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BEHAVIOR PREDICTION IN THE DUCTILE-TO-BRITTLE TRANSITION PART I: AN OVERVIEW

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ABSTRACT

In the ductile-to-brittle transition region the fracture toughness values exhibit large scatter due to a combination of brittle and ductile fracture mechanisms; these results are strongly influenced by the dimensions and the geometry of the specimens.

This work presents some aspects of the ferritic steel behavior in the transition region and a recently proposed methodology to predict this behavior based on the two-parameter J-Q theory. In the part II of this work a methodology is given to obtain the cleavage stress of a given material from experimental fracture toughness values.

I. INTRODUCTION

Life extension of nuclear power plants has been a major issue in nuclear technology research in the last few years. The materials in these plants, mainly the reactor vessel and the primary components and piping, are subjected to neutronic and thermal aging effects for years. The need for safety and reliability of these structures in these plants created a need for fracture mechanics studies for the characterization of the brittle-to-ductile transition region exhibited by the ferritic steels, of which the pressure vessel and main primary components in a nuclear power plant are made. Only ferritic steels exhibit this transition region between the two well defined/characterized fracture regimes: the brittle and the ductile fracture. The problem of characterizing the behavior of the steel in this transition region is an important problem concerning the nuclear industry and others as, for instance, the naval industry.

A steel can show brittle fracture at low temperatures and, subjected to thermal aging (thermally cyclic load) or neutronic irradiation (that causes an embrittlement of the material), can show this behavior at higher temperatures. Essentially its toughness x temperature curve is shifted to higher temperatures. This shift becomes greater as the neutronic irradiation and the thermal aging are increased.

In this transition region the measured fracture toughness by the stress intensity factor K (or J integral) exhibits extreme scatter. This scatter is functon of the temperature, due to the combination of ductile and brittle fracture: in the low temperature range the brittle mechanism prevails while in the higher temperatures the prevailing mechanism of fracture is the ductile one. This toughness scatter is also function of the geometry and the dimensions of the specimen being tested. So it is difficult to determine a unique fracture toughness value for the material in this region.

Fig. 1 shows a typical curve of toughness versus temperature showing the transition region between the brittle regime (low temperature, lower shelf) and the ductile regime (high temperature, upper shelf).

The large data scatter was originally explained by a loss of constraint argument. However this was not consistent with the measurements because it did not explain why some of the small specimens showed the lost constraint (those ones with higher toughness) and other did not.

Therefore a statistical treatment was necessary to handle this large scatter, although a parameter related to the constraint level could be used to take care of the influence of geometry and planar dimensions.

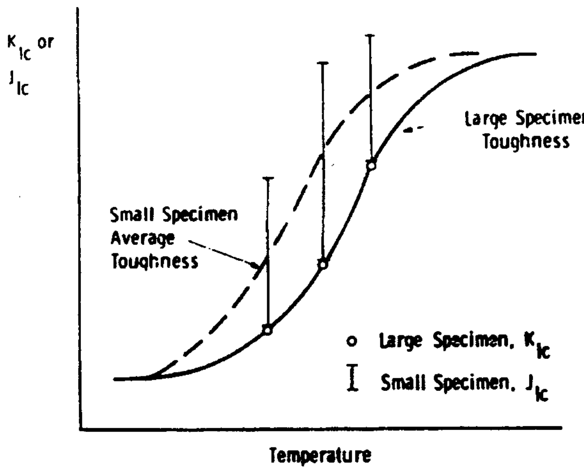


Figure 1. Typical Variation of K (or J) with the Temperature (Ferritic Steel)

II. STATISTICS - THE WEIBULL PROBABILITY DISTRIBUTION

In applying a statistical approach the weak-link principle can be used, in analogy with the principle of the resistance of a chain: no matter how many and how strong they are, the resistance of the whole chain is given by the resistance of its weakest link.

In this approach the Weibull probability distribution function can be used. It states that, if P is the probability to have cleavage with a toughness value Jc less than a given J, then:

$$P(J_c\langle J) = 1 - e^{-\left(\frac{J}{\theta}\right)^m} \quad (1)$$

In eq. (1) the fitting parameters θ (scale parameter) and m (Weibull slope) represent, respectively, the J value when Log[-Log(1-P)] = 0 (i.e.: P = 0.632) and the slope of the best fitted line when the points are plotted as Log[-Log(1-P)] x Log J.

It was observed that m tends to 2 as the number of specimens increases [1] (as K = √(J.E), m → 4 if the K values are to be used. In the remaining part of this section K will be used as the toughness parameter.).

As stated in eq. (1) this approach predicts a zero value of K for the zero probability of cleavage. But it is known that there should be a minimum of applied energy to break the already cracked material, i.e.: there should be a minimum toughness value (Kmin). Besides, experiments showed that the predicted range of results using eq. (1) is larger than the one experimentally measured [2]. Due to these facts a new expression, known as three-parameter Weibull probability, was adopted.

As well as m, Kmin should be a best fit parameter; however, from the observation of the experimental results, a constant value of Kmin = 20 MPa√m [3] is adopted. So, only Ko remains to be determined by a best fit procedure. To do this, according [3], and considering N measured results:

For the probability distribution the reference [3] adopts the expression (4.a). This expression gives a greater spread of the results than the expression (4.b).

$$P(K_c\langle K) = 1 - e^{-\left[\frac{K_c - K_{min}}{K_o - K_{min}}\right]^4} \quad (2)$$

$$K_o = \sum_{K_{c,i}=1}^{N}\left(\frac{\left(K_{c,i} - K_{min}\right)^4}{N - 0.3068}\right)^{1/4} + K_{min} \quad (3)$$

$$P = \frac{i-0.3}{N+0.4} \ \text{(a)} \quad \text{or} \quad P = \frac{i}{N+1} \ \text{(b)} \quad (4)$$

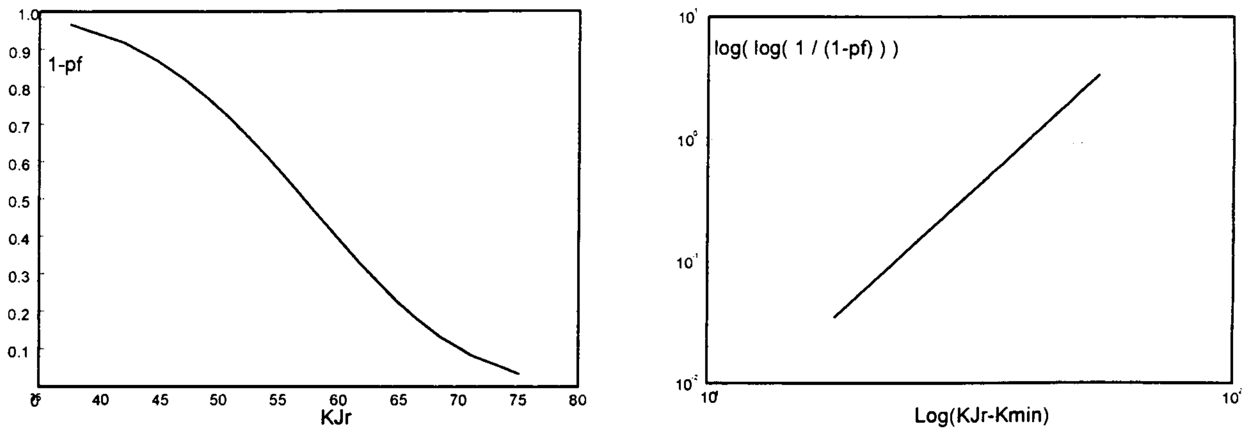
A typical Weibull 'perfect' distribution (obtained using the expression 4(a) and for N=20 points) is presented in fig. 2.a, the corresponding 'Weibull Plot' (LogLog x Log) being presented in fig. 2.b.

DATA SCATTERING. A statistical approach combined with the weak link principle can be a way to handle the large scatter of the toughness values in the transition region.

Usually for large specimens the toughness varies along with the crack-tip front more than in the smaller ones. Besides that, larger specimens can have several of those weak links and one of them can trigger the cleavage - that one nearest the crack-tip.

Small specimens will contain less of these points exhibiting, on the average, greater medium toughness values (due to its intrinsic small variation of toughness along with the crack front) ranging from values near those obtained with the larger specimens to much greater toughness values. This range will be due to the range of the distances between the crack tip and the weak link only. Fig. 3 shows a rationale for this hypothesis.

The distribution of the weak link distances can be assumed to be a material property.



(a) (b)

Figure 2. Weibull Distribution (a) and Weibull Plot - LogLog x Log (b) with 20 Values/Points for T-To=-50 °C

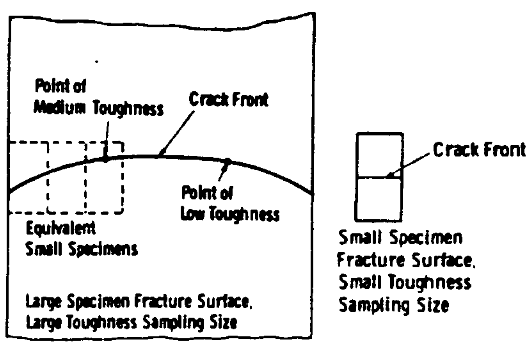


Figure 3. Crack Front in a Large and a Small Specimen

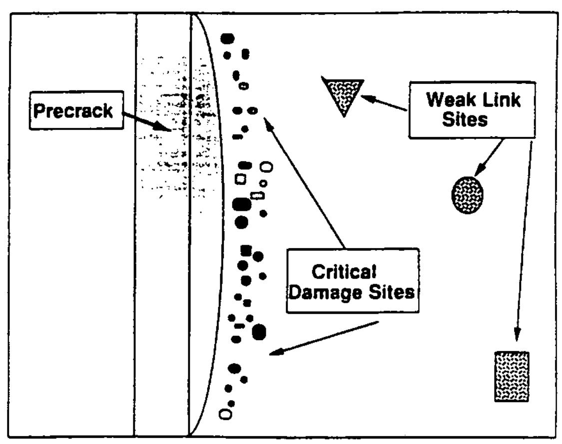


Figure 4. Initiation Sites - Weak Links and Critical Damage Sites

III. WEAK-LINK SITES X CRITICAL DAMAGE SITES

The high stresses produce microcracks in the material. These microcracks can propagate in a very localized region: the material grain. If one of these microcracks reaches a critical size the entire specimen or structure can fail.

The peak stress ahead of the crack-tip is a function of the material hardening and its yield stress (σ_{ys}). It was observed that these peak stresses do not vary significantly with the increasing loading but the stressed area increases with load.

A model was proposed [1] to explain the whole process of cleavage in the transition by two possible initiation zones: the Weak Link Sites and the Critical Damage Sites (CDS). The later occurs in great quantity but are smaller than the former, as indicated schematically in fig. 4. A given number of CDS should be activated by the stress fields (i.e.: the stress fields should spread over a large area) in order to have cleavage. On the other hand just one weak link should be activated to have the cleavage (with a stress level lower than that needed by the CDS).

The CDS mechanism is characteristic of the low transition region while the Weak Link mechanism is associated with the middle to upper transition region.

When stresses are high enough the fracture occurs by the CDS. If the peak stresses are not high enough to activate the CDS the fracture will occur only by the weak link mechanism. Between these two extreme conditions a mixed condition can occur.

IV. CONSTRAINT

As mentioned, initially the large scatter of the results in the transition region was explained by the differences between plane stress (small thickness) and plane strain conditions (larger thickness). When the region near the surface of the specimen, where the plane stress prevails, is small compared with its thickness, the behavior becomes independent of the thickness. To assure this behavior a usual criterion is given in the eq. (5) (where B is the thickness, a is the crack length) and, so, the stress field can be characterized by only one parameter like K (or J):

$$B = W - a \geq 200\left(J / \sigma_s \right) \quad (5)$$

For some conditions the stress field ahead of the crack tip cannot be well characterized by just one parameter (K or J). This characterization can be improved if one considers the plasticity level in the specimen and its constraint level

In [4]-[6] a theory developing a second parameter Q, related with the constraint level is presented, to characterize the stress field ahead of the crack tip along with the J integral. It was shown that this parameter Q is somewhat dependent on the radial distance r from the crack tip. Due to this the Q parameter is usually calculated at a normalized distance $r/(J/\sigma_o)=2$, where σ_o is the flow or the yielding stress. In a simplified manner this parameter can be seen as the second term in the expansion of the stress field expressions in a series and it is given by

$$Q = \frac{\sigma_{\theta\theta}}{\sigma_o} - \left(\frac{\sigma_{\theta\theta}}{\sigma_o} \right)_{SSY} \quad (6)$$

where $\sigma_{\theta\theta}$ is the stress ahead the crack tip and SSY stands for "Small Scale Yielding".

This parameter depends on the material hardening exponent n, geometry (a/w ratio) and loading (J). As defined by eq. (6), when the constraint is high $Q \rightarrow 0$. Typical examples this parameter are given in curves presented in fig. 5 [4,5].

V. BEHAVIOR PREDICTION IN THE TRANSITION

A new methodology [7]-[9], based on the two-parameter J-Q theory, was proposed to predict the fracture behavior of a given material in the brittle-to-ductile transition region considering the influence of the size, geometry, thickness and constraint level, besides the loading and the temperature itself.

With this approach it is possible to obtain the toughness distribution values J_{c2} for a given geometry G_2 and temperature T_2 from the results J_{c1} obtained from another geometry G_1 and temperature T_1.

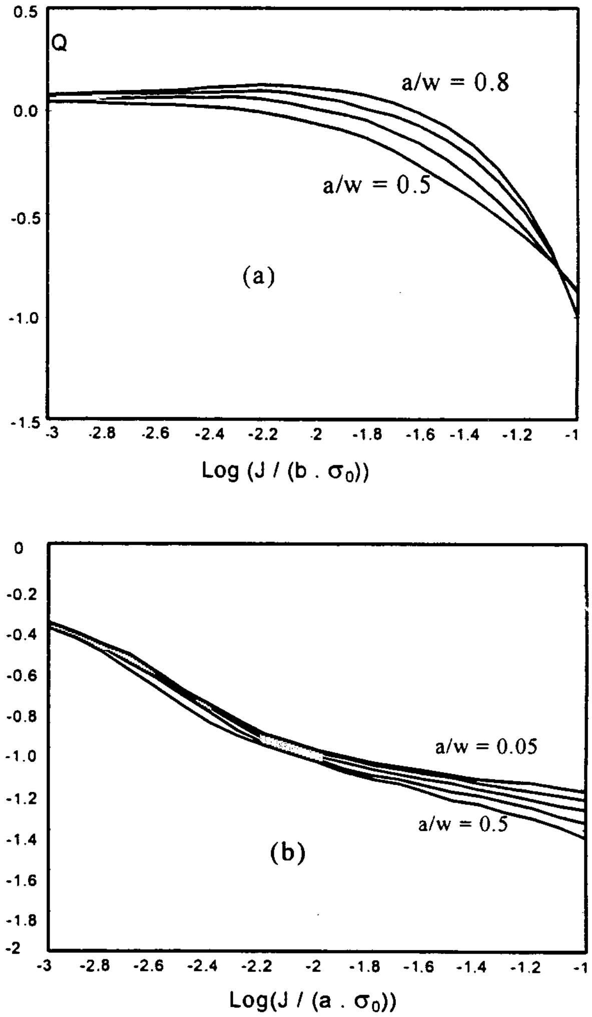


Figure 5. Parameter Q for n=10: (a) Three Point Bend Bar and (b) Center Cracked Panel [6]

Its basic hypotheses are: a) the cleavage fracture is triggered in the weak-link sites, b) the distribution of the distance r between the crack tip and the nearest weak link is a material property, c) the stress level to trigger the fracture is the cleavage stress σ_c (modified by the constraint parameter - Q) and once this level is reached, at the location of a weak-link, an instable crack growth occurs and the specimen fails, d) this cleavage stress is a material property and is assumed to be invariant with the temperature.

The basic input is the toughness distribution J_{c1} values for a given temperature T_1 and from a given geometry G_1. Also needed are: the yeld stress at T_1 and T_2, the Q parameter for the geometries G_1 and G_2 and the normalized stress fields as given in fig. 6, taken from [6].

When applying this methodology, initially for each value of the J_{c1} distribution ($J_{c1,i}$), the normalized distance r_{w1} is obtained using the dimensionless stress fields $\sigma_{\theta\theta}/\sigma_o$ given in [6] adjusted by Q (given also in [6] for some geometries).

This r_{w1} distance is measured from the crack tip to the point where the dimensionless cleavage stress (σ_c/σ_o) equals the dimensionless stress field (adjusted by Q). The actual distance is given by r_{w1} x ($\sigma_o/J_{c1,i}$).

The r_{w1} distribution obtained from this analysis is considered a material property and can be used to predict the J_{c2} values for another geometry and/or temperature using the inverse sequence followed to obtain r_{w1}. The J_{c2} values to calculate the Q values is unknown in this step so an iterative process is needed to determine the correct Q and hence the J_{c2} values.

It is possible to use this approach to make predictions for specimens/geometry with 2 crack tips using input from the standard single crack-tip specimens. In this case the probability of a weak link be triggered increases and a statistical adjustment is needed - basically the predicted results should be divided by $\sqrt{2}$ (if the J values are being used and a Weibull angle equal to 2 is assumed).

In reference [9] there are some hints on how to apply this methodology for surface flaws (tridimensional cracks) where the toughness and the constraint level vary with the position along the crack front.

A fundamental value in the briefly described methodology is the cleavage stress σ_c and this material property (microscopic measurement) is hard to determine because its value is greater than the usual material ultimate strength limit (a macroscopic measurement).

For this work the cleavage stress was available for only two materials: a 20MnMoNi55 steel [10] and a CrMoV steel [11]. It would be helpful in applying the method to have a way to estimate this property from results of the fracture mechanics experiments. It will be shown that this is possible, with the present methodology.

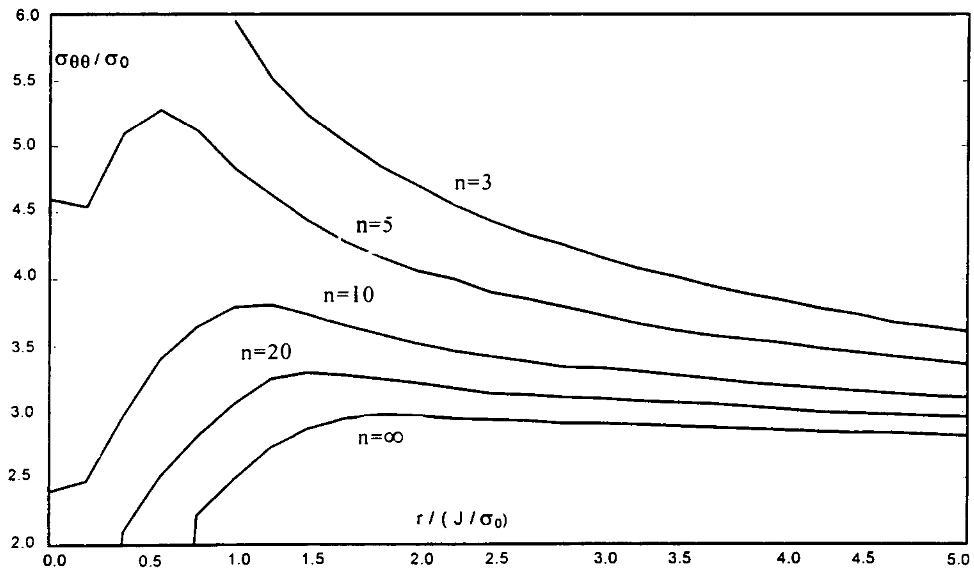


Figure 6. Normalized or Dimensionless Stress Field [6]

VI. DISCUSSION

The methodology presented to predict the behavior of a ferritic steel in the brittle-to-ductile transition region showed good results in those cases where it was applied [7]-[9]. However, until now, its application was limited: the cleavage stress of the material is usually not available.

In [13] this new utilization for this methodology is presented and the mean σ_c values for the already mentioned steels are predicted fairly accurately. The methodology was also applied to predict the σ_c values for other materials (the A533B and the A508 steels).

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