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ON PREDICTIVE MODELING FOR THE ASSESSMENT OF FRACTURE BEHAVIOR IN FERRITIC ALLOYS

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ABSTRACT

A new simplistic model is proposed for structural alloys for assessing the macroscopic fracture behavior in the upper shelf region. A local approach integrating the stress and strain distribution in the vicinity of the crack tip has been followed. The model is based on uniaxial tensile ductility and fracture strength as these two are assumed to have greater significance and control on the fracture process. J-integral toughness values are assessed from the proposed model and also experimentally determined at various temperatures. Ferritic alloys with a wide variation in composition, treatment and microstructure are used to check the validity of the model. The experimental data for the upper shelf region are found to lie within the upper and lower boundaries as set by the limiting number of major dimple sizes. The proposed model also provides reasonable indication of the temperature for transition to upper shelf region.

KEYWORDS: J-integral toughness, strain, stress, ferritic alloys, dimple, upper shelf, temperature

INTRODUCTION

Considerable amount of research efforts have been directed over the past decades towards understanding of the micromechanisms of fracture process in structural parts and components operating under various service conditions [1-3]. In numerous applications (for instance, nuclear reactor plants) a classical fracture mode transition from low energy brittle fracture to high-energy ductile fracture occurs due to increase in operating temperature and/or decrease in strain rate [1]. A prediction of such transition in the behavior is highly significant for the assessment of the integrity of all critical components and structures. Two approaches have been commonly followed for assessing fracture behavior of structural steels, namely, global and local approaches. The fracture mechanics based parameters (like K_{IC}, COD, J_{IC} etc.) are determined at the critical condition in the global approach [2]. The local approach integrates micromechanistic criterion of failure with analytical or numerical crack tip stress-strain distribution to model the macroscopic fracture behavior. Void nucleation and coalescence mechanisms leading to localized failure are dubious issues as various criteria are proposed [4,5]. The present work is an attempt towards the development of a simplistic model using uniaxial tensile test data that can be used in the upper shelf regime for assessing the fracture toughness values as well as the prediction of transition temperature.

THEORETICAL CONSIDERATION

Stress Strain Gradient

A steep gradient in stress and strain ahead of sharp stationary crack exists in small scale yielding situation as demonstrated by HRR crack tip analysis. Rice and Johnson model accounts for the crack blunting effect and large crack tip geometry changes in the stress and strain fields in the close vicinity of crack tip [6,7]. Modeling of crack initiation process by local criterion requires both stress and strain factors and consideration of either of them is not likely to yield realistic assessment of ductile fracture behavior. The local approach defines the crack initiation event as the coalescence of blunting crack tip with at least one of the growing voids [8,9]. Both stress and strain fields control the crack initiation process and should be taken into consideration for dealing with local failure criterion.

Failure Criterion

A new parameter giving equal significance and weightage to both fracture stress and fracture strain terms is proposed as $\phi = \sigma_{fc}^{N} \times \varepsilon_c^{pl.}$. ϕ represents the local failure criterion where σ_{fc}^{N} is true fracture stress in normal and $\varepsilon_c^{pl.}$ is the equivalent plastic strain. ϕ may be defined as the plastic energy density having the dimension as Joule per cubic meter. The normalized (non-dimensional) form of ϕ may be given by $\phi_N = \sigma_{fc}^{N} \times \varepsilon_c^{pl.} / \sigma_y$ where σ_y is the uniaxial yield strength of the material in tension.

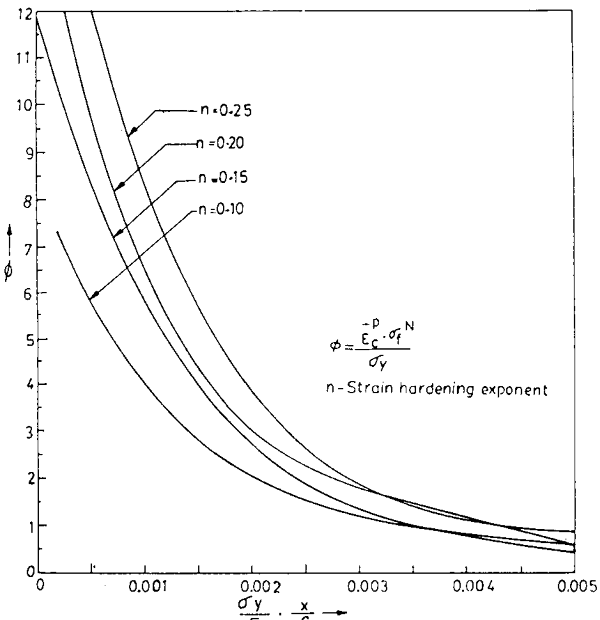

Figure. 1 Normalized composite parameter, ϕ vs. normalized distance from crack tip

A limiting amount of energy per unit volume of material i.e. ϕ or ϕ_N is required for crack tip deformation leading to void formation and void coalescence mechanisms prior to crack initiation. A polynomial function of 4th order is established to represent ϕ or ϕ_N mathematically and the graphical variation of ϕ or ϕ_N vs. normalized distance is shown in Fig. 1.

Assessment of J-Integral

The macroscopic fracture behavior of ferritic alloys in the upper shelf region is assessed by the critical J-integral value, J_{IC}. The critical plastic energy density is expected to prevail over the process zone at the onset of local failure. J_{IC} may now be obtained as

$$J_{IC} = \phi_c \times \text{ process zone size in joules / } m^2$$

Mathematical description of the model is based on the stress distribution as represented by $\sigma_{yy} / \sigma_y = f(E, n, x/\delta\ldots)$ where n is the strain hardening exponent, E is the elastic modulus, x is the distance from crack tip and δ is the crack opening displacement. The master curve can be used for the determination of J-integral toughness values corresponding to crack initiation. Bridgeman's analysis has been used to obtain equivalent plastic strain as $\varepsilon_c^{pl.} = 2 \log_e d_0 / d_f$ where d_0 and d_f are the initial and final diameters of a cylindrical specimen [10]. Experimental ϕ_{NC} value is used to determine a constant, k which is a function of both σ_y and E. The minimum number of major dimples constituting the process zone is one. The critical δ i.e. δ_c value may be further used to obtain J-integral value as $J_{IC} = m.\sigma_y. \delta_c$, where constant 'm' defines the state of stress condition prevailing at the crack tip. An approximate and rapid estimation of J_{IC} may be obtained from the experimental value of plastic energy density, ϕ. ϕ_C when multiplied with x_c yields J_{IC}. The schematic representation of the J-integral measurement procedure is shown in Fig. 2. The size of x_c is assumed to be related with the critical length and depends on the major dimple size.

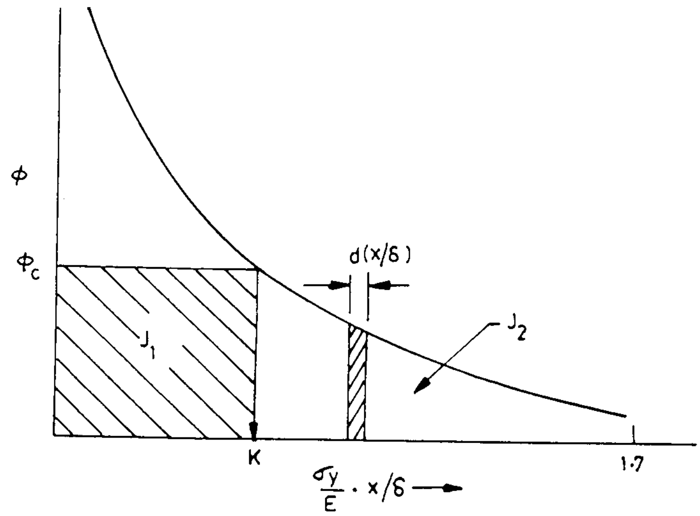

Figure. 2 Schematic illustration of J-integral computation from the proposed model

Sufficient Condition

It is argued that J_I is necessary to satisfy the requirement for local criterion for fracture. However, the global condition (region surrounding PZ) must also be set prior to local failure and accept any eventuality caused by local failure. In different words, J_I is a necessary criterion for localized failure, but not sufficient to meet the global requirement. If plastic energy density equivalent to J_I is supplied to cracked specimen. An estimate of J_2 may be made by considering the area under ϕ vs. x/δ plots (Fig. 2).

EXPERIMENTAL DETAILS

Fracture Toughness Test

Fracture toughness data were determined for a number of ferritic alloys at temperatures ranging from lower shelf region (≈ 140K) to upper shelf region (≈ 320K). Critical J- integral values were determined using 1T CT specimens following ASTM standards. Three J-values those are of primary interest to designers were determined, namely

(i) J_i at the onset of ductile crack initiation which is followed by stable crack growth,

(ii) J_c at the onset of cleavage fracture prior to initiation of ductile crack and

(iii) J_u at the onset of cleavage fracture following initiation of ductile crack.

A general variation of the fracture toughness with test temperature is displayed in Fig. 3 illustrating the region of temperatures where J_I, J_C and J_U were measured. Electrical potential technique was employed for monitoring crack initiation and growth in the CT specimens. At least four specimens were tested at each temperature to confirm the results. Uniaxial tensile tests were also conducted at each temperature using specimens of round cross-section (8 mm in diameter). The critical plastic energy density, ϕ was obtained from the tensile data at the corresponding temperature.

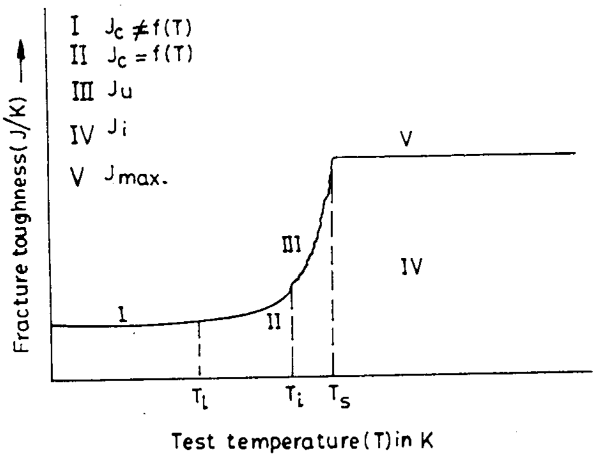

Figure. 3 Schematic representation of the fracture toughness with test temperature

Inclusion and Dimple Size Analysis

The small cut-out parts of the fracture surface from tested CT specimens were examined under SEM at different magnifications to facilitate measurement of the dimple size The fracture surfaces were gold coated for enhancement of contrast before examination. The average size of the primary voids (large) is given as 'D' while the average size for secondary voids (remaining) is represented as `d`. A typical fractograph displaying major dimples on the fracture surface is shown in Fig. 4. It was also found relevant to examine

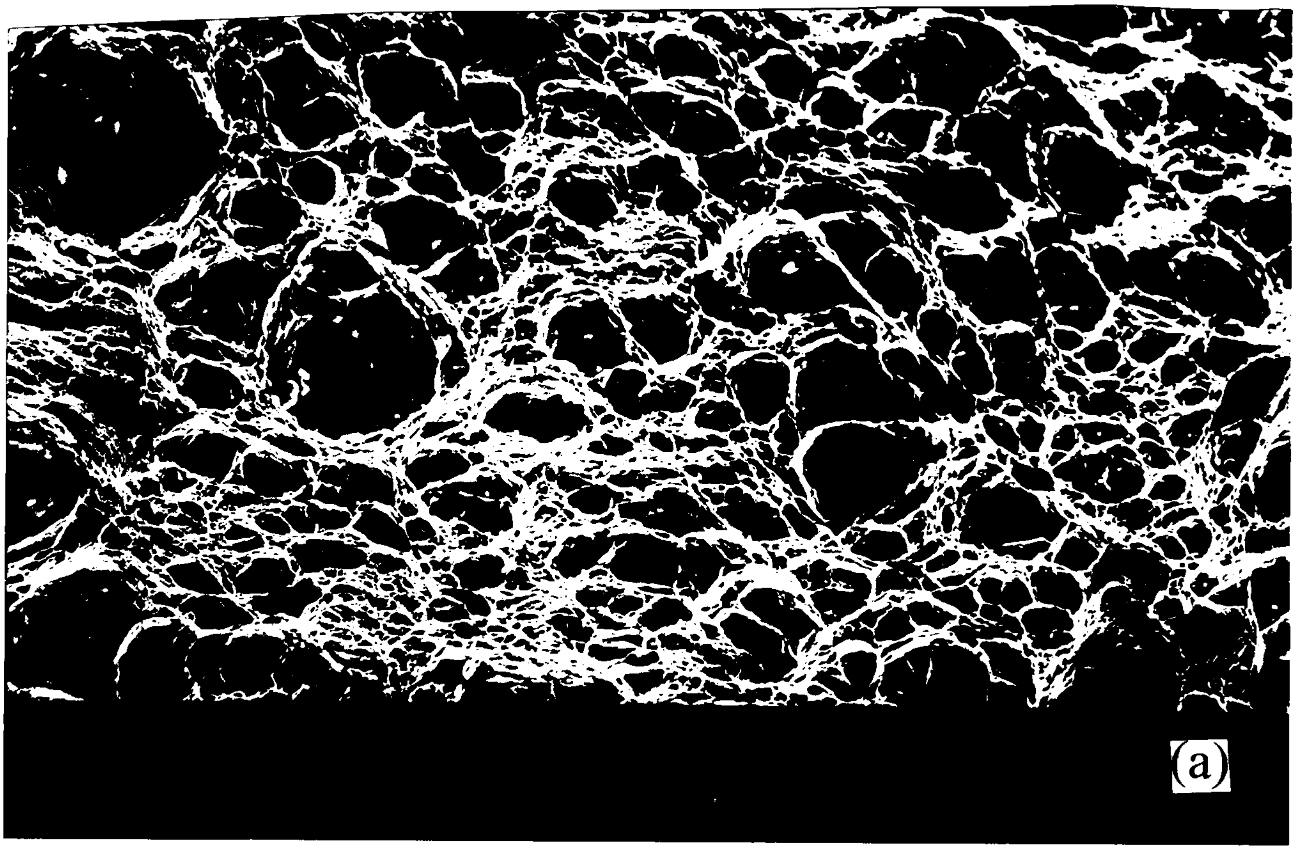

Figure 4. Typical fractograph showing major and minor dimples on the fracture plane in the thermomechanically treated sample.

the microstructures and the inclusion size distribution of the alloys. The inclusions and second phase particles are known to be the potential void initiators during the ductile fracture. The inclusions are occasionally observed inside the dimples irrespective of the microstructures. The inclusions are found to be dominantly of manganese sulphide type (MnS) and mostly in globular shapes. An attempt was made to establish a quantitative relation between the inclusion and dimple size to measure the extent of void growth up to the point of ductile failure initiation.

VERIFICATION OF MODEL

The validity of the proposed model is checked by comparison with the experimental data. The proposed model is essentially established for assessing the crack initiation fracture toughness, J_i in the upper shelf region. Fig. 5 displays the experimental J_i values for some of the alloys at different test temperatures. The J_C values corresponding to the cleavage fracture toughness in the lower shelf and transition temperature are also included in the figures. Considerable scatter of the observed data is evident. However, the J_i values are also found to be independent of temperature in the upper shelf region. The predicted values of J_i using the model are included for two conditions for each temperature of testing namely, assuming D =1 and D=2. Interestingly, in all most all cases, it is observed that the experimental data are falling within the two limits

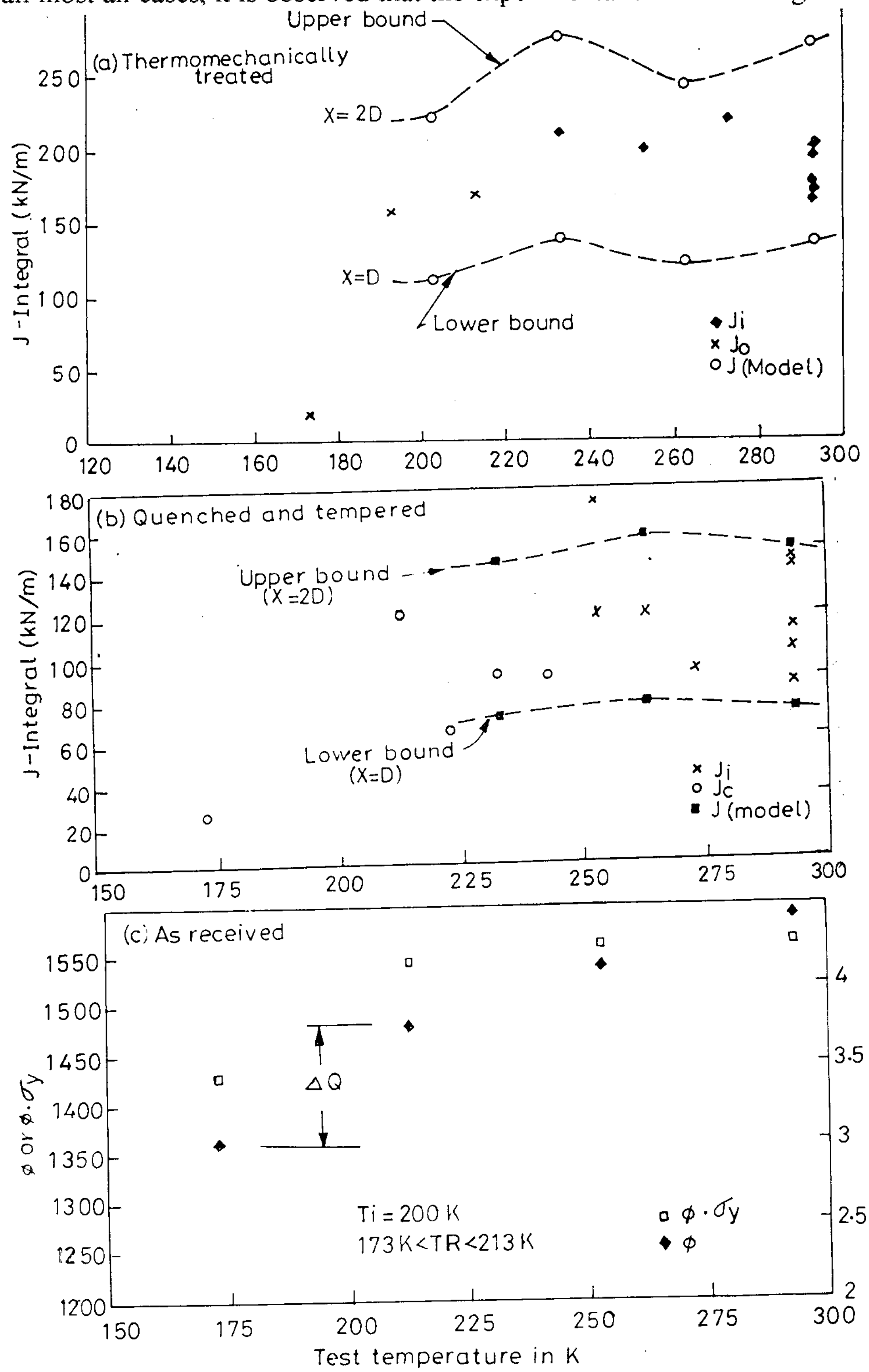

Figure 5. Comparison of the experimental and predicted fracture toughness data for ferritic alloys;

i.e. upper bound and lower bound values as shown in Fig. 5. The boundaries are shown by dotted lines. The lower line corresponds to D equals to 1 while D equals to 2 represents the upper boundary. The limits set by the two values of D represent the upper and lower bound for the scatter of the experimental data. Fig. 5c shows the quantum jump in the computed values of either ϕ or $\phi.\sigma_y$ around the transition temperature. The largest difference in the values of ϕ or $\phi.\sigma_y$ is proposed to give an indication for the transition to upper shelf region. In the particular case, the prediction for the transition is around 200K while the observation during the testing indicated the transition temperature to lie in the range of 173 K and 213K. This finding appears to be in contradiction to earlier claim that the process zone consist of a number of voids ahead of a sharp crack and linkage of all these voids are necessary for localized failure [1,11]. The present model clearly demonstrates that it is the formation, growth and coalescence of just one or two void(s) is sufficient for causing local failure. The blunted crack tip as gets deformed under increasing load links up with the major void formed over one or two inclusions. The number of voids taking part in the effective process of ductile crack initiation is thus found to be one at the least and two at the most. Consideration of the least number of dimple results in a conservative estimation of macroscopic fracture toughness values in the ferritic alloys.

CONCLUSIONS

1. A simplistic model based on the local fracture criteria is proposed, which integrates both the uniaxial fracture stress and fracture strain properties at the temperatures of interest. A composite dimensionless parameter, ϕ is found to be more logical and adequate to describe the fracture initiation behavior in the upper shelf region of the ferritic alloys. The proposed model based on the critical value of the parameter determines the fracture toughness data in structural alloys with fairly good matching with experimental data.
2. The macroscopic fracture toughness values have been assessed for a number of ferritic alloys with different microstructures and treatments using the proposed model. The lower and upper bound of the J-integral fracture roughness data are set by the limiting numbers (one to two) of the major dimples (voids) in all most all cases. The region between the two boundaries may be considered as the scatter band of the measured data. The critical J_{IC} values appear to be lowered by around 10 to 15 percent when the minor dimples are not taken into account. The quantum jump in the values of the critical energy density is observed and can be used to predict the transition temperature of the alloys.

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REFERENCES

1. Ritchie, R. O., Server, W. L. and Wullaert, R. A. (1979), *Metall. Trans.*, 10A, 1557.
1. Pineau, A. (1981), Procee. ICF5 (ed. Francois, D. et. al) 565-577.
2. Mackenzie, A. C., Hancock, J. W. and Brown, D. K.(1977), *Eng. Fract. Mech*, 9, 167.
3. Beremin, F. M. (1981), *Metall. Trans.*, 12A, 723
4. Chu, C. C. and Needleman, A. (1980), *J. of Engg. Mater. and Technol.*, 249.
5. Rice. J. R. and Rosengren, G. F.(1968), J. Mech. Physics of Solids, 16, 1.
6. Rice, J. R. and Johnson, M. A. (1970), Inelastic behavior of Soilds (Eds. Kannienen M. F. et. al.), Mc Graw Hill, NY, 641-672.
7. Hancock, J. W. and Mackenzie, A. C. (1976), *J. Mech. Phys. Solids*, 24, 147.
8. Ritchie, R. O., Knott, J. F. and Rice, J. R. (1973), *J. Mech. Phys. Solids*, 21, 395.
9. Bridgeman. P.W. (1952), Studies in large plastic flow and fracture, McGraw Hill, New York.
10. Kumar, A. N. and Pandey, R. K.(1984), *Eng. Fract. Mech.*, 19, 239