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Procedia Structural Integrity 42 (2022) 88–95

Structural Integrity Procedia

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23 European Conference on Fracture - ECF23

# History of ductile-to-brittle transition problem of ferritic steels

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**Abstract**

This paper presents a review of different approaches through history concerning DTB transition phenomenon of ferritic steels and their characterization using FM concept, from the earliest studies based on LEFM to the application of the EPFM concept. The large scattering of the experimental fracture toughness data, characteristic of all ferritic steels in the transition temperature region, has imposed the need of including statistical methods for data processing. Such approach that began in the 1970s can be encountered even nowadays as the base of fracture toughness data interpretation in DTB problems. An overview of studies with statistical interpretation of experimental data in the transition temperature region is also given. Aforementioned provides a foundation for novel approaches in DTB transition problems, which include size effects and scaling of geometrically similar specimens.



*Keywords:* ductile-to-brittle transition; ferritic steel; fracture mechanics

## 1. Introduction

Ferritic steels are in common use for most of constructions like pressure vessels, large machinery and other critical components where structural integrity might be jeopardized for different reasons, including low temperature loss of ductility, [1-10]. Namely, as it has been experimentally determined, ferritic steels break in ductile manner at higher temperatures, but in a brittle one at lower temperatures. The transition from ductile to brittle behavior during fracture

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10.1016/j.prostr.2022.12.010

takes place in a certain temperature region. This temperature interval, called DTB transition temperature region, corresponds to the temperature range in which the material changes the mechanism (nature) of fracture [11-12]. Ferritic steels, with their BCC crystal lattice, change their mechanical characteristics with decreasing temperature. Most importantly, the toughness decreases and with it the FM parameters (Fig. 1a). Fig. 1b depicts the dependence of the absorbed energy during impact of Charpy specimens on the test temperature and outlines the DTB fracture transition. There are several criteria of defining the DTB transition temperature, but most common are those at which the fracture energy passes below a predetermined value.

**Nomenclature**

| | |
|---|---|
| BCC | body centered cubic (crystal lattice) |
| CDF | cumulative distribution function |
| COD | crack opening displacement |
| CTOD | crack tip opening displacement |
| DTB | ductile-to-brittle |
| EPFM | elastic-plastic fracture mechanics |
| FEM | finite element method |
| FM | fracture mechanics |
| $J_{Ic}$ | critical value of the $J$-integral required to initiate a growth of a pre-existing crack under plane strain condition |
| $J_c$ | critical value of the $J$-integral corresponding to the cleavage fracture |
| $K_{Ic}$ | plane strain fracture toughness (critical value of the stress intensity factor under plane strain condition) |
| LEFM | linear-elastic fracture mechanics |

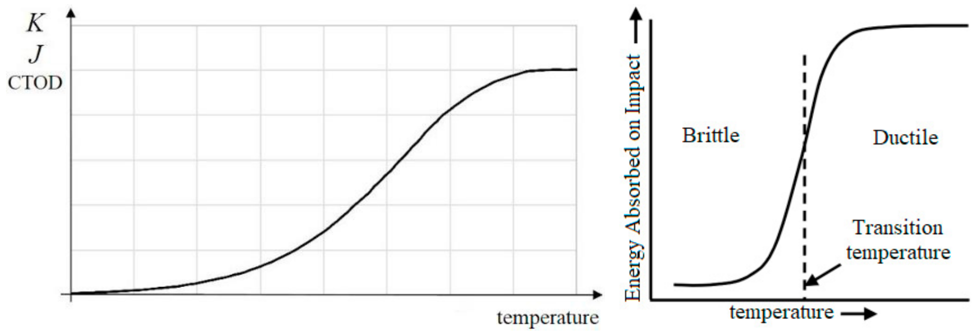


Fig. 1. (a) FM parameters dependence on temperature; (b) the DTB transition region.

In addition to the aforementioned, the change of fracture mechanism depends on the chemical composition of steel, or its sensitivity to changes of these properties due to temperature increasing/ decreasing. Thus, the conditions under which some ferritic steel undergo DTB transition depend on: shape of structure (e.g., presence of various stress concentrators), loading rate and temperature [13-15].

Studies that include determination of FM parameters necessarily dealt with data scattering in DTB region. Description, as well as interpretation, of these processed data most often represents the main challenge in defining the application domain of the tested ferritic steel. Simple fracture toughness characterization based on individual parameter values (such as $K_{Ic}$ or $J_{Ic}$) obtained during testing of a few, or even a single, specimen is not reliable due to the pronounced data scattering. Thus, the testing program should be optimized to result in a statistically meaningful sample size. The data scattering under the same testing conditions (temperature, displacement rate, etc.) necessitate involvement of other scientific disciplines, besides FM, and a short history to that extent is offered in the following chapters.

## 2. History of Fracture Mechanics in DTB transition region

The essence of the earliest studies was that the fracture toughness cannot be described only by the $K_{Ic}$ parameter due to potentially large plastic deformation in the DTB transition region, especially in the case of ferritic steels and general structural steels. With the EPFM development, the fracture toughness characterization in the DTB transition temperature region has gained a new impetus, but new requirements and limitations were encountered as well. To this date, a number of methods have been developed to analyze the results using LEFM and EPFM concepts.

Pioneer studies concerning fractures toughness of ferritic steels in the DTB transition region were naturally based on LEFM concept, more precisely on $K_{Ic}$ values. Begley and Toolin [16] calculated the fracture toughness and fatigue crack growth for Ni-Cr-Mo-V alloy in a transition temperature region during quenching followed by hardening. In the case of the tested alloy, they showed that fracture toughness increases until the room temperature, after which a stabilization follows that corresponds to an almost constant $K_{Ic}$ value in temperature range 90-260 °C. Unlike fracture toughness, the crack growth rate did not change significantly with temperature increasing. Campbell [17] conducted a similar study on a series of materials meant for application in extreme conditions. He got the first compilation of fracture toughness test data in strain-plain condition for different materials at various temperatures. Also, the strain-plain criterion and linear-elasticity were used to describe the fracture toughness ($K_{Ic}$). In the DTB transition region, the fracture toughness increasing of ferritic steels follows the temperature increasing. Campbell also concluded that at higher temperatures, the strain-plane criterion fulfillment requires larger specimen dimension, which is often not possible due to the apparatus limitations. Mager et al [18] made a significant contribution in the field of temperature dependence of the fracture toughness of ferritic steel A533, by pointing out the possibilities of statistical data processing.

However, the LEFM concept has an inherent limitation with regards to crack tip plasticity and the necessary extension to that extent was made with EPFM. One of the first studies describing the material fracture behavior in DTB transition temperature region using EPML was presented by Milne et al [19]. They investigated the influence of the specimen size on $J_{Ic}$ values using a relatively simple fracture model. Their idea was based on the fact that fracture mechanisms and the stable crack growth are in constant competition, where the initial crack growth leads to rapid brittle fracture. They noticed as well the effect of the tested specimen size on the results obtained in the transition temperature region. Due to plastic deformation that exceeds the criterion of small-scale yielding, Milne and coauthors introduced the stress intensity factor parameter $K$ in the plastic zone. Dawes [20], besides $J$-integral change, observed also the change of the COD parameter with temperature increasing on the welded joint made of steel BS4360 and the consequences of unstable fracture. It was also pointed out that the measured value of the $J_{Ic}$ affects the overestimation of the $K_{Ic}$ value in the case of steels yield strength below 700 MPa.

Heerens and Reed [11] in their study investigated the reasons for scattering of the obtained fracture toughness data using $J_c$ in the transition temperature region as well as the mechanisms that lead to fracture of C(T) specimens. The main conclusion of their study was that the scattering of $J_c$ values was due to scattering of the distances between the cleavage fracture initiation site (introduced parameter rc) and the fatigue crack tip. At first glance, Landes et al [21-22] explained basic concepts of ferritic steel behavior in the DTB transition temperature region, but most important contribution of their study was the method proposed for predicting the lower-bound of fracture toughness based on a single specimen testing. Landes further developed this method with other researchers as presented in [23]. A model proposed in [21] based on two criteria explained the nature of cleavage fracture scattering in the transition temperature region. Namely, two types of cleavage fracture initiation in C(T) specimen are possible. According to the first criterion, cleavage fracture occurs at the critical damage sites near the fatigue crack tip while, according to the second criterion, it occurs at the weakest links sites (that correspond to the pre-existing damage sites in the material a bit ahead of the fatigue crack tip and critical damage sites) (Fig. 2a). With his model used together with the Rice-Johnson model of stress concentration at the crack tip [24], Landes tried to explain two proposed aforementioned criteria. At lower temperatures, the yield stress has a higher value than at higher temperatures, so the stress concentration at crack tip (according to the Rice-Johnson model) is large enough to activate a fracture at the critical damage site. As the temperature increases, the yield stress decreases and, at some point, the activation of critical damages sites is no longer probable, so the cleavage fracture by activation of the weakest link sites becomes more favorable.

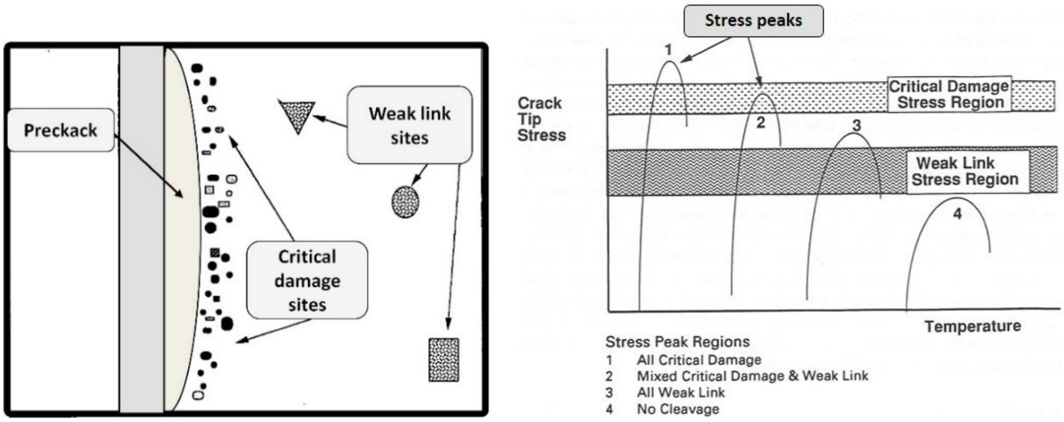


Fig. 2. (a) Schematics of the two proposed criteria of cleavage fracture initiation sites; (b) Schematic rationale of cleavage statistical zones [11].

Another important feature in the aforementioned studies, especially using of EPFM concept, was the scattering of the obtained results. New requirements and challenges have emerged from these scatterings, most notably in the field of interpreting test data and predicting fracture toughness in the DTB transition temperature region by using the statistical methods discussed in the next chapter.

## 3. Statistical Modelling of Cleavage Fracture in the DTB Transition Region

The large scattering of fracture toughness data (in either $K_{Ic}$ or $J_{Ic}$ form) of ferritic steels in the DTB transition region could be analyzed by statistical methods. This was a great challenge that required knowledge of material behavior, as well as fracture mechanisms; however, this also resulted in various limitations and simplifications of the proposed statistical models. Many studies were based on statistical processing of experimental results pertaining to cleavage fracture.

One of the trailblazing studies on the statistical processing in DTB transition region was the pioneering paper of Landes and Schaffer [25]. Based on the proposed statistical model, they concluded that it is possible to predict the results and general behavior of larger specimens based on the examination of smaller ones (e.g., C(T) ) in the transition temperature region for several types of steels. Their statistical model was proposed in the form of a two-parameter Weibull CDF (Eq. 1).

$$F_1(x) = 1 - e^{-(x/b)^c}, \quad x > 0 \tag{1}$$

The results of Landes and Schaffer study showed that extrapolation of the fracture toughness based on the of smaller specimens testing lead to "overestimating" predictions, so the conclusion was that this approach needed improvements.

Among the investigations that followed, stand out studies of Wallin [26] and Törrönen et al [27] that contributed significantly to the field of statistical characterization by explaining the influence of the size effect of Charpy specimens. It has to be emphasized that size effect is based on geometrical similarity of structures [28], in this case – the tested specimens. In the three-parameter Weibull CDF of cleavage fracture is defined as the function of $K$:

$$K_{B_2} = K_{\min} + (K_{B_2} - K_{\min})\left(\frac{B_2}{B_1}\right)^{1/4} \tag{2}$$

Wallin [26] has introduced a threshold value ($K_{\min}$) that limits the accessible material testing domain. Based on the test results on the smaller specimen thickness ($B_1$), the $K$ values of larger thickness specimen ($B_2$) could be predicted. A notable conclusion of both aforementioned studies was that, in the case of brittle cleavage fracture, the influence of the specimen thickness was closely related to the effect of the "weakest link".

Anderson and Stienstra [29] have investigated the scattering of fracture toughness results using "weakest link" model and analyzed the influence of the number of tested specimens (the statistical sample size) on the shape parameter (c) in the Weibull CDF in expression (3.1) in order to get best fitting curves. With specimen number increasing, shape parameter of Weibull CDF for $K_{Ic}$ or $K_c$ tends to 4, while the one for $J_c$ strives to 2. Stientra et al [30] and Landes [21] upgraded the previous studies by analyzing the appropriateness and reliability of the three-parameter Weibull CDF introduced by Wallin. Besides that, both studies have demonstrated the application of statistical methods to estimate the lower-bound value of the fracture toughness in the DTB transition region. Stienstra and co-workers [30] predicted the lower-bound value with a reliability of 5% by testing 3 or more specimens, while Landes [21] developed a method for the fracture-toughness lower bound estimation based on a single specimen testing. The only shortcoming of Landes method was its empirical setting and impossibility of verifying using any of the proposed statistical models.

The prediction of the fracture-toughness lower-bound in the DTB transition region was most often expressed in the form of the *J*-integral, but other parameters can be used, as demonstrated by McCabe et al [31]. To some extent, their method included constraint effect of C(T) specimen during testing by introducing the shape parameter Weibull CDF in the plane-strain condition. The fracture-toughness lower bound defined in this paper corresponds to fracture probability of 5%. A more detailed study on this topic and general effects that affect the experimental results (like defining the lower-bound of fracture toughness), reproducibility of the proposed method, limitations of the proposed methods and their individual applicability were presented by Zerbst et al [32-33].

It cannot be overemphasized that some studies were critical of the statistical approach and characterization of the fracture toughness in the DTB transition region and indicated the need for more in-depth analysis. As an example, Wei-Sheng [34] has raised the following questions:

- Is there is a sound theoretical basis for the application of two- and three-parameter Weibull statistics in describing the cleavage fracture toughness?
- Is it necessary for the Weibull CDF (K-form) shape parameter to be 4?
- What is the physical justification for fixing the fracture toughness lower-bound (threshold) $K_{min}$ introduced by Wallin [26] (which has later become the standard value in the ASTM 1921 standard)?

The conclusion was that the Weibull CDF fracture-toughness models with fixed shape parameter and the $K_{min}$ threshold were of dubious use without accompanying experimental data on temperature and constraint effects. This introduced a new topic, which is addressed in the following chapter.

## 4. Some novel approaches in DTB transition region studies

Recent studies concerning DTB transition region are based on predictions of cleavage fracture probability by fitting of Weibull CDF curves for any test specimen size taking into account the size effect. Still, the justification of statistical approach to the DTB transition can be met even nowadays by assessment of CDF cleavage fracture predictions using goodness-of-fit statistical tests. Influence of other effects, such as displacement rates during testing, as well as specimen pre-cracking (in laboratory conditions), provides broad insight into material behavior during cleavage fracture, along with transition temperature. These influences have been discussed hereinafter.

Djordjevic et al [35-36] have demonstrated the possibility of getting relatively good CDF cleavage fracture predictions for larger C(T) specimens made of steel 20MnMoNi 55 at low temperatures based on statistical methods and used Weibull model for the $J_c$ data manipulations. The CDF curves were obtained by using "weakest link" theory and the Weibull's two-parameter distribution. Testing was performed according to ASTM 1820 standard. Djordjevic and coauthors observed that the effect of temperature could be considered and interpreted individually, and that the Weibull scale parameter could be temperature dependent. It was also perceived that a certain effect of C(T) pre-craking (over $\Delta K$ values) on $J_c$ values exists, possibly due to greater deformation which might have caused plastic deformation at the crack tip (Fig. 3). However, improvement on the proposed approach should be advanced in further work, in order to confirm observed phenomena, especially the temperature dependence.

Previously obtained two-parameter Weibull CDF curves [35-36] provide a solid basis for further statistical processing by a custom-developed successive scaling approach. This novel treatment aimed to introduce a systematic approach to the C(T) specimen size effect analysis. To meet the stated objective, Mastilovic et al in [37-38] proposed an empirical expression of the Weibull CFD applicable to all C(T) specimen sizes at a fixed temperature in the DTB transition region (-60℃).

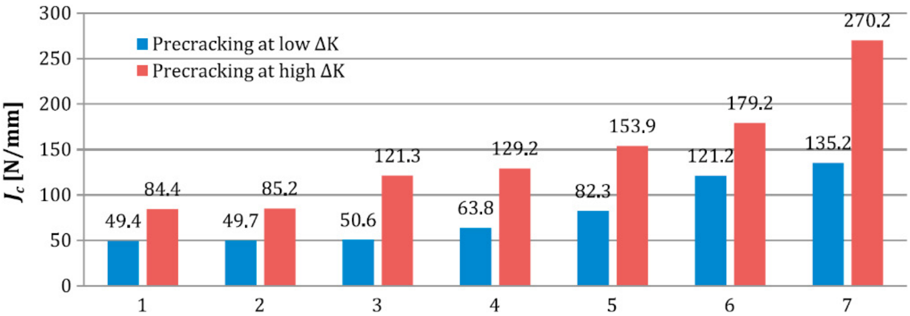


Fig. 3. $J_c$ values obtained by testing C(T)50 specimens at -90° C; blue – pre-cracking with low $\Delta K = 15.6$ MPa√m; red – pre-cracking with high $\Delta K = 38.9$ MPa√m [36].

The proposed scaling algorithm was developed and applied according to a two-step scheme schematically illustrated by Fig. 4. First, the $J_c$-scaling is performed (along the abscissa) to ensure the approximate overlap of the points that correspond to the Weibull CDF value $F(J_c = b) = 1 - 1/e \approx 0.632$ for different C(T) specimen widths ($W$), which assumes $b \cdot W^{\kappa} = \text{const}$. Second, the $F$-scaling was performed (along the ordinate) to ensure the equality of the slopes of the CDF in the scaled ($F \cdot W^{\xi}$ vs. $J_c \cdot W^{\kappa}$) space. These scaling steps define the values of the scaling parameters ($\xi$ and $\kappa$). The detailed analytical treatment is beyond the scope of the present review and only a succinct summary is deemed appropriate herein.

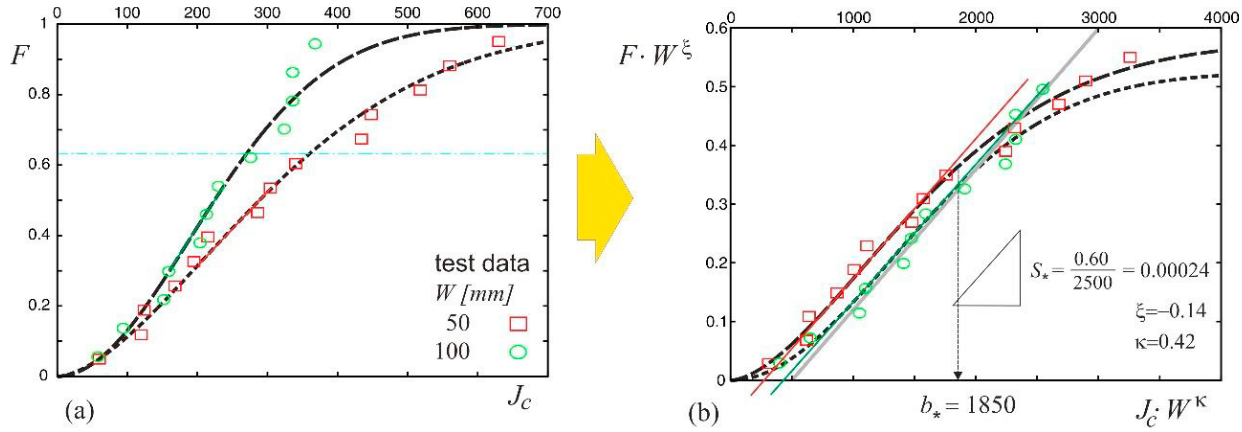


Fig. 4. Procedure of two-steps scaling for set of experimental results for 20MnMoNi 55 steel at -60 ℃: (a) fitting of CDF cleavage fracture probabilities of C(T)50 and C(T)100; (b) scaling along the horizontal and vertical axis [34].

As a result of the two successive scaling, in the proposed general expression, the Weibull CDF shape parameter c depends on the C(T) effective width ($W$) (the selected parameter defining linear size of the geometrically-similar specimen). The presented procedure [38] has provided the possibility of predicting fracture probability for C(T) sizes of a 20MnMoNi 55 steel at a temperature of -60 °C (Fig.5) by using only two experimentally availably C(T) data sets (e.g., $W = 50$, 100 mm depicted in Fig. 4) of a very moderate statistical sample size. Consequently, in the data interpolation range, the proposed methodology ensures very reasonable estimates of the Weibull $J_c$ CDF. More importantly, in the data extrapolation range, this novel approach based on two-step successive scaling of the experimental data, ensures that the lower-bound of the Weibull $J_c$ CDF is obtained (Fig. 5). With the C(T) specimen size increase, the lower-bound estimate becomes more and more conservative. The developed approach is applicable not only for ferritic steels but any material for which the Weibull statistics is deemed appropriate in the DTB transition region.

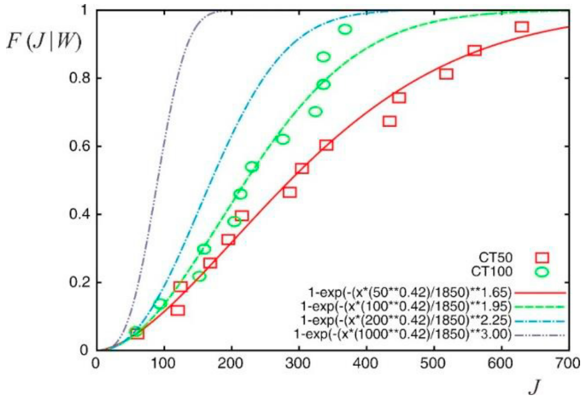


Fig. 5 Predictions of cleavage fracture probability based on the proposed successive scaling algorithm ( the test data corresponds to two C(T) specimen widths of 20MnMoNi55 steel at temperature of -60 °C) [38]

## 5. Conclusion

The main focus of all studies concerning the DTB transition of ferritic steels was a reliable assessment of characteristics and behaviour in transition temperatures in order to determine and assess the integrity of structures, as well as the application limits. Many studies have focused on the research of mechanisms that can trigger cleavage fractures. Although much has been done in this field, the conclusions drawn remain incomplete, limited or in some cases insufficient, due to the scarcity of experimental data or inability of adequate interpretation.

The Weibull's statistical model, used extensively in the past in many fields of science and engineering, was also used in the studies reviewed herein to explain the differences in the fracture toughness values of the specimens with different dimensions and the large data scatter of experimental data obtained for the same specimen dimension. Proposed models for fitting CDFs showed relatively reasonable prediction (or assessment) of results and supported the use of statistical models to explain the behaviour of the tested material in DTB transition temperature region.

Still, with recently performed research of DTB transition, a space was left for additional tests in a wider range of temperatures in order to verify the obtained dependence. Also, additional tests could include the dependence of displacement rates and temperature on fracture toughness. Finally, with more data available, the proposed scaling procedure can be improved, taking into account all of the aforementioned. This would increase the reliability of both the predictions (in the interpolation range) and the lower-bound estimates (in the extrapolation range). It has to be pointed out that the novel two-step scaling algorithm provides very reasonable estimates under constraint of a small statistical-sample size.

## Acknowledgements

This work is supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia (Contracts No. 451-03-68/2022-14/200105 and 451-03-68/2022-14/200213).

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