# Fracture Toughness Prediction for a Low-alloy Steel in the DBBT range

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**ABSTRACT:** *The aim of this paper is the determination of the fracture toughness from the Charpy impact test results in the ductile to brittle transition temperature range via the local approach to fracture.*

*Fractographic analyses showed that cleavage crack initiation is preceded by ductile crack growth. Furthermore, there is an evolution of cleavage fracture micromechanisms when the testing temperature increases: at low temperature, cleavage is triggered by second phase particle cracking, whereas at higher temperature another micromechanism induced by plastic deformation takes place.*

*Ductile fracture is modeled by the "Gurson Tvergaard Needleman" model, and brittle fracture is accounted for with Weibull type model. Finite element method was used to provide the local mechanical field needed for the local approach. Weibull parameters were found to vary with increasing temperature, which is consistent with fractographic observation. However, taking into account the evolution of cleavage micromechanisms in a phenomenological way, i.e. evolution of Weibull parameters with temperature is not sufficient to predict the fracture toughness from the Charpy impact tests. The influence of strain rate on the fracture criterion is discussed.*

## INTRODUCTION

Material's ductile-to-brittle transition temperature (DBTT) can be easily characterised using the Charpy impact test. However, Charpy impact energy cannot be immediately used for safety assessment, since fracture toughness is required. Some empirical formulas have been developed, but they have a limited validity domain, and have to be established for different materials.

Another way is to use the local approach, which aims to predict the fracture of any structural component using local criteria, providing that the mechanical fields in the structure are known. Ductile damage model, i.e. Gurson Tvergaard Needleman model [1,2] or Rousselier's model [3] can be applied in order to account for the ductile crack growth preceding cleavage in the DBTT range [4]. Cleavage fracture induced scatter in fracture energy can be modelled by Beremin model [5], which is based on Weibull statistics [6]. Previous works [7,8] using this approach showed that Beremin model fails to predict fracture energy in the ductile to brittle temperature transition range as it can be seen in figure 1. Therefore, considering only the temperature decrease of the yield stress is not sufficient to predict the increase of the mean value and the standard deviation of fracture toughness in the transition domain, even if the ductile fracture preceding cleavage is taken into account. In particular Rossoll et al. [7,9] pointed out that the hypothesis of temperature independence of Weibull parameters is probably the most questionable assumption of Beremin model. These authors proposed to rebuilt the fracture criterion on the actual micro-mechanisms of brittle fracture.

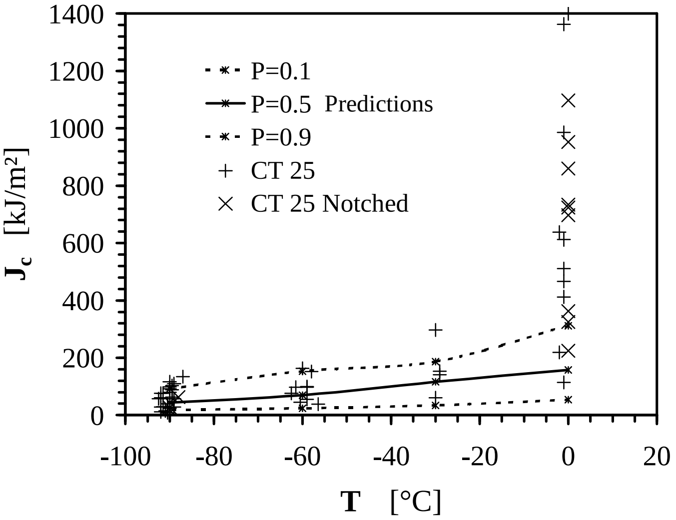

**Figure 1:** Fracture toughness prediction using the Weibull parameters identified from Charpy impact tests at low temperature (-90 °C) compared to experimental fracture toughness values.

In this paper, an extensive fractographic analysis is performed in order to determine the defects inducing cleavage fracture. Fracture surfaces of Charpy V-notch (CVN) and compact tensile (CT) specimens loaded at different temperatures in the DBTT range are observed. Consequently, the probability of cleavage fracture in the DBTT range is modelled by Weibull statistics based on fractographic results. For that purpose, local mechanical fields are computed by finite element method. The ductile crack propagation in Charpy and CT specimens is modelled using the Gurson-Tvergaard-Needleman (GTN) model. Weibull parameters are identified on Charpy impact tests and used for fracture toughness prediction. Finally, the numerical results are compared to experimental values.

## EXPERIMENTAL DETAILS

Material chosen for this study is French 16MND5 pressure vessel steel considered as equivalent to the American standard A508 Cl.3. The chemical composition is given in Table 1. Material had undergone a thermal treatment consisting of 2 austenitisations at 880°C followed by water-quenching, recovery annealing at 640°C and final stress relief treatment at 610°C.

The standard CT 25 and CVN specimens were taken from a nozzle cut-out of a pressure vessel (at ¾ thickness from the inner wall). The specimens were sampled in the T-S (long transverse-short transverse) orientation.

The tests were carried out at various temperatures ranging from -196 °C to room temperature. Three temperatures (-90 °C, -60 °C and –30 °C) were more detailed studied. About thirty CVN specimens were tested at each temperature for the statistical treatment of the cleavage fracture probability. The upper shelf impact energy reaches 160 J. The ductile-to-brittle transition temperature (defined as the temperature for which the mean fracture energy is half the sum of upper shelf energy and lower shelf energy) is –20 °C.

TABLE 1: Chemical composition of A508 Cl.3 steel (wt.%)

| C | S | P | Mn | Si | Ni | Cr | Mo | Cu | Al |
|---|---|---|---|---|---|---|---|---|---|
| 0.159 | 0.008 | 0.005 | 1.37 | 0.24 | 0.70 | 0.17 | 0.50 | 0.06 | 0.023 |

## FRACTOGRAPHY OF CLEAVAGE FRACTURE

Thirty among fractured CT and CVN specimens, in which the final failure was brittle (by cleavage), were carefully examined with scanning electron microscope.

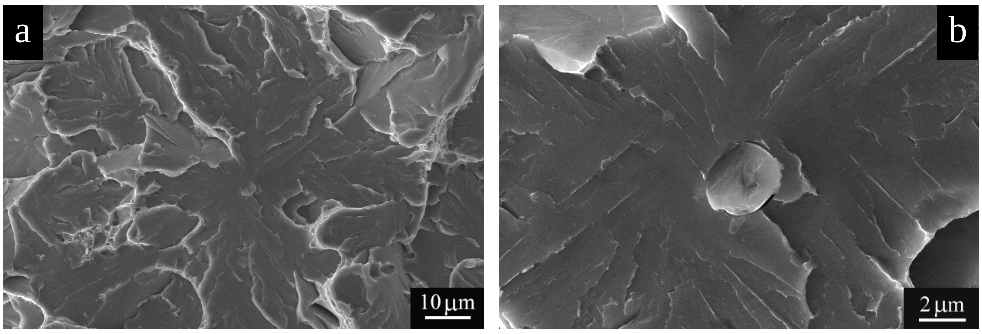

**Figure 2:** Cleavage initiation at low temperature (-90 ºC) – (a). Cleavage was triggered by cracked MnS inclusion (b).

Transgranular cleavage facets display more or less pronounced river pattern. Tracing back the river pattern, the most probable cleavage initiation sites could be found (Figs. 2 and 3). It should be emphasized that this fractographic analysis is considerably difficult. In most cases an area of several facets must be considered as a cleavage initiation site due to the lack of fractographic features.

At low temperatures, small broken inclusions (mainly composed of MnS) can be found in the centre of the initiating cleavage facets (Fig. 2a). These broken inclusions (Fig. 2b) create microcraks and the critical event in this case, is the growth of cleavage crack into the surrounding matrix.

At higher temperatures (near DBTT), the inclusions are rather debonded than cracked and even if they are cracked they participate in ductile fracture by cavity growth. Cleavage crack initiation is consequently preceded by

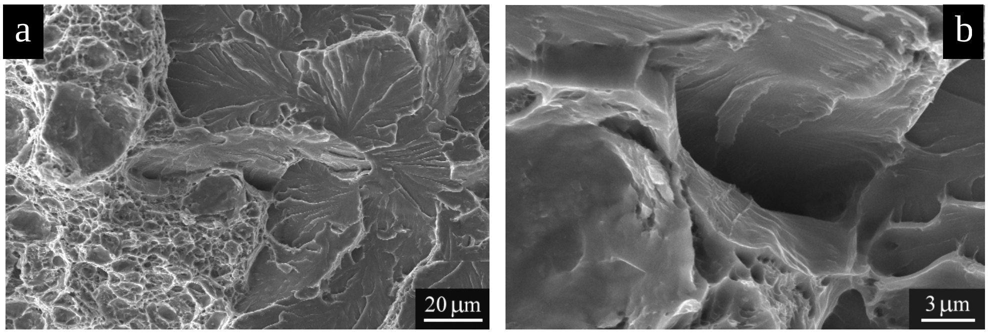

**Figure 3:** Cleavage initiation at higher temperature (20 ºC) – (a). Signs of significant plastic deformation on cleavage facets (b).

ductile crack growth. The ductile area situated next to the notch root is nearly correlated with the values of CVN impact energy even for the low values (< 20 J) [10]. The cleavage is then initiated by some plastic deformation induced mechanism (Fig. 3a) since no other remarkable fractographic features than signs of the significant plastic deformation can be found on initiating facets (Fig. 3b).

## DUCTILE FRACTURE MODELLING

For ductile crack growth modelling, a user-material subroutine incorporating the modified GTN model of porous metal plasticity was introduced into the ABAQUS™ software package. The initial void volume fraction was taken as the volume fraction of MnS inclusions given by Franklin formula [4]. The parameters of the critical void volume fraction inducing void coalescence, $f_c$, and the acceleration of the void volume fraction, $\delta$, were chosen in order to fulfil the load drop in the load vs. reduction of diameter diagram of notched tensile specimens NT2 and NT4 tested at 0 °C ($f_c$=0.04 and $\delta$=4). The temperature change caused by adiabatic heating during Charpy impact tests was taken into account. Other details on the mechanical behaviour can be found in Refs. [4,9,10].

Linear elements with selective integration were employed in the finite element analysis. The mesh size at the crack tip and/or notch root was (100 x 100) $\mu m^2$ in section. The computations were performed in the framework of finite strains, with an updated-Lagrangian formulation. The ductile crack growth during fracture toughness and Charpy tests was modelled in a 3D quasi-static formulation.

## PREDICTION OF CLEAVAGE FRACTURE PROBABILITY

The stress-strain fields ahead of the crack tip of the CT specimens and/or the notch root of the CVN specimens computed during the ductile crack propagation serve to the prediction of fracture probability, $P_f$, using the Beremin model based on two-parameter Weibull’s distribution:

$$P_f = 1 - exp\left[ -\int_{Vpl} \left(\frac{\sigma_1}{\sigma_u}\right)^m \frac{dV}{V_o} \right] \quad (1)$$

where $m$ and $\sigma_u V_0^m$ are the Weibull parameters, $V_o$=(100 μm)$^3$, $V_{pl}$ is the plastic volume, and $\sigma_1$ is the positive maximum principal stress.

The Weibull's parameters identified on CVN specimen are used for prediction of fracture probability as a function of fracture toughness computed by finite element method.

As has been said in introduction, using the Weibull's parameters identified on CVN specimen at low temperature leads to underestimation of the fracture toughness at temperatures near DBTT. Hence the first attempt is to develop the $\sigma_u$ parameter as an increasing function of temperature, $m$ being kept constant. The plasticity-based mechanisms inducing cleavage are probably associated with some thermally activated process so that it can justify an evolution of cleavage stress (and $\sigma_u$) with temperature. Thus the increase of the mean value of fracture toughness can be predicted. On the other hand, this approach fails to predict the increase of the standard deviation in the transition range. In fact, this approach supposes only an increase of the critical cleavage stress with temperature, but the fracture mechanism, i.e. the defect population remains unchanged, which is in contradiction with fractographic observations presented in the previous section.

For that purpose, the Weibull's parameters were identified at different temperatures (on CVN specimens) in order to account for the temperature evolution of cleavage fracture mechanism. So that identified Weibull's parameters are reviewed in Fig. 4. The temperature evolution of these parameters is chosen as an exponential function of temperature.

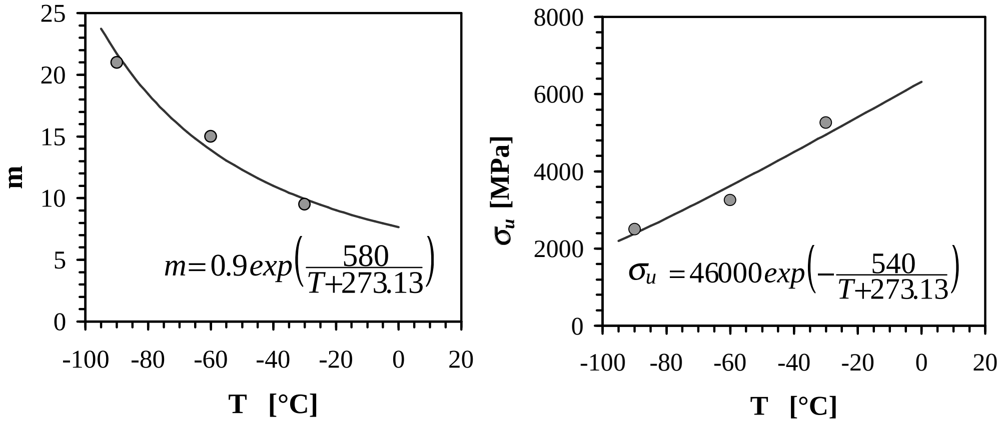

**Figure 4:** Weibull's parameters $\sigma_u$ and $m$ identified on CVN specimens, and their temperature dependence laws used for fracture toughness prediction.

Applying this approach, the increasing scatter of fracture toughness can be more or less satisfactorily modelled up to temperatures near the DBTT (Fig. 5). However, there are still some problems. The extrapolated Weibull's parameters still yield to inadequate predictions of fracture toughness at the DBTT. This could be explained in different ways. The exponential extrapolation can lead to low values of scatter parameter *m*, even though the real value becomes certainly nearly constant in the athermal domain, similarly as the yield stress.

Furthermore, the influence of strain rate on cleavage fracture mechanisms is not taken into account in this approach, even though the influence of strain rate on mobility of dislocations at low temperatures is well known. In other words, at the same temperature, the fracture mechanisms are supposed to be the same in dynamically loaded CVN specimens as well as in quasi-statically loaded CT specimens. This could explain the overestimation of the 90% confidence bound at -60 °C and -30 °C (see Fig. 5). However, the number of fracture toughness tests is small for a good statistical evaluation.

Finally, the cleavage fracture mechanisms, which are apparently different for low and high values of fracture toughness, i.e. at lower and higher temperatures, can coexist in the transition domain. In this case, a multi-modal fracture model should be used.

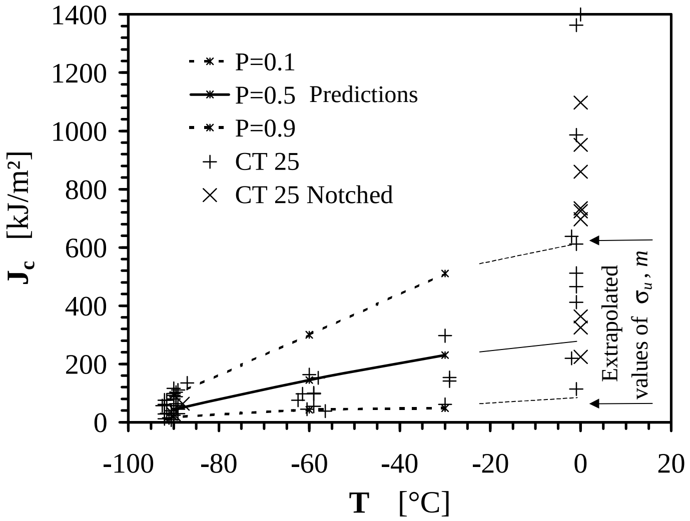

**Figure 5:** Fracture toughness prediction using temperature dependent Weibull parameters identified on CVN specimens.

## CONCLUSION

There is an evolution of cleavage fracture micromechanisms in A508 pressure vessel steel when the testing temperature increases. At low temperatures, cleavage crack initiates from second phase particles, whereas at higher temperatures (near DBTT), the size of cracked particles is not sufficient to provoke cleavage and another micromechanism induced by plastic deformation takes place.

Using the local approach, the Weibull parameters were found to vary with temperature. Varying the Weibull parameters with temperature, this approach can account for the increasing scatter of fracture toughness in the restricted domain. However, the fracture toughness cannot be correctly predicted with these extrapolated parameters.

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