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DEVELOPING THE METHODOLOGY FOR CHARACTERIZING FRACTURE BEHAVIOR IN THE DUCTILE-TO-BRITTLE TRANSITION FOR STEELS

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Abstract. *The characterization of the fracture behavior in the ductile-to-brittle transition for steels had been a problem for many decades. Fracture toughness values exhibited extensive scatter and severe size and geometry effects. The measured toughness was a strong function of temperature in the transition with the toughness values increasing rapidly over a relatively narrow temperature range. The toughness results would usually have a large range of values at a given temperature and therefore could not be easily used to evaluate integrity in structural components because of the uncertainty in how to handle these test results. Attempts to solve the transition fracture toughness problems began over 30 years ago, often without much success. However, in the past decade a methodology has been developed to handle all of these problems. The original concept for describing the complex character of transition fracture toughness behavior was to attribute transition behavior to constraint effects. Test results on different sizes and geometries showed a difference in the toughness that might be rationalized by a constraint argument; however, this did not account for the extensive scatter in results. A new look at the transition toughness character came with the suggestion that the behavior could be described by considering statistical influences. The use of weakest-link statistical models could handle the scatter as well as explain the size effect observed on proportionally sized specimen. After more than ten years of study, the statistical models were developed to the point that they could be applied universally to all transition fracture toughness results for ferritic steels using a three parameter Weibull distribution with two prescribed constants. What remained to be shown was how the temperature distribution of toughness could be characterized. The suggestion of a "master curve" that would describe the transition fracture toughness of all ferritic steels gave the basis needed to finally develop a complete methodology for characterizing transition toughness. This methodology can explain the scatter, size and temperature effects and provides some basis for differentiating between statistical influences and constraint effects. The master curve concept with Weibull statistics has revolutionized the approach used to characterize transition fracture behavior and has given a rationale for transferring test results to structural evaluation. This approach was several decades in the development stage. This paper will review some of the early models that were used to describe transition fracture behavior and highlight some of the important steps that went into the development of the current approach for handling transition fracture behavior. It is a companion paper with one to follow that will present the experimental verification of the present Master Curve approach for transition fracture.*

Keywords: *Ductile-to-brittle transition, Master Curve, Ferritic steels*

1. INTRODUCTION

Transition fracture toughness characterization had been a particularly difficult problem for the fracture mechanics technology. The fracture toughness in the early days of fracture mechanics was characterized by a K_{Ic} value (E399, 1970). This value had to meet a size limitation so that essentially linear-elastic and plane strain behavior would prevail during the K_{Ic} test. In the transition the toughness increased rapidly with an increase in temperature. One attempt to meet the size requirement for a K_{Ic} test used specimens that were up to 12 inches thick and proportionally sized in the other dimensions (Wessel, 1968). The result was that the transition fracture toughness was measured to a fairly high level but the toughness of the entire transition region could not be measured in terms of K_{Ic} even with these large specimen sizes.

The development of the elastic-plastic fracture mechanics methodology provided a method for extending the measurement of the transition fracture toughness up to the point of purely ductile fracture (Begley and Landes, 1972). This was called the "upper shelf" fracture toughness regime from a similar result found in Charpy testing. The fracture toughness for elastic-plastic conditions was characterized either by a J value, from Rice's J integral (Rice, 1968) or a crack-tip opening displacement, CTOD, value (Wells, 1961). A schematic illustration of the transition toughness behavior for steels is given in Fig. 1 showing a fairly narrow and smooth toughness trend with temperature. When actual fracture toughness data are measured in the transition, the result is much different. This is illustrated in Fig. 2 (Landes, 1992). Here fracture toughness results from five different steels in the transition shows the transition toughness problem; there is extensive scatter with no well defined trends through the transition. Besides this scatter, the toughness measured in the transition has size and geometry effects so that it was difficult to tell what value of toughness to use at a given temperature for the prediction of failure behavior in a structural component.

There were several reasons suggested for the fracture behavior observed in the transition. One argument attributed the size and geometry effects to constraint differences (Milne and Chell, 1979). This approach could explain the fracture toughness trends on the average but could not explain individual results. A second approach tried to explain the size effects and scatter by a statistical argument (Landes and Shaffer, 1980). This approach seemed to give a rationale for transition fracture toughness behavior that gained the interest of several new investigators. The development of new statistical approaches was a great help in explaining the transition fracture toughness behavior and led to the present scheme used for organizing the results. Based on this modern approach an ASTM standard test method was written that allows a complete characterization of the transition fracture toughness for ferritic steels (E 1921, 1997). In this paper some of the methods that led to the modern development of transition fracture toughness characterization are discussed starting with the constraint-based arguments and going through the statistical development and the master curve formulation.

2. CONSTRAINT ARGUMENTS

The first argument for the differences in fracture toughness were attributed to the constraint encountered in the different sizes and geometries (Milne and Chell, 1979). Larger sized specimens had higher constraint than smaller specimens; bending loaded specimens had higher constraint than tension loaded ones. It could be shown from existing data that these effects did exist. The toughness results showed trends on the average that would suggest that constraint differences were causing some of the problems in transition toughness measurement. Figure 3 shows the different trends that are observed for relatively high and low constraint levels. On the average the more highly constrained geometries and sizes have lower toughness and have a higher transition temperature than the lower constrained geometries and sizes.

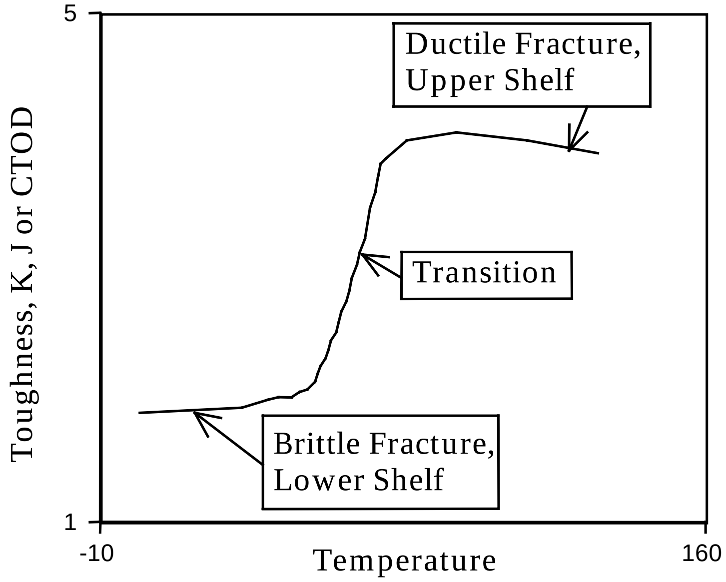

Figure 1 - Schematic showing region of transition fracture

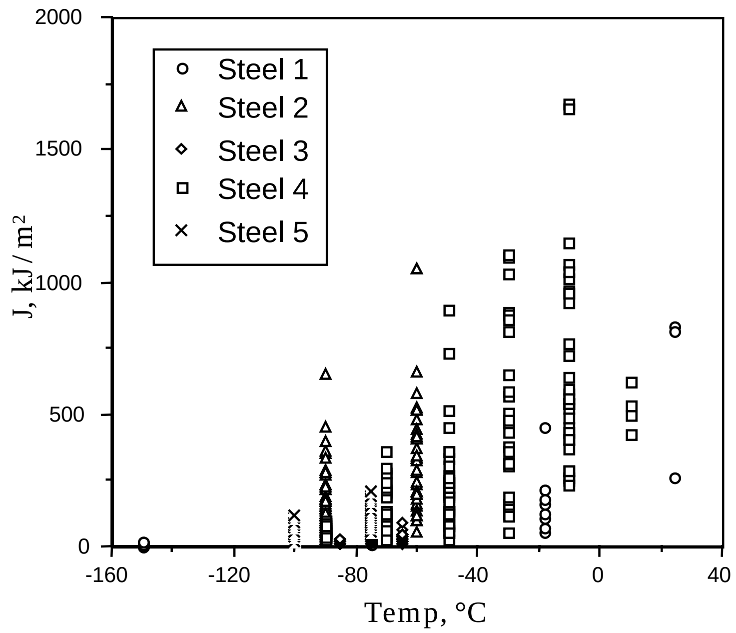

Figure 2 - Transition toughness results for five steels

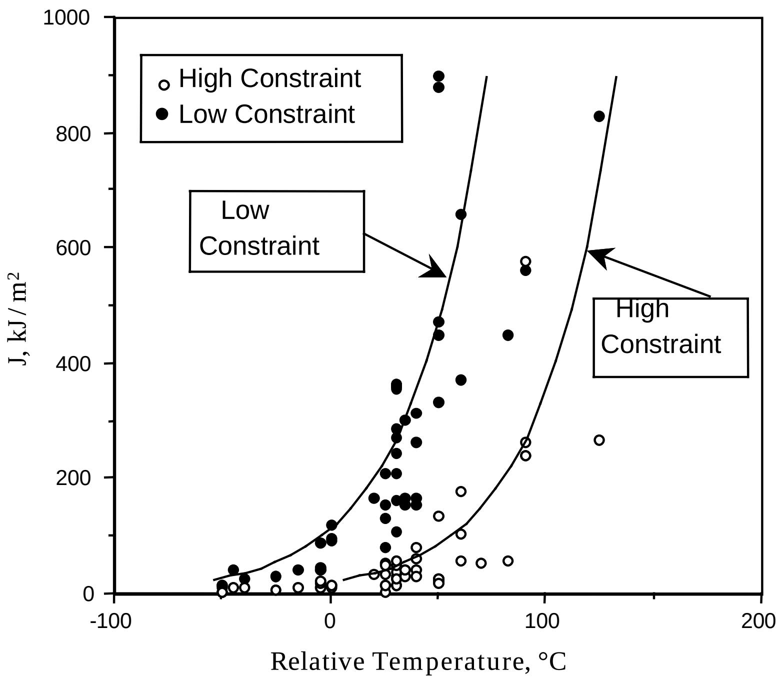

Figure 3 - Transition fracture toughness data with constraint trend lines

Constraint differences were always observed on the average of results, but individual results did not always show these trends. Sometimes the lower constrained specimen showed lower toughness at a given temperature than the higher constrained specimen (Iwadate, et. al, 1983), the reverse of the average trend that was observed. This raised the question of why constraint effects appeared to cause one toughness trend on some results but the opposite on another one. The extreme scatter in the transition caused confusion so that the exact role of constraint could not be separated from the scatter. It was obvious that more than just the constraint effects were controlling the transition fracture toughness behavior and additional modeling was needed. This additional modeling was based on statistical distributions. It was not until the statistical aspects of the transition problem were quantified that the constraint issues could be studied in a more logical manner.

3. ORIGINAL STATISTICAL STUDIES

The first suggestion that transition fracture toughness problems could be handled with statistical arguments came about 20 years ago (Landes and Shaffer, 1980). The statistical approach was based on a two-parameter Weibull distribution.

$$p = 1 - \exp[-(\frac{J_c}{J_o})^m] \tag{1}$$

Here p is the probability that fracture will occur below a value of J_c, m is a shape parameter, also called Weibull slope, and J_o is a scale parameter related to the mean of the distribution. It was suggested that fracture occurred when a weak link in the material was ruptured, hence triggering global fracture in the specimen or structure. This failure of a weak link was a random event and depended on the availability of such a feature near the crack tip as well as a crack tip stress value large enough to trigger the weak link failure. The statistical argument for size effects suggested that the greater the size of the specimen the more likely it is to contain such a weak link and the easier it is to obtain a global fracture event. This makes it more likely to have a low fracture toughness value.

The two-parameter Weibull parameters could be determined from a fit of test results showing the characteristic transition scatter. The toughness results for a single test condition, temperature and specimen size, are organized going from lower to higher values of toughness. A probability is assigned to each toughness value using a distribution law. Originally the law was

$$p = \frac{i+1}{N} \tag{2}$$

Where N is the total number of tests and i is the individual ranking of a test. The Weibull law was written as 1 – p

$$1 - p = \exp[-(\frac{J_c}{J_o})^m] \tag{3}$$

which is the probability that a toughness value is greater than J_c. The exponent, m, is a slope determined when the toughness results are plotted on Weibull paper, Fig. 4. This is a plot of Eq. (3) with logarithms taken twice on both sides.

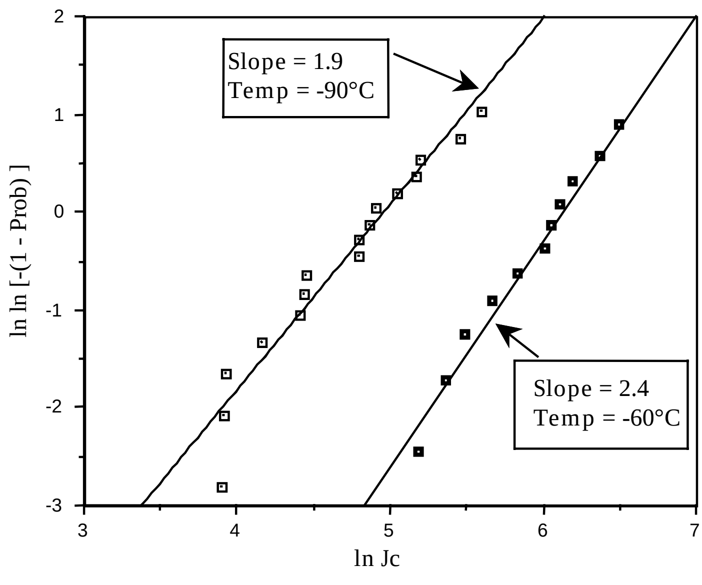

Figure 4 – Weibull plot for transition toughness of a steel at two temperatures

The statistical model was used to explain size effects by assuming that the larger specimens had more volume to produce a weak-link site that would produce a fracture than the smaller specimens. A schematic of the rationale is shown in Fig. 5. Comparing the probability of fracture on a size Y specimen with a unit size. The probability that a weak link exists in size Y is that many times more likely than that a weak link exists in the unit size. The probability from Eq. (3) becomes

$$1 - p_Y = (1 - p_1)^Y = \left[\exp\left(-\left(\frac{J_c}{J_o} \right)^m \right) \right]^Y = \exp\left[-\left(\frac{J_c}{J_o / Y^m} \right)^m \right] \quad (4)$$

The 1 – p_Y probability of Eq. (4) is similar to the unit size 1 – p_1 probability of Eq. (3) except that J_o is divided by a factor on Y^m. Since J_o is related to the mean of the distribution, the mean in size Y is changed by the factor $(1/Y)^m$ compared to the unit size.

A value of Y larger than unity would lower the mean and visa versa. In this way the statistical model clearly predicts a size effect. Preliminary results from the first work on statistical modeling showed that the model prediction of size effect was essentially the same as that observed from the data (Landes and Shaffer, 1980). Therefore, the statistical model could both characterize the large scatter in transition toughness results as well as predict the observed size effects. Although the two–parameter Weibull distribution had some conceptual difficulties and was not the approach ultimately chosen, it did give a new methodology for studying transition fracture toughness behavior. This study ultimately led to a more satisfactory approach.

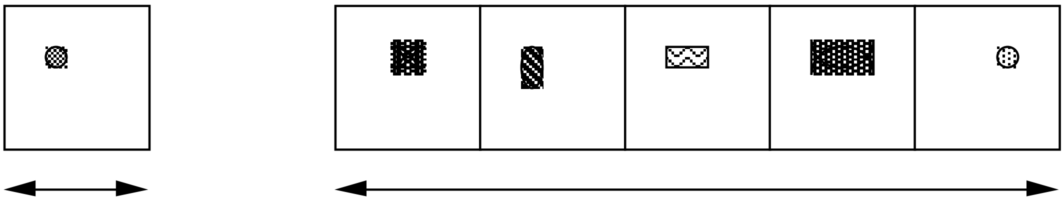

Figure 5 - Schematic showing how the statistical model works

4. NEW STATISTICAL MODELS

With the development of a statistical approach more investigators began the study of the transition fracture toughness trends with the goal of applying the results to the prediction of structural fracture behavior. The two-parameter Weibull distribution was not entirely satisfactory. The two-parameter Weibull distribution gave a probability of fracture toughness ranging from zero to infinity. This did not seem realistic because the minimum toughness value that could ever be encountered in ferritic steels in terms of a J value, should be about 3 to 5 kJ/m^2, not zero. To give toughness a nonzero minimum, a three-parameter Weibull distribution was suggested (Landes and McCabe, 1984).

$$1 - p = \exp\left[-\left(\frac{J_c - J_{min}}{J_o - J_{min}} \right)^c \right] \quad (5)$$

Here, J_{min} is the third parameter and is a nonzero minimum value of toughness that could be part of the Weibull distribution. This equation with three fitting parameters was a more realistic description of the distribution of fracture toughness values at a fixed temperature but also as much more difficult to fit to the data. The original methods for fitting the three-parameter Weibull distribution of Eq. (5) gave a lot of scatter in all of the fitting constants. The problem was that it would take a very large database to get a good characterization of a complex fitting law like Eq. (5).

One suggestion for simplifying Eq. (5) was to convert the elastic-plastic J toughness parameter to the equivalent linear-elastic parameter, K. This would put the analysis in a framework that could be more easily applied to structure evaluation. The plane stress K equivalent of J, labeled, K_{Jc} was used where $K_{Jc} = \sqrt{J_c E}$, where E is the elastic modulus of the material. K_{Jc} was then introduced into the Weibull distribution and it became

$$1 - p = \exp\left[-\left(\frac{K_{Jc} - K_{min}}{K_o - K_{min}}\right)^n\right] \tag{6}$$

where the three constants, K_o, K_{min} and n are the analogous constants from Eq. (5). To help with statistical modeling a large quantity of data were generated and the various parameters in the three-parameter Weibull model were calibrated (Wallin, 1989). It was found that fracture toughness results for ferritic steels did not go below 20 MPa√m, so that was chosen as the lower limit for the data, the third parameter, K_{min}. Theoretical arguments for the probability of finding a flaw in a volume of material ahead of the crack gave a value of four for the slope, n. The results of many tests showed that the slope of four was approached when a large database was generated. Therefore, a Weibull slope of four was chosen. Then Eq. (6) became

$$1 - p = \exp\left[-\left(\frac{K_{Jc} - 20}{K_o - 20}\right)^4\right] \tag{7}$$

Along with this change, the distribution of probabilities was given a new equation to spread the ends of the distribution. It was

$$p = \frac{i - 0.3}{N + 0.4} \tag{8}$$

where i and N have the same definitions as in Eq. (2).

The resulting Weibull distribution in Eq. (7) had only one parameter to be fitted from the test results, K_o. This could be done with a least squares fit on a Weibull plot, similar to Fig. 4, were the fit is forced to have a slope of 4. To make the analysis of the data easier, a statistical method called “least likelihood” was used to fit the data (Wallin, 1994). This gave the following expression to find K_o from a series of N fracture toughness tests conducted on identical specimens at a fixed temperature.

$$K_o = \left[\sum_{i=1}^{N}\left(K_{Jc(i)} - K_{min}\right)^4 / (N - 0.3068)\right] + K_{min} \tag{9}$$

The value of K_o is related to the average of the distribution. Actually it occurs at the 63% probability. To base the analysis on a median probability value the 50% probability was used, p = 1- p = 0.50. This median value was labeled $K_{Jc(med)}$.

$$K_{Jc(med)} = \left(K_o - K_{min}\right)\left(\ln 2\right)^{1/4} + K_{min} \qquad (10)$$

The temperature distribution of the $K_{Jc(med)}$ value was studied for several heats of ferritic steels with yield strength levels ranging from 275 to 825 MPa. It was found that this temperature distribution fit on a common curve for all ferritic steels in the transition (Steinstra, 1990 and Wallin, 1989). This common curve was given the label "master curve". The master curve was fitted with an equation that is given by

$$K_{Jc(med)} = 30 + 70\exp\left[0.019\left(T - T_o\right)\right] \qquad (11)$$

where the K values are measured in MPa√m and temperature in °C. The master curve fit of Eq. (11) gives is based on a reference temperature T_o. T_o is the temperature where the $K_{Jc(med)}$ on the master curve reaches a value of 100 MPa√m. An example of the master curve trend is shown in Fig. 6.

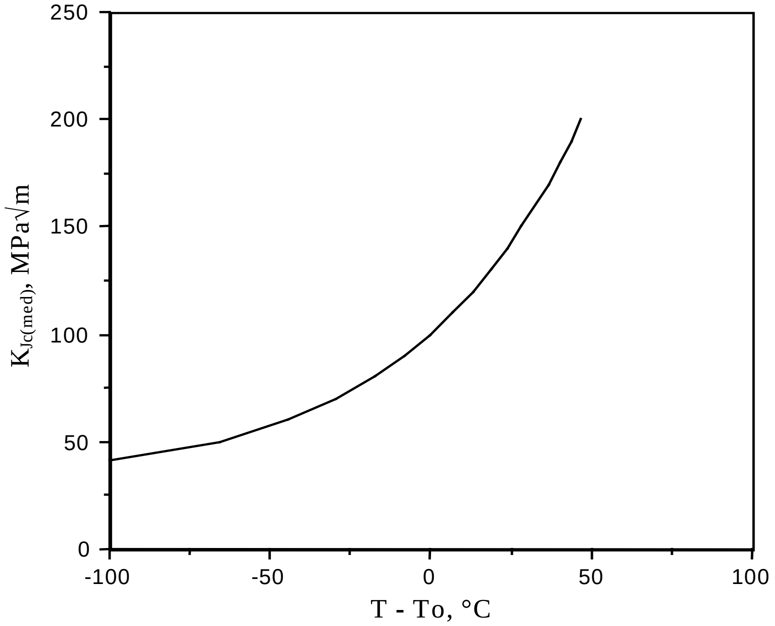

Figure 6 - Master Curve of KJc(med) values in the transition

Since there is a size effect that is predicted by the statistical distribution, this had to be part on the methodology used for the new Weibull statistical modeling. Whenever a unit size specimen was tested, defined as 25 mm thick with other dimensions being proportional, the toughness result could be directly entered into the analysis method of the above equations. However, if a larger or smaller size specimen was tested the toughness result must be given a size adjustment that comes from the statistical model. A specimen of thickness B_X, not 25 mm, is adjusted by

$$K_{Jc(unit)} = 20 + \left[K_{Jc(X)} - 20\right]\left(\frac{B_X}{B_{unit}}\right)^{1/4} \qquad (12)$$

where B_X is the thickness of the specimen and B_{unit} is 25 mm. For this and all of the analysis, the units must be SI, that is K in MPa√m and temperature in °C. The size adjustment can be applied to individual test results or it could be applied to the K_o or $K_{Jc(med)}$ values if these were generated from a single specimen size, not unit thickness, at a fixed temperature.

Then Eq. (11) gives the transition temperature fracture toughness distribution for all ferritic steels. Using this curve a set of fracture toughness tests conducted at a single temperature can be used to predict the fracture toughness at any other temperature in the transition. At a different temperature the distribution would follow the three-parameter Weibull distribution of Eq. (7) with the value at 50% failure probability $K_{Jc(med)}$ given by Eq. (11). The testing required to determine the fracture toughness behavior of ferritic steels throughout the transition is one to determine the value of T_o. Given a set of N tests conducted at a fixed temperature the value of $K_{Jc(med)}$ is first determined using Eqs. (9), (10) and (12). Then T_o can be determined from

$$T_o = T - \frac{1}{0.019}\ln\left[\frac{K_{Jc(med)} - 30}{70}\right] \tag{13}$$

The fact that all ferritic steels seem to fit the scheme of the Weibull statistics, Eq. (7), and the master curve, Eq. (10), is demonstrated empirically by examining transition fracture toughness data for many heats of steels. This has been done and virtually all cases where the strength of the steels lies between 275 and 825 follow this unique master curve trend (Kirk and Lott, 1999). The experimental evidence for this statistical approach and master curve evaluation is given in the companion paper to this one, also presented at this conference (McCabe and Sokolov, 1999). With the success of the approach the next step was to write a standard test method so that the methodology could be given a uniform testing and analysis procedure that could be followed by all laboratories interested in developing transition fracture toughness data in the transition for ferritic steels.

5. ASTM TEST METHOD

The method for analyzing fracture toughness in the transition has been standardized in the ASTM method E 1921 (E1921, 1997). In that method six or more fracture toughness tests must be conducted at a single temperature. The test results must fit a size criterion to be valid. This is given by

$$K_{Jc(limit)} = \left(E b_o \sigma_{ys} / 30\right)^{1/2} \tag{14}$$

where E is the elastic modulus of the steel, b_o is the original uncracked ligament size and σ_{ys} is the 0.2% material yield strength. The process of evaluating the validity of the test results and handling the invalid results is called censoring the data. Invalid values are not explicitly used in the data analysis but the $K_{Jc(limit)}$ value is substituted and the total number of specimens are used to determine N. The details of data censoring are given in the standard.

The results are analyzed with the Weibull statistical distribution in Eq. (7). The value of K_o is determined by the least likelihood analysis of Eq. (9). From this a $K_{Jc(med)}$ value is obtained and the master curve can be obtained by calculating T_o, Eq. (12). Having obtained the 50% probability of fracture and knowing the statistical distribution then allows one to determine a failure probability at any temperature in the transition. The failure probability of interested usually depends on how critical the design safety requirement is. For example if a 5% probability of failure is desired, the value of 1- p would be 0.05. Using a p value of 0.05 in the Weibull equations, a line of this probability can be put on the master curve plot as shown in Fig.7. That means that 95% of the toughness values would be greater than the ones represented by this line. Here lines representing probabilities of 1%, 5% and 95% are plotted with the master curve. Also, the original data that was used to obtain the master curve, six, specimens tested a fixed temperature is included on this figure. This illustrates how results from as few as six tests at a single temperature can be used to predict the toughness throughout the entire transition, the median toughness as well as any tolerance bound.

The ASTM test method E1921 then gives the organization for handling transition fracture toughness results for ferritic steels. The goal of understanding and organizing this problematic behavior has been realized after more than three decades of effort. Fracture toughness values for predicting fracture behavior in structural components can now be based on a statistical probability of fracture. With this method the large scatter in the transition can be organized and other effects, like the role of constraint can be studied on a more reasonable basis.

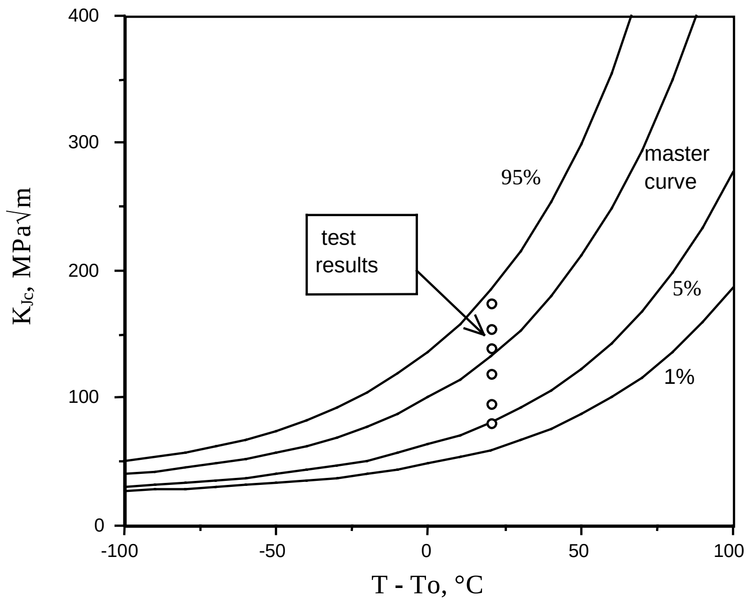

Figure 7 - Master Curve with tolerance bounds

6. SUMMARY

After several decades of concern about the characterization of fracture toughness in the transition for ferritic steels, a methodology has been developed based on Weibull statistics and a master curve. This method organizes the large scatter observed in the transition with a three-parameter Weibull probability distribution, gives a rationale based on these statistics for predicting size effects and allows tolerance bands predicting a given probability of fracture to be established on throughout the entire transition. This methodology has been empirically demonstrated to work for all ferritic steels examined. It has led to the development of an ASTM standard test method that can be used to characterize toughness in the transition. With this standard method only six valid test results are required at a fixed temperature to predict the entire distribution of toughness in the transition and to determine the probabilities of fracture. These results can then be applied to the prediction of fracture in structural components as well as examine other effects like the role of constraint on transition fracture toughness.

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