COBEM 99
XV Congresso Brasileiro de Engenharia Mecânica
15th Brazilian Congress of Mechanical Engineering
22 - 26 de Novembro de 1999 / November 22 - 26, 1999 Águas de Lindóia, São Paulo,

DETERMINATION OF THE CLEAVAGE STRESS OF FERRITIC STEELS IN THE DBT REGION USING SEM AND THE FRAMTiC MODEL

Carlos Tasso E. DeAquino
Itamar Ferreira
Universidade Estadual de Campinas, Faculdade de Engenharia Mecânica
Departamento de Engenharia de Materiais, Cx. P. 6122 – 13083-970 – Campinas, SP, Brasil
John D. Landes
University of Tennessee – MAES Department
310 Perkins Hall, Knoxville, TN 37996, USA
Arnaldo H. Paes de Andrade
IPEN/CNEN-SP – Instituto de Pesquisas Energéticas e Nucleares
Travessa R, 400, Cidade Universitária 05598-900 – São Paulo, SP, Brasil

Abstract. *The purpose of this work is to present a new approach based on fractographical observations, accomplished with scan electronic microscopy, developed for obtaining the necessary level of stress necessary to cause cleavage fracture in ferritic steels in the ductile-to-brittle transition (DBT) region. This approach uses a model, named FRAMTiC, based on analytical and experimental procedures and applicable to ferritic steels, that was initially conceived for making possible a better understanding of the fracture toughness behavior in the ductile-to-brittle transition. The model uses a numerical characterization of the crack tip stress field modified by the J-Q constraint theory and a weak link assumption to predict behavior in the transition. The model is able to predict the fracture toughness scatterband for any defined geometry from the knowledge of a toughness scatterband measured on test specimen geometry and can determine the end of the transition region. A new application of the model is applied, together with fractographical observations of fracture surfaces, is here presented: the computation and/or assessment of the level of stress related to the cleavage fracture initiation, namely cleavage stress.*

Keywords: *Fracture Mechanics, Ductile-to-Brittle Transition, Cleavage, FerriticSteels, Fractographies*

1. INTRODUCTION

FRAMTiC, **FRA**cture mechanics **M**odel for the prediction of the transition **T**oughness **i**n **C**leavage (DeAquino, 1997), is a model developed to predict the fracture behavior of ferritic steels in the ductile-to-brittle transition. Having been initially developed for predicting the fracture toughness value for a certain new combination of geometry and temperature from the knowledge of an initial situation (DeAquino et al., 1998a), it has its application extended for the determination of the end of the transition regime (DeAquino et al., 1998b) and the computation or assessment of the stress level, named cleavage stress, responsible for causing a cleavage fracture failure in the material under consideration.

2. THE FRAMTiC MODEL – GENERAL CONSIDERATIONS

The model here introduced, named **FRAMTiC** is based on the observations made by Heerens et al. (1991), that the cleavage stress of a given material (ferritic steel) is independent of the tested geometry, size and temperature, but that the fracture toughness, obtained in the ductile-to-brittle transition region, nevertheless exhibits a great scattering in its results. This toughness is dependent on the distance from the dominant weak-link responsible for triggering the cleavage process to the crack tip (Fig. 1), which is known as r_{wl}, the weakest-link distance. It should be noticed that many weak-links can exist ahead of the crack-tip, but only one is a trigger particle. As the r_{wl} distance varies from one tested specimen to another, the experimental results of two toughness tests in the transition can be very different, even when the specimens are manufactured from the same heat and same orientation of a given material and tested at the same temperature. The closer the weakest link is to the crack tip, the smaller the toughness will be. FRAMTiC considers that r_{wl} is at the same time a variable and a material property, being responsible for the toughness data scattering in the ductile-to-brittle transition region.

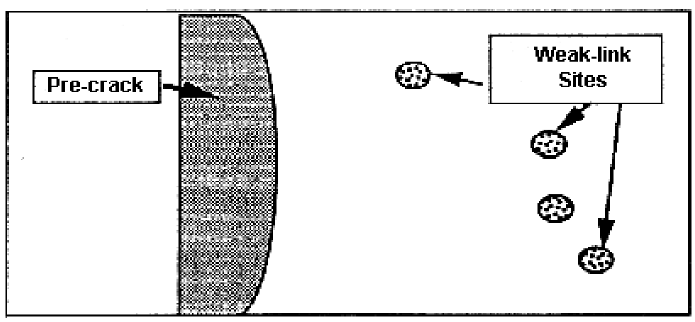

Figure 1–Weak-link positions ahead of the crack-tip

The model assumes as initial hypothesis that the r_{wl} scattering band is a material property, where r_{wl} is the distance from the trigger particle (weak-link) of the cleavage fracture process to the crack-tip. In the FRAMTiC model, the weakest-link position responsible for the cleavage fracture process initiation is defined as the intersection of the curve representing the crack-tip stress field with the straight line defining the cleavage stress level, as shown in Fig.2. Similarities can be noticed between this approach and the one proposed by Ritchie, Knott and Rice (1973), in its RKR model, where the cleavage failure is related to the occurrence of a stress level larger than the cleavage stress along a specific area ahead of the crack-tip.

The Heerens approach did not incorporate the effect of the crack-tip plastic constraint when modeling the conditions that lead to cleavage fracture. To solve this problem, in the FRAMTiC model the crack-tip stress field is modified by the Q parameter, as defined by O'Dowd and Shih (1991, 1992, 1993), for the plastic constraint level characterizing each particular geometry.

The methodology here presented can be applied not only to the prediction of the transition fracture behavior in a given geometry from experimental results accomplished in a different test geometry, but also to obtain the behavior of a same geometry in different temperatures. For both situations, it is necessary the cleavage toughness scattering band to be available in the initial situation, as well as the values of the Q parameter for this geometry and temperature condition. In the next step, one obtains the r_{wl} scattering band, which is considered to be a material property in the FRAMTiC model, allowing the prediction of the fracture behavior for other geometries and temperatures.

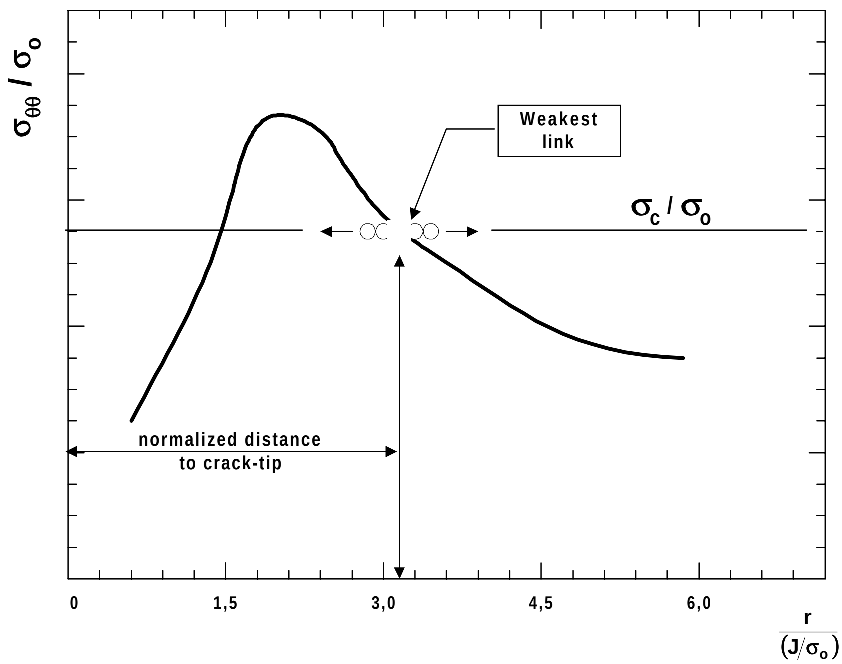

Fig. 2 – Definition of weakest-link location in the FRAMTiC model

3. THE FRAMTiC MODEL - METHODOLOGY

The FRAMTiC model is based on a Weibull statistical distribution (1951) and on a weakest link model (Landes and Shaffer, 1980) to explain the scattering of fracture toughness values in the transition area and uses a numerical characterization of the crack tip stress field modified by the J-Q constraint theory (O'Dowd and Shih, 1993) to eliminate the geometric dependence of the results. In a first step of its original application (DeAquino, 1998a), the objective is to compute r_{wl}, the distance from the crack-tip to the weak-link-weak responsible for triggering the cleavage stress. For that to be accomplished, the following material information has to be available:

- Yielding and tensile strength values for the initial temperature;
- Elastic Modulus for the initial temperature;
- Q curve for the initial geometry;
- Assumed value of the cleavage stress;
- Value of the cleavage fracture toughness J_C for the initial situation.

FRAMTiC was initially developed with the main purpose of allowing the fracture toughness prediction of ferritic steel structures containing 2-D cracks in the DBT region. In order to achieve such predictions using the FRAMTiC, it is necessary to start from the knowledge of toughness values obtained experimentally for a certain geometry and temperature, and then follow the steps listed below.

A. Gather material properties, in the initial condition, necessary for the application of FRAMTiC (specimen type and dimensions; assumed cleavage stress, σ_c; test temperature; toughness values, J_C, obtained from tests; yield strength, σ_{ys}, and tensile strength, σ_{uts}, measured experimentally);
B. Compute the r_{wl} scattering band, from the toughness values measured in tests;
C. Predict the toughness values for the new desired situation, that can be a new temperature, a new geometry, a new size, or a combination of those situations.

As part of the FRAMTiC development activities, a series of experiments were conducted at the Oak Ridge National Laboratory (Tennessee, USA) on a Brazilian A 508 Class 3 steel of nuclear classification (DeAquino & Liendo, 1995). Tension tests, Charpy-V impact tests and transition fracture toughness tests were performed to compile a small database necessary for the experimental validation of the FRAMTiC model. It is worth to mention that the fracture tests in the transition were accomplished following the rules of a new ASTM standard, E1921 (ASTM, 1998), still in a draft version by the time the tests were performed.

The strategy used for the experimental validation of FRAMTiC was to perform tests in two different temperatures, on specimens of a Charpy precracked geometry,and then, from the knowledge of the experimental data at one situation, predict the toughness values at the second situation. Finally, a comparison between the predicted values and the available experimental results was performed, being the results then evaluated. This process was repeated for specimens prepared in two different orientations, namely L-T and T-L. The chosen test temperatures were –120°C and –106°C, both in the transition region for the material under analysis.

Tables 1 and 2 present comparisons of the toughness values predicted using the model, in terms of J_C, with those obtained experimentally at -106°C, in terms of the average value and of the lower and upper bounds. From the observation of these tables it can be concluded that the predictions are quite close, mainly for the average value, being conservative in the definition of the fracture toughness scatterband. Figures 3 and 4 present graphically those results for the orientations T-L and L-T, respectively.

Table 1– Experimental Results x FRAMTiC Predictions (T-L Orientation)

J_C (kJ/m^2)	Measured value at–106°C	Predicted value
Lower Bound	52,99	39,45
Average value	97,30	91,42
Upper-Bound	179,61	183,80

Table 2–Experimental Results x FRAMTiC Predictions (L-T Orientation)

J_C (kJ/m^2)	Measured value at–106°C	Predicted value
Lower Bound	**31,09**	**28,35**
Average value	**95,22**	**107,19**
Upper-Bound	**169,46**	**171,84**

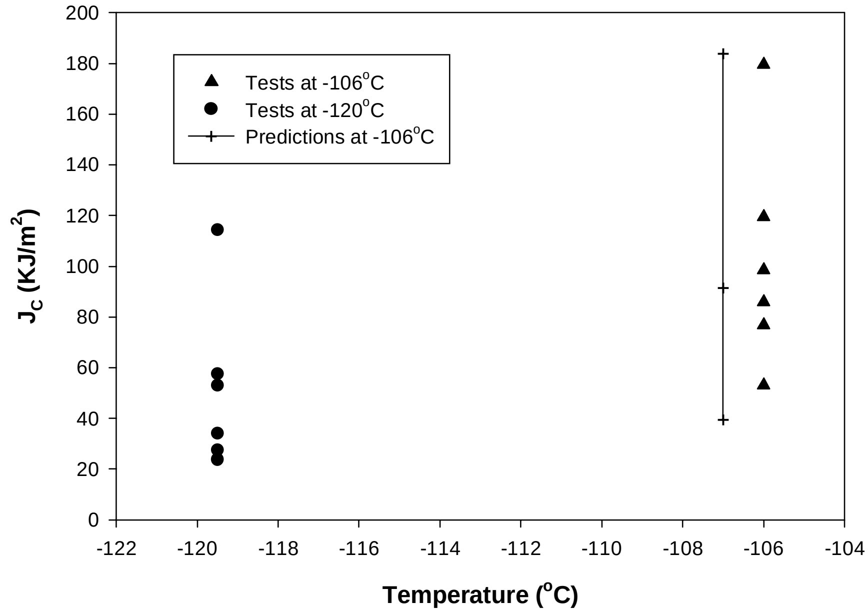

Figure 3 - Experimental Results x FRAMTiC Predictions –T-L Orientation

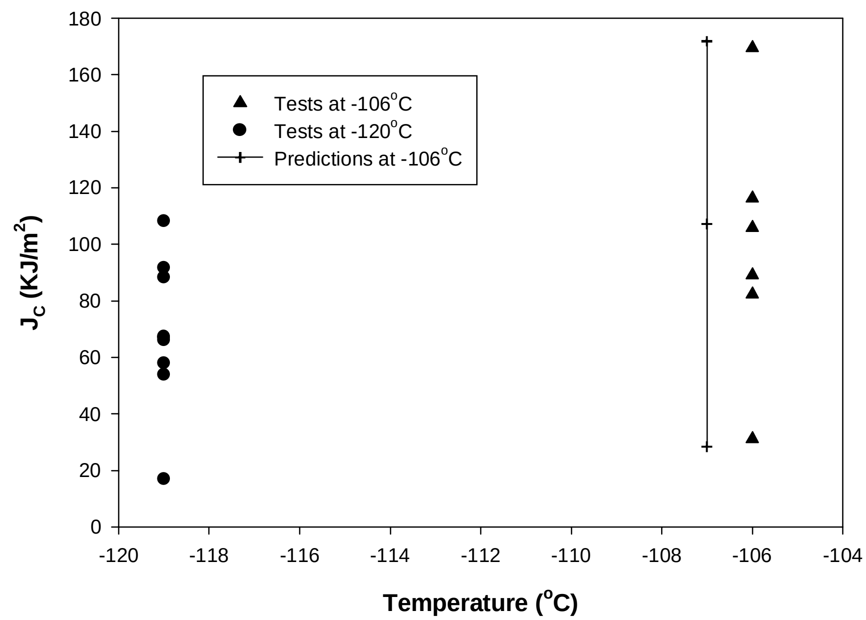

Figure 4 - Experimental Results x FRAMTiC Predictions–L-T Orientation

4. USING THE FRAMTiC MODEL TO PREDICT CLEAVAGE STRESS

If r_{wl} can be obtained through fractographical observations, accomplished by using a scan electronic microscope (SEM) to measure that distance directly in the tested specimen, instead of being calculated using the FRAMTiC Model, then it can be assumed that the only unknown of the problem becomes the cleavage stress. Furthermore, if one uses the procedures defined for the FRAMTiC Model in a reverse sense, it becomes possible to compute the cleavage stress numerically. This was initially used during the development of the FRAMTiC Model, to validate one of its main assumption: that the cleavage stress, as stated by Heerens et al. (1991) is independent of the temperature and remains in the same range for ferritic steels.

In order to validate this application, the authors used cleavage stress results, for a German 20MnMoNi55 steel, available from the literature (Heerens et al., 1991). For such a case, the cleavage stress varied in an interval from 1500 to 2000MPa, with an average value of 1750 MPa. For the comparison, experimental data was used, from fracture mechanics testing performed on a Brazilian A508 Class 3 steel at the Oak Ridge National Laboratory following the new ASTM E1921 standard (ASTM, 1998). The two materials considered in this analysis present similar mechanical behavior.

5. CLEAVAGE STRESS COMPUTATIONS USING EXPERIMENTAL DATA

After having tested the A508 Class 3 specimens, fractographies of the fracture surfaces were taken for a total of 8 specimens, in order to identify the location of the cleavage initiation site or the so-called weak-link responsible for the trigger of the fracture process. Figures 5 and 6 correspond, respectively, to the fracture surfaces of specimens L-T 6 and L-T 11, showing the fatigue precrack boundary and the trigger particle approximate site (identified in the photographs by the arrows). All the fractographies refer to Charpy V-notch precracked specimens, which present the geometric and mechanical characteristics listed in table 3.

The FRAMTiC model methodology was then applied to the experimental results for the computation of the cleavage stress. The obtained stresses are inside or close to the interval of values defined by Heerens et al. (1991) for the 20MnMoNi55 steel and similar steels, among which is the A508 Class 3 steel used in this work. In Fig. 7 the results of the cleavage stress predicted with FRAMTiC are shown, together with the maximum, average and minimum values as defined by Heerens. It might to be noticed that Heerens average cleavage stress (1750 MPa) was the value assumed in the development of the FRAMTiC model to make predictions of the transition fracture toughness values

Table 3 – Geometric and Mechanical Characteristics of Specimens

B = W	10 mm
b	5 mm
a/W	0,5
n (*)	10
σ_c	1750 MPa
σ_{ys}	550 MPa (for -106°C) 600 MPa (for -120°C)

(*) = Material's strain-hardening exponent

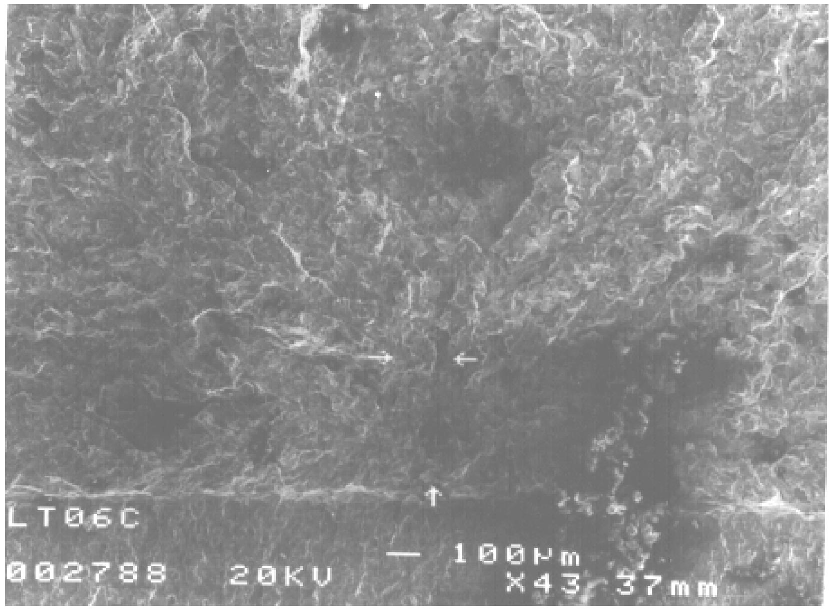

Figure 5–Fracture Surface– Specimen L-T 6

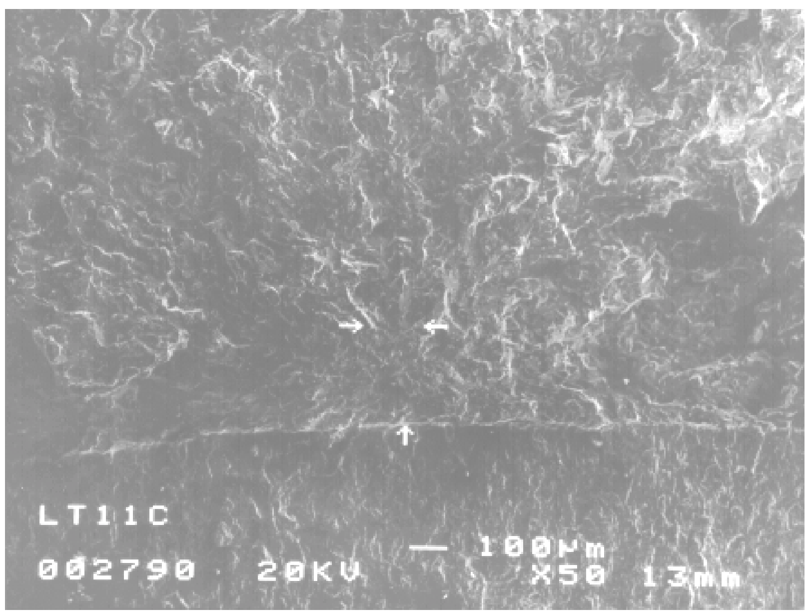

Figure 6–Fracture Surface– Specimen L-T 11

6. THE FRAMTiC MODEL AND OTHER APPLICATIONS

Other applications of the FRAMTiC model would include the prediction of fracture toughness values in the transition for structures / components with surface and internal cracks (still in research) and the correct determination of the end of the transition (DeAquino et al, 1999b). They, however, do not belong to the scope of this paper.

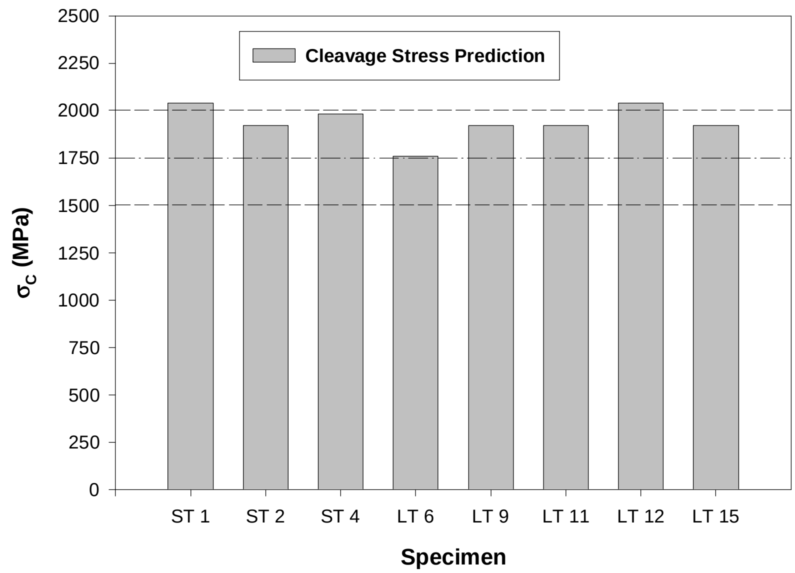

Figure 7–Cleavage Stress Assumed (1750 MPa) x Predicted (A 508 Class 3)

7. CONCLUSIONS

The FRAMTiC model presented in this work is a valid tool for the prediction of fracture behavior of ferritic steels in the ductile-to-brittle transition region. From the knowledge of results obtained in the tests performed on a Brazilian A508 Class 3 steel at the Oak Ridge National Laboratory, the model was validated for fracture toughness predictions in geometries containing 2-D cracks. From the observation of Fig. 7, one can conclude that the FRAMTiC is capable to aid in the estimation and in the assessment of cleavage stress values of structural materials that possess behavior characterized by a ductile-to-brittle transition. The presentation of new applications, such as the determination of the end of transition region and the fracture toughness prediction of structurae containing 3-D cracks, will be discussed in subsequent papers.

Ackowledgements

The authors would like to thank FAPESP, Fundação de Amparo à Pesquisa do Estado de São Paulo, for funding part of this research through Project 97/13023-4. The authors wish also to express their gratitude to the engineer Marcos Augusto and to the physicist Léa Sarita Montagna from the Navy Technological Center at São Paulo (CTMSP), that helped in the preparation of the fractographies, and to the engineer Marcelo Fabien Liendo, from Argentina, without whom the success in the experimental part of this work would have never been accomplished.

REFERÊNCIAS

ASTM - American Society for Testing of Materials, 1998, Test Method for the Determination of Reference Temperature, T_o, for Ferritic Steels in the Transition Range. (E1921). In: 1998 ANNUAL Book of ASTM Standards, Section 3: Metals Test Methods and Analytical Procedures, vol.03.01, Philadelphia, Pa., USA.

DeAquino, C.T., 1997, Uma Nova Abordagem ao Fenômeno da Variação da Tenacidade à Fratura na Transição Dúctil-Frágil de Aços para Vasos de Pressão Nucleares, Ph.D. Thesis, IPEN, University of São Paulo, São Paulo..

DeAquino, C.T. ; Ferreira, I. ;Landes, J.D. ; Andrade,A.H.P, 1999a, Fracture Characterization in the Transition – Part II: FRAMTiC – A Methodology to Predict the Fracture Behavior in the Transition Region, submitted for publication in Revista Brasileira de Ciências Mecânicas,

DeAquino, C.T. ; Ferreira, I. ;Landes, J.D. ; Andrade, A.H.P., 1999b, Fracture Characterization in the Transition – Part III: Determining the End of the Transition Region, submitted for publication in Revista Brasileira de Ciências Mecânicas.

DeAquino, C.T. & Liendo, M.F., 1995, Brazilian A508 Class 3 Steel - Test Results Using a New Proposed Standard for Evaluating Fracture Mechanics in The Transition Region. University of Tennessee: Department of Engineering Science and Mechanics, Knoxville, TN, EUA.

Heerens, J. ; Read, D.T. ; Cornec, A. ; Schwalbe, K.H-., 1991, Interpretation of Fracture Toughness in the Ductile-to-Brittle Transition Region by Fractographical Observations. In: Defect Assessment in Components - Fundamentals and Applications, London, England: Mechanical Engineering Publications, ESIS / EGF9, pp. 659-678.

Landes, J.D. ; Shaffer, D.H., 1980, Statistical Characterization of Fracture in the Transition Region. In: Fracture Mechanics: Twelfth Conference. Philadelphia, PA: ASTM STP 700, pp. 368-382.

O'Dowd, N.P. ; Shih, C.F., 1991, Family of Crack-Tip Fields Characterized by a Triaxiality Parameter: Part I - Structure of Fields. Journal of the Mechanics and Physics of Solids, vol.39, No. 8, p.989-1015.

O'Dowd, N.P. ; Shih, C.F., 1992, Family of Crack-Tip Fields Characterized by a Triaxiality Parameter: Part II - Fracture Applications. Journal of the Mechanics and Physics of Solids, vol.40, p.939-963.

O'Dowd, N.P. ; Shih, C.F., 1993, Two-Parameter Fracture Mechanics: Theory and Applications, NRC Rept. NUREG/CR-5958, Washington, DC, USA.

Ritchie, R.O. ; Knott, J.F. ; Rice, J.R., 1973, On the Relationship Between Critical Tensile Stress and Fracture Toughness in Mild Steel. Journal of the Mechanics and Physics of Solids, vol.21, p. 395-410.

Weibull, W., 1951 A Statistical Distribution Function of Wide Applicability, Journal of Applied Mechanics., Sept. 1951, pp. 293-297.