher than 50% of the median toughness.

Transposition of data using β_{Jc}-β_{Ic}, on the other hand, requires no prior determination of Weibull fitting parameters and the transposed size effect data are better fit to the distribution function.

A few K_{Jc} values that were obtained after some slow-stable crack growth (at −18 and +24°C) were adjusted using the Wallin correction model. Although there were not enough data available to make unassailable claims, it seemed as though there was very little difference in the before and after adjusted K_{Jc} values. The fact that K_{Jc} data fall on the R-curve for slow-stable tearing suggests that the impact of stable growth on cleavage volume elements and critical stress models is relatively minor in comparison to the extremal size effect model. On the other hand, the reduction of constraint during stable growth seems to exert significant influence on K_{Jc} data which handicaps the extremal statistics model.

The extremal statistical model is most reliable between the lower- to mid-transition toughness part of the transition range. Size effects become difficult to predict where large specimens enter the rapidly increased toughness part of the transition curve.

Conclusions

1. Extremal statistics (Weibull method in this case) are useful only in a limited range of K_{Jc} toughness between the lower- to mid-transition range. This range of usefulness can be decided on the basis of calculated β_{Jc} values.

2. The β_{Jc}-β_{Ic} model for variable constraint can be used to predict specimen size effects, but there is a limitation that data distributions for which β_{Jc} values are predominantly greater than π should be used with an awareness of a tendency for over conservatism.

3. To establish a standard practice that advises the use of extremal statistics on surveillance data, the following requirements should be addressed: upper- and lower-bound limits on β_{Jc} values, number and size of surveillance specimens required to obtain good K_{min} determinations and good scale parameters, and specifics on fitting three parameter Weibull to data sets. These issues can be resolved with more supporting experimentation.

4. β_{Ic} analysis to project specimen size effects has an advantage that only one assumption or postulate must be true to transpose data.

5. If it is a correct assumption that the Weibull slope fitted to the transposed values is fixed at b = 4, the number of data required to model a data distribution can be substantially reduced.

6. The postulate that slow-stable growth in and of itself causes Weibull slope change is not substantiated. Slope change is more likely due to loss of constraint. The postulate that slow-stable crack growth causes slope change is questionable.

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6. The postulate that slow-stable growth in and of itself causes Weibull slope change is not substantiated. Slope change is more likely due to loss of constraint. The postulate that slow-stable crack growth causes slope change is questionable.

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Appendix A

Individual K_{Jc} Data for A 533 Grade B Class 1, Plate 13A

Table A-1. Individual K_{Jc} data for A 533 grade B class 1, Plate 13A

Specimen size	Test temperature (°C)	K_{Jc} (MPa$\sqrt{m}$)	Δa (mm)
1TC(T)	24	247.7	0.875
		431.9	3.180
		437.5	2.660
		a	2.040
		a	2.100
1TC(T)	-18	115.9	0.064
		131.1	0.069
		160.9	0.112
		168.0	0.160
		192.3	0.196
		321.9	1.049
2TC(T)	-18	202.2	0.221
		224.8	0.366
1/2TC(T)	-75	91.4	0.0
		93.7	0.0
		95.2	0.0
		95.7	0.0
		100.9	0.0
		103.1	0.0
		110.8	0.0
		111.9	0.0
		116.6	0.0
		117.4	0.0
		120.3	0.0
		122.0	0.0
		122.6	0.0
		122.7	0.0
		133.5	0.0
		144.4	0.0
		147.3	0.0
		162.3	0.0
		164.0	0.0
		188.4	0.0
1TC(T)	-75	35.9	0.0
		54.9	0.0
		55.2	0.0
		62.9	0.0
		64.3	0.0
		74.5	0.0
		85.8	0.0

Table A-1. (continued)

Specimen size	Test temperature (°C)	K_{Jc} (MPa$\sqrt{m}$)	Δa (mm)
		89.5	0.0
		93.3	0.0
		94.7	0.0
		95.8	0.0
		97.1	0.0
		97.6	0.0
		103.9	0.0
		105.4	0.0
		107.7	0.0
		109.3	0.0
		119.1	0.0
		125.3	0.0
		129.5	0.0
		129.6	0.0
		134.2	0.0
		137.3	0.0
		143.7	0.0
		160.9	0.0
		175.1	0.0
2TC(T)	-75	61.4	0.0
		69.3	0.0
		90.7	0.0
		90.9	0.0
		94.4	0.0
		95.5	0.0
		101.8	0.0
		116.2	0.0
		116.6	0.0
		118.6	0.0
		132.0	0.0
		138.4	0.0
4TC(T)	-75	59.1	0.0
		68.3	0.0
		77.9	0.0
		97.9	0.0
		100.9	0.0
		112.4	0.0
1/2TC(T)	-150	27.9	0.0
		28.8	0.0
		32.2	0.0
		32.4	0.0
		33.2	0.0
		34.1	0.0
		36.1	0.0

Table A-1. (continued)

Specimen size	Test temperature (°C)	K_{Jc} (MPa$\sqrt{m}$)	Δa (mm)
		37.2	0.0
		39.6	0.0
		40.0	0.0
		41.0	0.0
		45.1	0.0
		47.6	0.0
		48.6	0.0
		49.9	0.0
		50.3	0.0
		52.7	0.0
		58.7	0.0
1TC(T)	-150	35.3	0.0
		37.1	0.0
		37.7	0.0
		38.4	0.0
		38.6	0.0
		39.6	0.0
		41.2	0.0
		41.2	0.0
		43.5	0.0
		43.7	0.0
		44.4	0.0
		46.6	0.0
		48.1	0.0
		51.1	0.0
		54.5	0.0
		54.6	0.0
2TC(T)	-150	33.1	0.0
		36.3	0.0
		40.2	0.0
		40.7	0.0
		43.3	0.0
		43.9	0.0
		45.0	0.0
		45.6	0.0
		46.4	0.0
		51.1	0.0
		53.5	0.0
		58.5	0.0

[a]R-curve.

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11. ABSTRACT (200 words or less)

Characteristics of extremal statistics that are used to predict size effects on cleavage fracture toughness in the transition range were explored. A 533 grade B steel base and weld metals were tested using compact specimens ranging in size from 1/2TC(T) to 8TC(T) and with sufficient replication in some cases to provide good fits to Weibull distributions. The classical specimen size effect on data scatter and median K_{Jc} toughness at a given test temperature was observed in the low- to mid-transition range. These effects were well predicted with extremal statistics. However, the same model is not applicable on the lower shelf, and it also becomes extremely weak and unreliable in the mid- to high-transition range. The Irwin β_c-β_{Ic} relationship was also explored as a model and was found to predict similar size effects. The predictive characteristics of the latter seemed better suited to deal with the diminution of size effects in the near- to low-shelf toughness range. In the rising toughness part of the transition, the predictive characteristics were about the same as the statistical model up to where β_c (β_{Jc} in this study) of the baseline (small specimen) data were π or less. This work could be used in the establishment of a framework for transition temperature test criteria. Upper- and lower-bound β_{Jc} criteria could be used to define optimum conditions for the application of either of the aforementioned models. For surveillance programs, sensible rules should be specified as to specimen size requirements and numbers of specimens to be tested in order to apply these analytical models. Another need would be the definition of a procedure for the Weibull distribution fitting. The present report suggests items to be considered for requirements in application of these predictive techniques.

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