An Application of the J-Q Model for Estimating Cleavage Stress in the Brittle to Ductile Transition

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Abstract

A recent model has been proposed by the authors to predict cleavage failure in the transition for steels based on a weak link mechanism and a crack tip stress field modified for planar constraint by the J-Q theory. The model uses the distribution of toughness results at a single temperature to predict the same at a different temperature or for a different geometry. In this model a material cleavage stress is needed to predict when the weak link fracture is triggered. This cleavage stress is a key input for the application of the model but is not a property that is routinely measured and is hence not available for most steel alloys. Using a characteristic of the model this cleavage stress can be estimated from the result of two distributions of toughness values tested at two different temperatures in the transition. In this paper the method to estimate a value of cleavage stress is presented and the result is used to predict the toughness distributions for structural component models. Examples are given for several steels to show that a measured value of cleavage stress and one determined from the model result in nearly the same prediction of cleavage fracture toughness from the model.

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Introduction

Predicting the fracture behavior of steels in the ductile to brittle transition region has been a problem because the toughness exhibits size and geometry effects as well as extensive scatter [1]. One way to handle size effects and scatter is through the application of statistical models. The use of Weibull statistics and a master curve concept [2] has led to the development of a uniform standard test procedure as well as a way to handle the statistical treatment of the data and temperature effects in a reproducible manner. In addition the development of the two parameter fracture characterization [3-6] has allowed fracture behavior to be predicted with a fracture locus concept [7].

The master curve is used to predict the temperature effect on toughness for the test specimen geometry. It does not give guidance on the prediction of fracture in a structural component with a different geometry from that of the test specimen. The fracture locus concept has also been observed to have a geometry dependency that might cause difficulty in the prediction of fracture behavior for component geometries [8]. Therefore the problem of the geometry effect on toughness has not been completely solved by these methods. An approach that can be used is a mechanistic one rather than the traditional correlative approach. Mechanistic models could use a local crack tip fracture criterion to predict global fracture in a component.

Models for the prediction of brittle cleavage fracture in steels have been based on the attainment of a critical stress at some characteristic distance. Wilshaw et. al [9] proposed a model for brittle failure in notched bar under a bending loading. Ritchie et. al [10] proposed a model for the brittle fracture of cracked bodies based on the attainment of a critical stress over a critical distance. Heerens et. al [11] proposed a model based on the attainment of a critical cleavage stress at the point where a weak link existed in the material. To apply these models some knowledge of the stress field in front of the notch or crack is needed. Wilshaw et al [9] based the stress distribution on the slip line field analysis. Rice and Johnson [12] analyzed the stress distribution in front of a blunted crack tip with a slip line field analysis which included large deformation effects; this was used in the Ritchie et. al model [10]. Heerens et. al [11] based the stress distribution on an analytical model developed by Schwalbe [13]. These stress models did not account for constraint differences that would be caused by large scale yielding or the effect of the geometrical shape of the body being analyzed.

The recent development of the two parameter fracture mechanics models [6-9] allows the determination of crack tip stresses as a function of constraint. Hence the influence of size, geometry and thickness can be included in the calculation of crack tip stress as a constraint effect. With the development of the two parameter fracture characterization it is possible to reformulate the traditional stress based cleavage failure model to reflect the influence of such things as geometry or loading conditions. A recent model has been proposed by the authors to predict cleavage failure in the transition for steels based on a weak link mechanism and a crack tip stress field modified for planar constraint by the J-Q theory [8,14]. The model uses the distribution of toughness results at a single temperature to predict the same at a different temperature or for a different geometry. In this model a material cleavage stress is needed to predict when the weak link fracture is triggered. This cleavage stress is a key input for the application of the model but is not a property that is routinely measured and is hence not available for most steel alloys. Using a characteristic of the model this cleavage stress can be estimated from the result of two distributions of toughness values tested at two different temperatures in the transition. In this paper the basic components of the model will be presented. Then the method to estimate a value of cleavage stress is presented and the result is used to predict the toughness distributions for structural component models. Examples are given for several steels. Examples are given for several steels to show that both measured and predicted values of cleavage stress result in nearly the same prediction of cleavage fracture toughness from the model.

Review of Model

The model is based on a weak link failure mechanism. It is assumed that a weak link exists at some distance from the crack tip. The weak link requires a given value of stress, labeled here the cleavage stress, σ_c, to trigger failure. Once the failure of the weak link is triggered, the entire specimen fails. The cleavage stress is a material constant with a fixed value that is not influenced by temperature. However, other material properties such as the yield stress are a function of temperature. The crack tip stress is determined by a large strain numerical analysis which allows crack tip blunting and is put in the format of the J-Q model [4,5].

A schematic of how the model works is given in Fig. 1. The crack tip stress field has the characteristic pattern which can be developed numerically for large strain analysis. Distance from the crack tip in Fig. 1 is normalized by the blunted crack tip opening. The normalized parameter that gives the distance is $r/J/\sigma_o$, where r is distance from the crack tip, J is the crack tip loading parameter and σ_o a yield or flow stress. In terms of the normalized distance from the crack tip the stress pattern is stationary. An absolute distance r moves into the crack tip as loading is increased, that is J as is increased. A weak link at a given distance, r, from the crack tip will move into the stress pattern. If the stress peak is greater than the cleavage stress, the weak link will eventually touch the stress distribution at some point, that is, the stress level at the weak link will be greater than the cleavage stress needed to cause failure of the weak link. At that point a global failure will be triggered. The absolute level of the peak is not a factor in the failure if it is above the stress needed to trigger the failure, σ_c.

The maximum peak of the $\sigma_{\theta\theta}$ stress is scaled to the yield stress σ_o. As the yield stress decreases with temperature increase, the stress peak will eventually drop below the level needed for cleavage. In this regard the model is similar to others which have been proposed [11, 15]. The additional feature is that the stress peak is also scaled by the Q parameter where the value of Q is given by

$$Q = \left[\frac{\sigma_{\theta\theta}}{\sigma_o}\right] - \left[\frac{\sigma_{\theta\theta}}{\sigma_o}\right]_{(SSY)} \qquad (1)$$

As the loading is increased, hence J is increased, the constraint may begin to decrease and the peak of the stress field can decrease as illustrated in Fig. 2. The

value of Q also depends on the geometry and mode of loading of the body so the level of the crack tip stress distribution depends on the overall geometry of the body being analyzed as well as the loading condition and temperature.

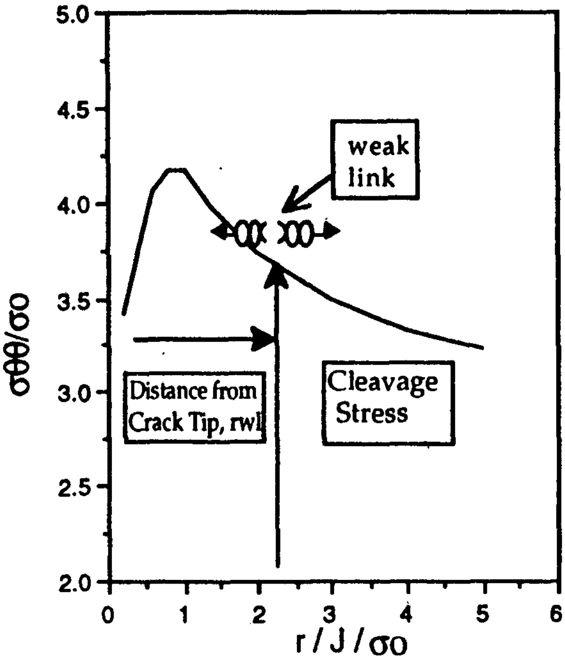

Fig. 1 - J-Q Based Weak Link Model

As the loading is increased, hence J is increased, the constraint may begin to decrease and the peak of the stress field can decrease as illustrated in Fig. 2. The value of Q also depends on the geometry and mode of loading of the body so the level of the crack tip stress distribution depends on the overall geometry of the body being analyzed as well as the loading condition and temperature. The presentation of the stress distribution in Figure 2 is different from that in Figure 1 in that the abscissa is not normalized but is absolute. Therefore the stress distribution moves to the right and down with loading.

The material characteristic in the model that quantifies the toughness scatter is the distance from the crack tip to the weak link. To make a prediction of fracture toughness an input set of fracture toughness values from a given geometry at a fixed temperature are used [8]. For the material a value of cleavage stress is determined separately [11]. The yield strength is measured at the temperature for which the model is applied. Then for each toughness given in terms of a J value, a distance from the crack tip to the weak link can be determined, here labeled r_{WL}. This determination uses a crack tip stress, $\sigma_{\theta\theta}$, which has been adjusted for Q. In the previous work [8] the Q values were taken from the work of O'Dowd and Shih [4, 5]. To predict the toughness distribution for a different temperature or geometry, a new value of σ_o corresponding to the new temperature is needed as well as a set of Q calibrations for the geometry. The value of cleavage stress is the same as before; it is assumed to be independent of temperature. From a value of r_{WL} determined above, the value of J which causes the crack tip stress, $\sigma_{\theta\theta}$, to reach the cleavage stress at r_{WL} is the toughness value for the predictive case. Then from the set of input toughness values, that is a set of r_{WL} values, a scatterband of toughness values can be predicted for the new temperature and/or geometry.

An important input to the model is the invariant cleavage stress. It can be measured by separate experiments [11], but is not often measured or reported in the literature. It would be desirable to make an estimate of the cleavage stress from other measurements. Using the fracture toughness results from tests at two different temperatures, an estimate of the cleavage stress can be made that gives reasonable results when used in the model. This procedure is discussed in the next section.

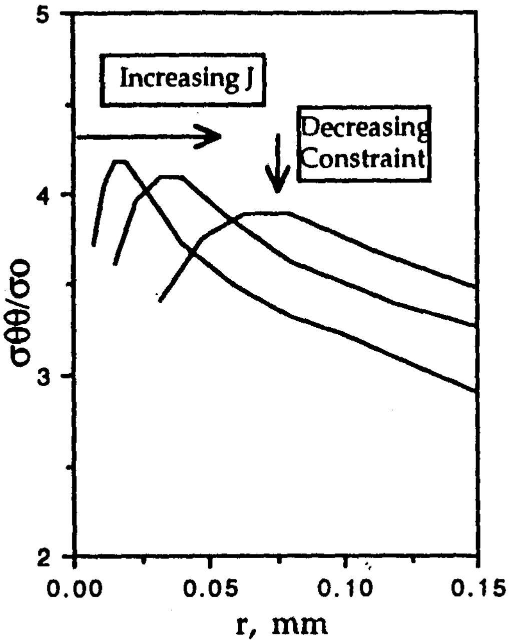

Fig. 2 - Change in Crack Tip Stress with Increasing J and Decreasing Constraint

<u>Prediction of the Cleavage Stress</u>

The cleavage stress, σ_c, is a key input to the model and is a material property that must be measured; it cannot be predicted from theory. Using the result of the model, that is that given a cleavage stress, a fracture toughness can be predicted at one temperature from a toughness value at another temperature, a method to predict a cleavage stress value was developed. If two toughness values exist at two different temperatures, it should be possible to predict the cleavage stress by an application of the model where cleavage stress and not toughness is the unknown. Since the toughness values measured at a given temperature show a lot of scatter, it would not work well to predict this cleavage stress from two single values of toughness at two temperatures. Rather a number of tests should be conducted at each temperature and an average or median value of toughness used for the prediction.

In the case studied here a median value of toughness was used for sets of data containing 10 or more data points. Two materials were used to evaluate σ_c, a CrMoV steel [15, 16] and a 20MnMoNi55 steel [15, 17]. For both of these steels a cleavage stress had been measured separately so that a comparison could be made. The approach was to use the median toughness at one temperature and try to predict the median toughness at the second temperature by guessing a cleavage stress and applying the model in the normal way. The guess of the cleavage stress was incremented and a second application of the model made. This procedure was continued until a range of predictions was made. It was discovered that in incrementing the cleavage stress to make a prediction, a local minimum or maximum was reached at the appropriate value of toughness, hence the correct cleavage stress. The prediction made from a higher temperature to a lower one causes a minimum and a prediction from a lower temperature to a higher one causes a maximum.

Examples are given for the two steels in Figures 3 and 4. For the case of the CrMoV steel the prediction was made from 80°C to 100°C and visa versa, Figure 3. For the 20MnMoNi55 steel the prediction was made from -90°C to -60 °C steel and visa versa, Figure 4. The prediction value of J_c in the figures was normalized by the absolute minimum or maximum in the group to allow comparisons to be made on the same scale. These normalized predictions are plotted as a function of the guessed value of σ_c. For the 20MnMoNi55 steel the local minimum and maximum are clearly seen and they occur at about a cleavage stress of 1600 MPa. For the CrMoV steel the minimum and maximum were not as distinct but they occurred at about 2000 MPa. The measured values of σ_c were about 1750 for the 20MnMoNi55 steel and 1900 MPa for the CrMoV steel. The predictions were not much different from the measured values.

In applying the model with these values of cleavage stress the result is not very sensitive to a variation in terms of predicted toughness. The model is sensitive to the value of σ_c for the prediction of the end of the transition region. This prediction corresponds to a point where the cleavage stress is higher than the crack tip stress predicted numerically and altered by the constraint as given by Q. Therefore a lower cleavage stress extends the transition temperature to higher temperatures. However, the actual toughness values predicted at not sensitive to values of σ_c as will be illustrated in the next section.

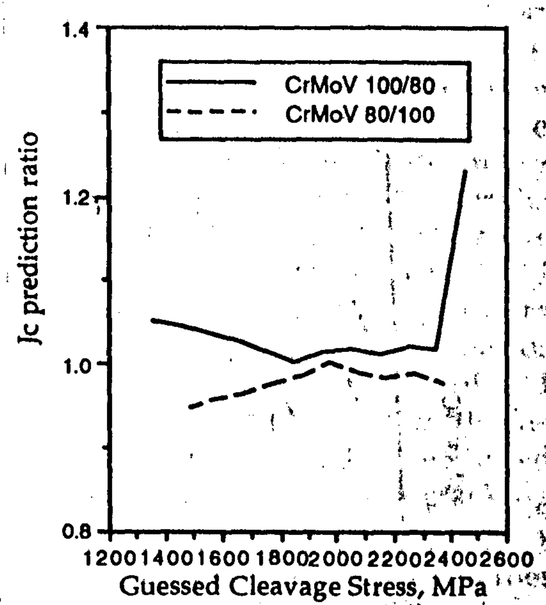

Fig. 3 - Ratio of Jc Predicted versus Guessed Cleavage Stress for CrMoV Steel

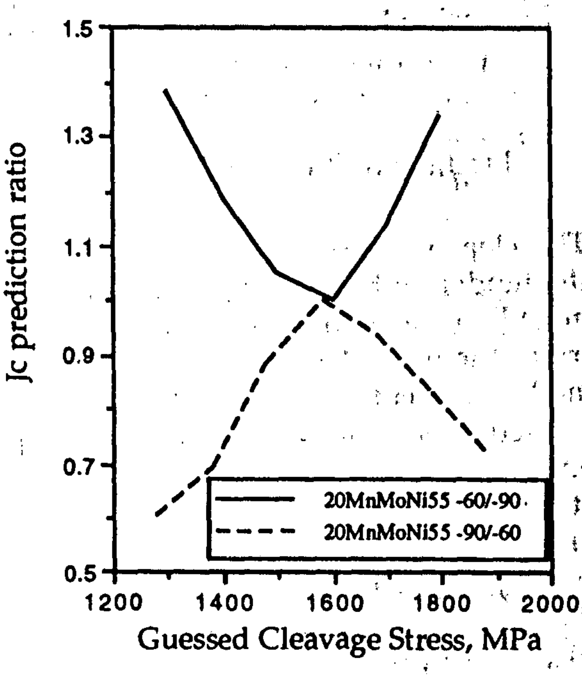

Fig. 4 - Ratio of Jc Predicted versus Guessed Cleavage Stress for 20 MNMoNi55 Steel

Demonstration of Model Predictions

Some examples of the application of the model are given first to illustrate how it works and second to compare the model predictions with different values of σ_c. The examples are given only for the 20MnMoNi55 steel where the difference between the measured and estimated values of σ_c were greatest. In Figure 5 a prediction is given for the fracture toughness of the 20MnMoNi55 steel at through the transition from input data at -90°C. The predictions are made from the median toughness value and from the upper and lower bound values of toughness at -90°C. The input data are the closed points, the predictions are given as trend lines. Measured values of cleavage fracture toughness at -60 °C are given as open points. Also on this figure the prediction of the end of the transition is given as a closed square. These features in Figure 5 illustrate the types of things that can be predicted from the model.

The predictions in Figure 5 are made for the measured value of σ_c 1750 MPa. To illustrate the effect of the cleavage stress on the prediction, the same predictions are made for the estimated value of σ_c, 1600 MPa. In Figure 6 the prediction of the range of cleavage toughness values at -60 °C is made using the two values of σ_c. As can be seen the scatterbands predicted from the -90 °C input data set are nearly identical. Also the predicted median value is not much different. In this case the predicted median toughness is 250 kJ/m^2 from with the 1750 MPa σ_c and 300 kJ/m^2 with the 1600 MPa σ_c. The overall effect of the value of cleavage stress is reflected more in the prediction of the end of the transition. This prediction is illustrated in Figure 7. The two values of σ_c are used to predict the end of the transition and a third value, 1900 MPa, is added to illustrate the trend of the prediction of the end of the transition. As can be seen in this Figure, there is an effect of the σ_c value on the temperature predicted as the end of the transition. Between the measured and estimated values of σ_c this is 20°C. Although this is visible on the figure, it is not a large effect for such a prediction. The actual end of the transition was not carefully measured for this material and is usually difficult to measure accurately. At the end of the transition the data include both test results that exhibit cleavage fracture, sometimes at surprisingly low values of toughness and those tests that are completely ductile fracture, exhibiting large values of toughness. In this regard the ability to predict the end of the transition could be valuable.

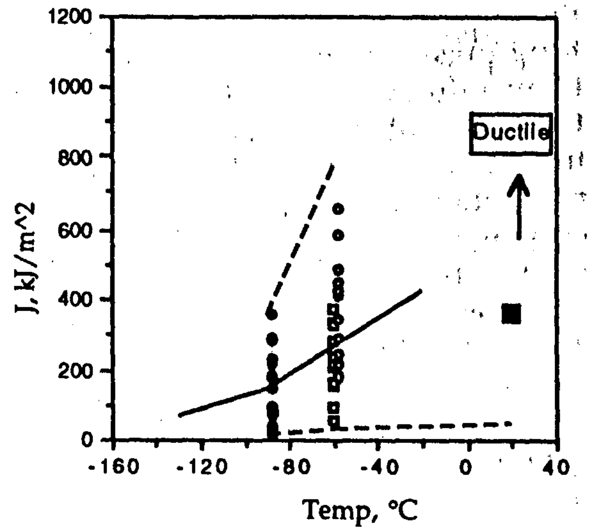

Fig. 5 - Transition Fracture Toughness Prediction for 20MnMoNi55 Steel

The result of these two predictions with the measured σ_c and the value obtained from the model are not very different.

For the prediction of actual toughness values the difference in the range of toughness predicted from a scatterband of input toughness value is very small. The prediction of the end of the transition is influenced more by the σ_c value but is also not very great. Therefore for materials that do not have a measured σ_c the prediction model for the σ_c would be satisfactory. However two sets of cleavage fracture toughness values at two different temperatures is needed as input. This is often available for materials whose transition fracture toughness trends has been studied [15].

Summary

The model to predict cleavage failure in the transition for steels requires a value of cleavage stress to make the prediction of a cleavage fracture toughness at one temperature from input at another. This value of cleavage stress can be estimated using the model from two sets of toughness values at two different temperatures. The values estimated for two different steels were reasonably close to the measured values. When the predicted and measured values of cleavage stresses were used with the model, the difference in the predicted toughness was not much. When the two different values of cleavage stress were used to predict the end of the transition a larger effect resulted but it was not a very significant one when compared with the uncertainty of test results.

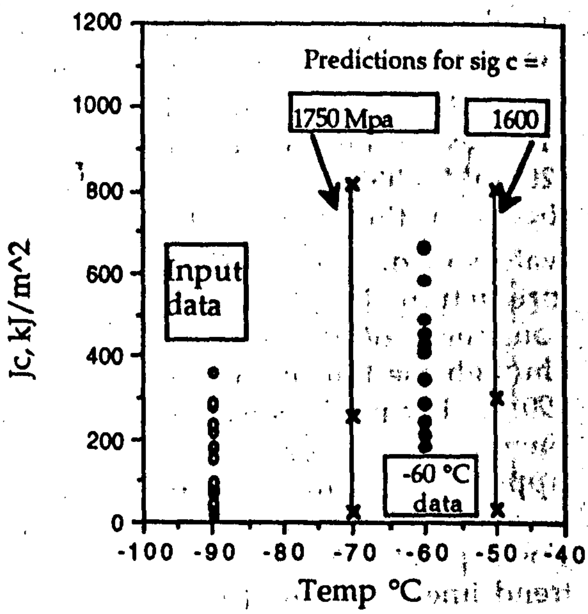

Fig. 6 - Prediction of Transition Cleavage with Different Cleavage Stresses

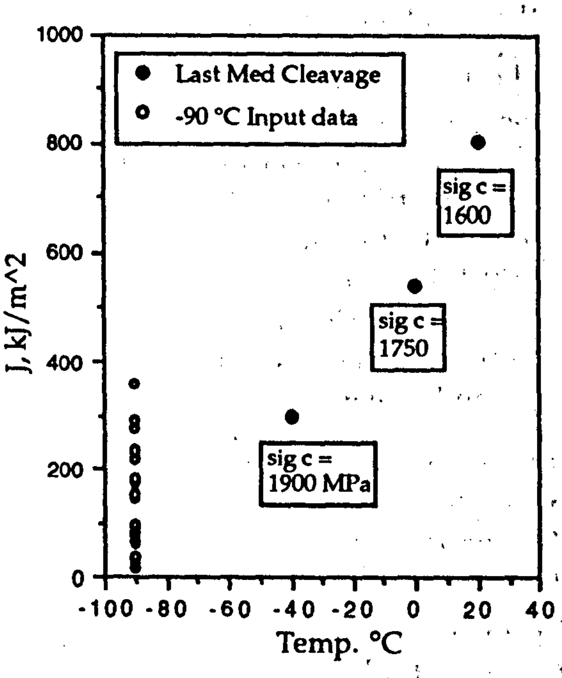

Fig. 7 - Prediction of Transition End with Different Cleavage Stresses

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