MICROMECHANISMS OF FRACTURE IN MODERN LOW CARBON HIGH STRENGTH STEELS

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Introduction

The understanding of failure mechanisms is an important challenge to improve the fracture resistance of materials. During the last thirty years, the development of fracture criteria for steels has been mainly supported by experimental results and observations carried out on relatively high impurity, alloy and carbon contents. More recently, in order to meet the requirements of steel users, new production routes combined with low carbon and alloy contents have been developed.
Thus, the aim of the present work is to contribute to the existing knowledge on fracture behaviour of these modern steels and to examine the application of existing micromechanistical based failure models (Local approach to fracture, Beremin model for brittle fracture). The main targets can be summarised as follows:

- verification of the physical basis of the local approach methodology: identification of the microstructural constituents acting in the cleavage process and relations with the measured micromechanical parameters,
- transferability of these micromechanical parameters, evaluation of geometrical constraint and strain effects on the model parameters.

Materials studied

The fracture behaviour of E450 and E690 steel grades, whose chemical compositions are given in table 1, was investigated. The first one has been obtained by controlled rolling and accelerated cooling whereas the second one has followed a Quenched and Tempered processing route. The resulting microstructures, respectively ferrite pearlite and tempered martensite, are presented in the figures 1 and 2. Their mechanical properties, measured at room temperature on specimens sampled at mid-thickness in the transverse direction, are reported in the table 2.

Grade	C	Si	Mn	P	S	Al	Mo	Ni	Cu	Nb	Cr	V
E450	0.07	0.32	1.5	0.012	0.001	0.027	0.119	0.468	0.164	0.014	/	/
E690	0.16	0.34	1.43	0.014	0.001	0.065	0.36	0.11	/	/	0.47	0.03

Table 1: chemical compositions in weight percent

Grade	Thickness (mm)	YS (MPa)	UTS (MPa)	A (%)	TK28J (°C)
E450	40	435	535	22	-100
E690	30	735	795	17	-80

Table 2: mechanical properties (mid-thickness, transverse direction)

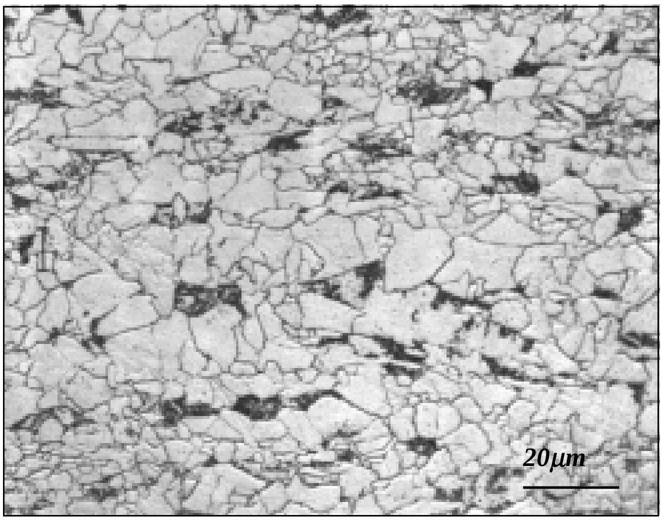


Figure 1: ***microstructure of the E450 steel at mid-thickness, transverse direction***

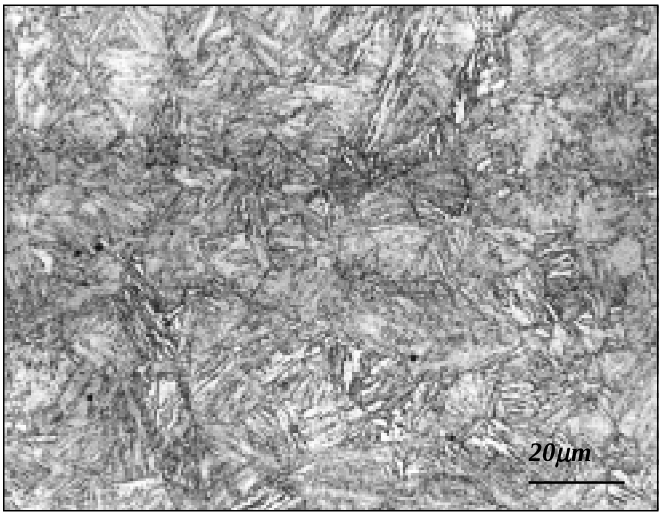


Figure 2: ***microstructure of the E690 steel at mid-thickness, transverse direction***

Micromechanical model investigated

The investigations presented in this paper all rely on the cleavage criterion proposed by Beremin [1].
This criterion is based on two main features of the cleavage fracture mechanism in low carbon steels [2]:

- the instability of existing microcracks in the material. This is described by the critical cleavage stress concept. This cleavage stress exhibits a large scatter as well as a scale effect. This is taken into account using a Weibull's statistic,
- the need for plastic deformation for the initiation of microcracks in the material. This is introduced by equating the volume integration used in Weibull's statistic to the plastic zone.

For an homogeneous material, a quantity called "Weibull stress", denoted σ_w, is introduced:

$$\sigma_w = \sqrt[m]{\int_{P.Z.} \sigma_1^m \frac{dV}{V_0}} \quad (1)$$

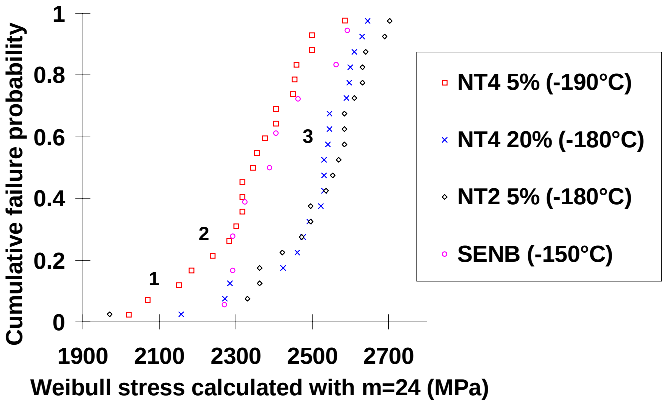
where m is the exponent of Weibull's statistics, V_0 an arbitrary unit volume and σ_1 the maximal principal stress.
This quantity is then used to estimate the fracture probability:

$$P_f = 1 - \exp\left(-\left(\frac{\sigma_w}{\sigma_u}\right)^m\right) \quad (2)$$

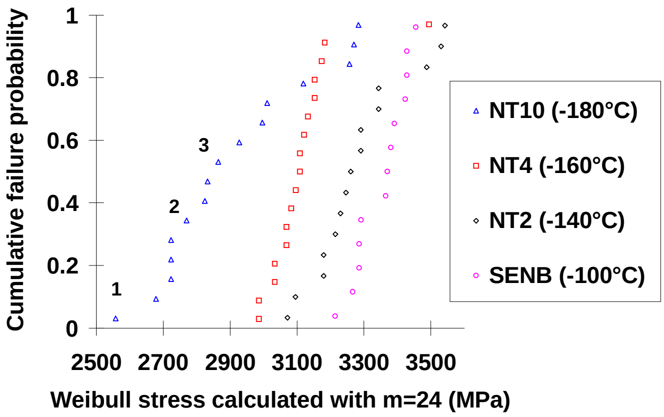
where P_f stands for the fracture probability and σ_u is the critical cleavage stress for the elementary volume V_0.
To determine the parameters of this model, the usual procedure consists in carrying out tensile tests on round notched specimens at low temperatures where cleavage fracture occurs. Alternative procedure using higher constraint specimens (fracture mechanics specimens) is more and more encountered [3,4]. Usually, it is claimed that this method provides more relevant values of the Beremin parameters as the stress-strain fields are more representative of cracked structure on which will be carried out the fracture predictions. This question of transferability between various specimen types will be treated in the first part of the discussion by comparing the Beremin parameters derived from notched tensile tests to those obtained from fracture mechanics tests (precracked 3 point bend specimen).
These mechanical tests are coupled with metallographic and fractographic examinations in order to verify the matching of the observed fracture mechanisms with the applied micromechanical model. The results of these investigations are presented in a second part of the paper.
Finally, in order to take into account the observed features, an evolution of the model is proposed. Its ability to describe the mains trends regarding test or material parameters is discussed.

Mechanical tests

Tensile round notched (radii of 2, 4 and 10mm) and precracked bend specimen (W=35mm, B=17.5mm, a/W=0.5) tests were carried out with the aim of measuring the geometrical constraint effect on the Weibull stress distribution. In order to facilitate the comparison between the different distributions, the parameter m of the model, which is required for the calculation of the Weibull stress, has been fixed equal to 24. This can be considered as a medium value referring to those usually encountered in the literature.
The derived cumulative failure probabilities as a function of the Weibull stress are presented in the figures 3a (E450) and 3b (E690). The main results are summarised in the table 3.
For both steel grades, a slight effect of the specimen type clearly appears in the diagrams as the lowest data are obtained with the lowest stress triaxiality geometry (NT specimens of 4 or 10 mm radii). However, increasing the temperature and, thus, increasing the strain at fracture also leads to a shift of the NT4 distribution measured on the E450 steel (figure 3a, table 3) which is then very close to NT2 one. In our test conditions, this combined effect of both strain and stress triaxiality on the critical cleavage stress is contained in a range of about 6 percent (table 3).



a : E450



b : E690

Figure 3 : Weibull stress distributions derived from different specimen types

Grade	Specimen	σ_m/σ_{eq}	T_{test} (°C)	$\varepsilon_{average}$ (max. stress peak)	$\sigma_{u\ m=24}$ (MPa)
E450	NT4	1.2	-190	0.06	2400
	NT4	1.2	-180	0.18	2560
	NT2	1.5	-180	0.05	2580
	SENB	2.5	-150	0.01	2455
E690	NT10	0.85	-180	0.14	3010
	NT4	1.2	-160	0.06	3180
	NT2	1.5	-140	0.06	3350
	SENB	2.5	-100	0.02	3380

Table 3 : summary of the test results

Examination of the fracture surfaces

Fracture surfaces of specimens corresponding to the lowest, highest and median values of the Weibull stress distributions were examined with a Scanning Electron Microscope (SEM). The examination of the specimen was conducted in two stages: first, the sample was observed at low magnification in the aim of determining the macroscopic location of the fracture initiation area. Then, when this work was successful, a progressive zoom of this zone was undertaken in order to catch an eventual role of metallurgical constituents in the fracture process.
Similar trends were observed on both steels. They can be summarised as follows:

- Dealing with the lowest stress triaxiality, e.g. the notched tensile specimens of 4mm radius (E450) or 10mm radius (E690), and focusing on the lowest points of the distributions (figures 3a and b, plots 1 and 2), the cleavage facets patterns indicate clearly a single site as initiation of fracture which corresponds to an inclusion. For the E450 steel, this is a (O,Al,Ca) inclusion (figure 4.1) whereas for the E690 steel, a

(Ti,N) inclusion is detected (figure 5.1). Regarding the size of these inclusions, a decreasing trend is observed with an increase of the Weibull stress (figures 4.2 and 5.2 to be compared with 4.1 and 5.1).

- Moving to the upper part of these distributions or dealing with higher stress triaxiality specimens (NT2 or precracked bend specimens) does not conduct to the same observation. In general several cleavage facets seem to be involved in the initiation area instead of one single site as previously. When a specimen presents, however, such patterns, the river lines never point out a macro constituent like an inclusion as cleavage initiating component. At this scale of observation, no particular metallurgical feature is identified at the convergence point (figures 4.3 and 5.3). One could connect it to a carbide constituent although this hypothesis was not further investigated in the frame of this study.

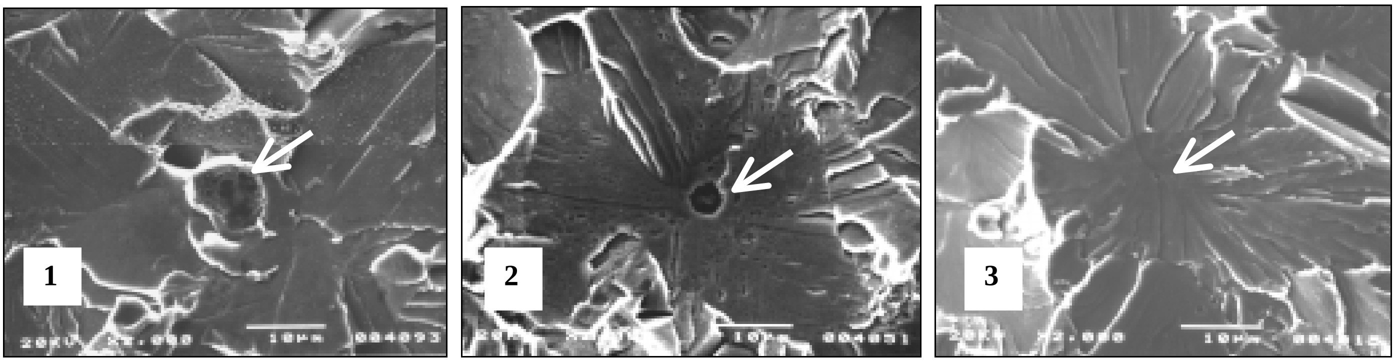


Figure 4: fracture surfaces of notched tensile specimens observed by SEM(E450). See the references in figure 3a

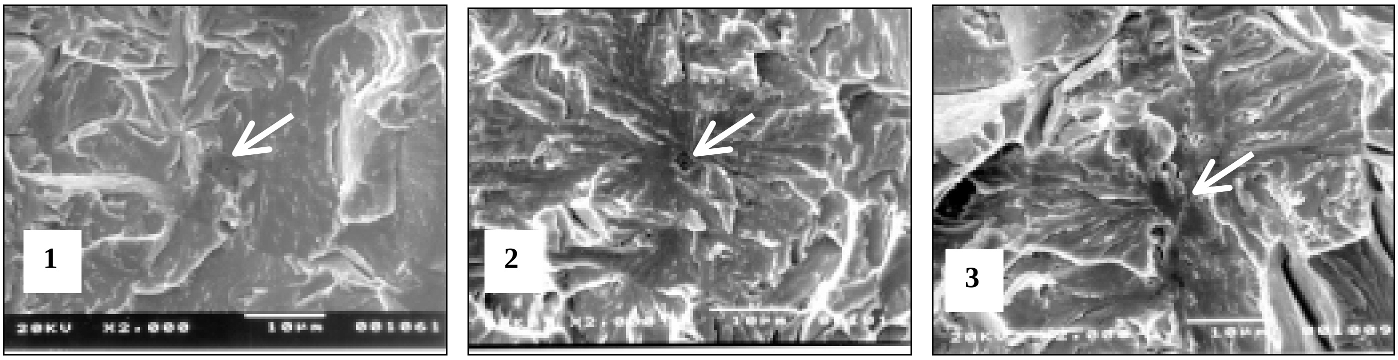


Figure 5: fracture surfaces of notched tensile specimens observed by SEM (E690). See the references in figure 3b

Discussion

Transferability of the parameters

It has been seen that the Weibull distributions of the notched tensile specimens could be composed of two different cleavage mechanisms. Thus, the data corresponding to an inclusion initiated fracture have to be removed to obtain a consistent comparison of the results derived from the various specimen types. These new diagrams are presented in figure 6. Even if a better agreement is noticed between the sets, a slight effect of both constraint and strain on the model parameters is still remaining.

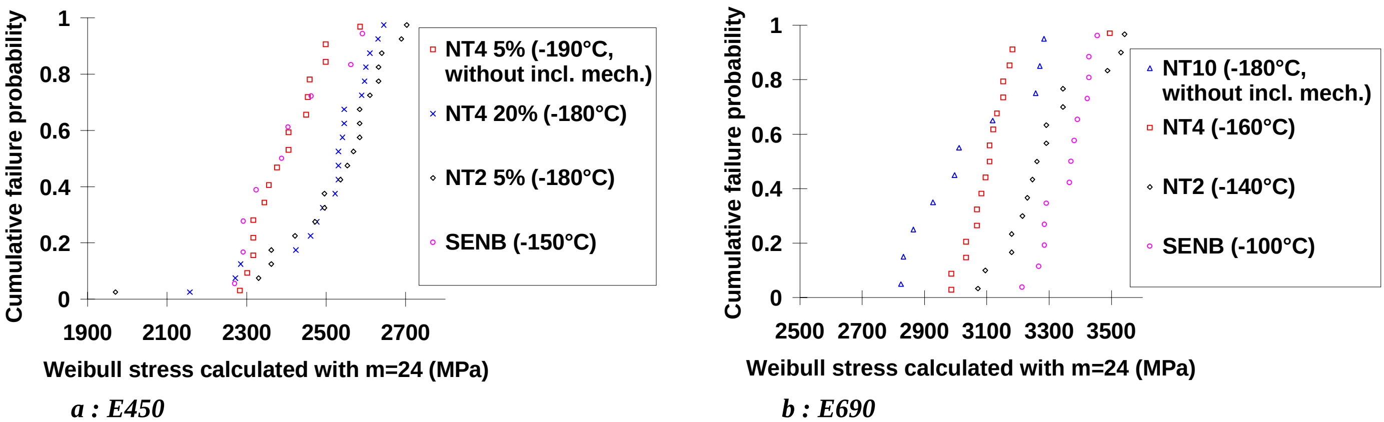


Figure 6 : Weibull stress distributions derived from different specimen types. The plots corresponding to the inclusion mechanism are removed (to be compared with figure 3)

Modified cleavage criterion

For both steels, a possible role of the inclusions in the cleavage process has been highlighted. This mechanism was only observed on notched tensile specimens which are characterised by a high stressed volume and a relatively low peak stress. It clearly highlights that the probability of finding an inclusion of sufficient size in the stressed zone is a controlling parameter of this mechanism. This scale effect must be therefore described by the cleavage criterion. This condition is verified in the Beremin model through the integration of the maximal principal stress over the plastic volume.

It has been also seen that, beside this inclusion initiation mechanism, cleavage fracture could be triggered by a second mechanism whose controlling microstructural feature is less easily defined. In order to describe the competition existing between these two mechanisms, a double Weibull distribution can be used as already suggested by [5]:

$$P_f = 1 - \exp\left\{ \int_{\varepsilon > \varepsilon_{c1}} \left(\frac{\sigma_I}{\sigma_{u1}}\right)^{m1} \frac{dV}{V_0} - \int_{\varepsilon > \varepsilon_{c2}} \left(\frac{\sigma_I}{\sigma_{u2}}\right)^{m2} \frac{dV}{V_0} \right\} \qquad \textbf{(3)}$$

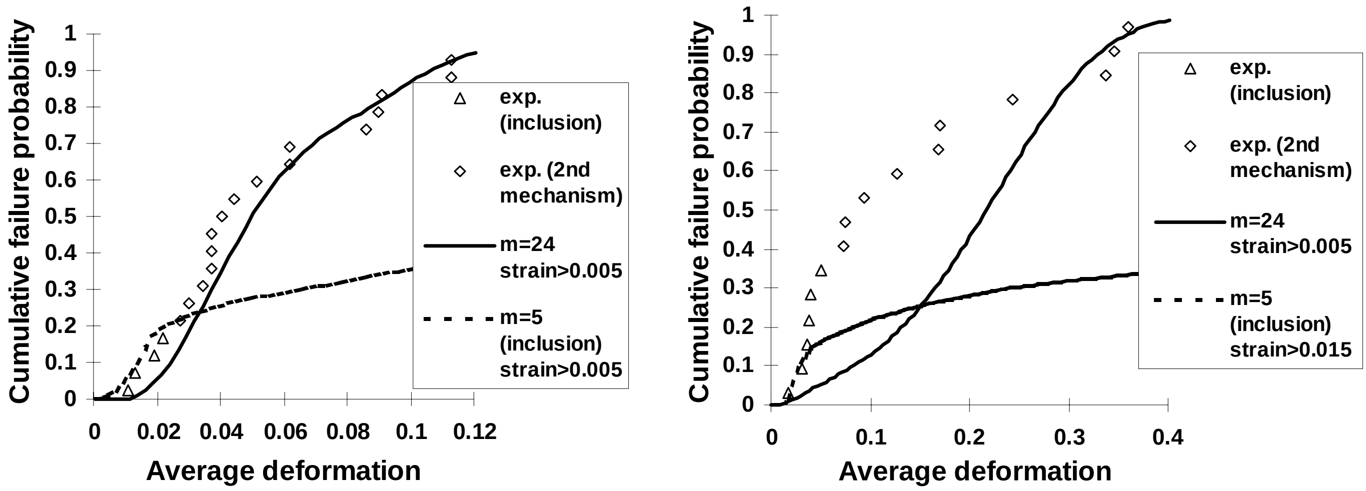
In this relation, the first Weibull distribution (index 1) is assigned to the inclusion initiation mechanism and the second one (index 2) to the second mechanism. As proposed by [6], a critical plastic strain concept (ε_c) is also added to the original Beremin model in order to take into account an eventual threshold in deformation for the nucleation of the micro-crack (crack of (Ti,N) inclusion for instance).

Determination of the parameters

Following [1], the scatter parameter m_1 of the model can be related to the size distribution of the inclusions. If it is assumed that the distribution of the largest ones is described by a curve given by $\alpha.a^{-\beta}$, then m=2β-2. Fitting this parameter on the experimental distributions leads to a raw determination of m_1 equal to 5 in both cases. Regarding the second mechanism, the parameter m_2 is maintained to the usual value used in the previous calculations, i.e. 24.

Dealing with the inclusion mechanism on the E450 steel, the level of the critical plastic strain is fixed to 0.005. It corresponds approximately to the minimum local strain (obtained from the numerical simulation) recorded at fracture in the vicinity of the (O,Al,Ca) inclusion (lowest plot of the NT4 distribution). Following the same methodology for the E690 steel leads to fix this critical level to a higher value of 0.015. This minimal value to break the (Ti,N) inclusions is consistent with the data reported in the literature [7]. Finally, based also on the data determined on a low alloy steel [6], a value of 0.005 is assigned to the critical plastic strain of the second mechanism which is assumed to be rather similar for both steels.

Then, the critical cleavage stresses σ_{u1} and σ_{u2} can be fitted on the experimental plots, corresponding to each mechanism, derived from notched tensile specimens tests, i.e. the lower part of the distribution for the inclusion mechanism and the median or upper part for the second mechanism. With the very low input value of m corresponding to the inclusion mechanism, a strong effect of the stressed volume is expected. A rapid increase of the failure probability is effectively obtained at low deformation (volume effect) and, as predicted, this increasing trend is not continued with the subsequent increase of loading. Thus, as shown on the figure 7a and b, a higher probability of occurrence of the inclusion mechanism can be mainly expected at low deformation whereas a high level of loading (or stress) will promote the second mechanism.

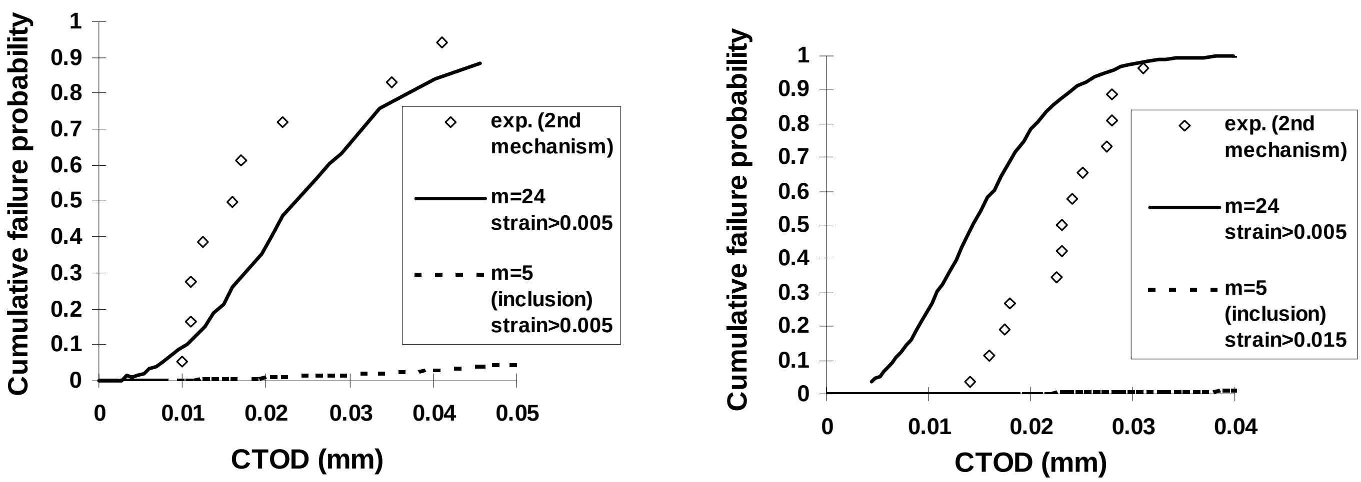


a : E450, NT4 (-190°C) *b : E690, NT10 (-180°C)*

Figure 7: fitting of the model parameters on the notched tensile tests

Predictions of the model on precracked specimens

Using the same parameters, the model can be applied to any other specimen type. In the figure 8, it is shown that the predicted probability of occurrence of the inclusion mechanism is negligible with a precracked bend specimen whatever the level of loading. This situation is consistent with the experimental results. It can be understood by the poor combination of high stress and plastic volume above the critical strain.



a : E450 (-150°C) *b : E690 (-100°C)*

Figure 8: predicted and experimental failure probabilities corresponding to each mechanism for a precracked bend specimen

Conclusions

In this study, the cleavage fracture behaviour of two steel grades (E450 and E690) was investigated. The coupling of different fracture tests with fractographic observations has led to the following conclusions:

- two competitive cleavage mechanisms were observed. One of them is characterised by the role of inclusions in the initiating process. Due to the low density of the largest inclusions, this mechanism was triggered only when using specimens with a large process zone e.g. notched tensile specimens,
- in order to describe this competition, a modified Beremin model with a double Weibull distribution was applied to predict the failure behaviour of the two steel grades studied. Its ability to describe the main

trends regarding the volume, stress and strain effects on the probability of occurrence of the different mechanisms was presented,

- in the present case, it was shown that the probability of occurrence of the inclusion mechanism with precracked specimens is very low. However, following this model, this trend could be reversed with a material exhibiting high density/tight distribution of inclusions (weld metal for instance [8,9]),
- for identical fracture mechanisms, a slight effect of both constraint and strain on the Beremin model parameters was noticed,
- the tests were carried out at low temperatures. It was assumed that the cleavage mechanisms are mainly dominated by the characteristics of the potential initiating constituents (one step process). At higher temperatures, an increasing role of the matrix in the cleavage process can be expected [10,11].

Acknowledgement

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