A LOCAL APPROACH TO CLEAVAGE FRACTURE OF A508 STEEL

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The fracture behaviour of a bainitic A508 Cl.3 steel has been investigated on the lower shelf of fracture toughness (lower transition). Different specimen geometries have been tested in a large number. Fractographic examination yielded both the type and co-ordinates of the cleavage initiation sites. It was found that cleavage initiation is often associated with the presence of inclusions. FEM analyses allowed to associate the local failure stress with each of the sites. Finally, in a local approach to fracture, the Beremin model is applied to the entire set of specimen geometries, and a possibility for an extension of this model is discussed.

INTRODUCTION

The fracture behaviour of ferritic steel exhibits a ductile-to-brittle transition with decreasing temperature. The brittle (cleavage) fracture as well as the transition domain are characterised by a large scatter of results in terms of global fracture stress (tensile specimens), *CVN* (Charpy impact energy), or K_{Ic} (fracture toughness). In order to deal with this scatter, Beremin (1) proposed the application of Weibull statistics (weakest link theory) to a cleavage stress criterion. However, the model seems to work well only under severe restrictions, e.g. as specified in the ESIS recommendations (2). Böhme et al (3) and Bernauer (4) showed that the transferability of parameters between several specimen geometries is not given.

In order to improve the stability of the model, several authors proposed modifications. For instance, Beremin (1) proposed a strain-correction, and Chen et al (5) introduced additional triaxiality and strain criteria. However, the former does not bring significant improvement (4), and the latter only applies to pre-cracked specimens, thus not improving transferability either. The purpose of the present study is to gain better insight in the physical failure process, through fractographic observation, and to propose a modified model allowing a better transferability of parameters.

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EXPERIMENTAL AND NUMERICAL PROCEDURE

A large experimental study has allowed to acquire an extensive data base on notched tensile (AE2 and AE4), Charpy V-notch (CVN) and 1-T (25 mm) compact tension (CT) specimens, on the lower shelf of fracture toughness (lower transition). The material is a A 508 Cl.3 low alloy construction steel of bainitic microstructure. Specimens were machined in the T (AE) and T-S (CVN and CT) orientation. Failure occurred by cleavage fracture, eventually preceded by ductile crack initiation. As is typical in the transition region, results obtained on the 'global' parameters (i.e. fracture stress, *CVN*, K_{Ic}) were subject to a large scatter.

In order to identify the potential sites of cleavage initiation, all specimens were examined in a fractographic study, by the aid of a scanning electron microscope (SEM), see Renevey (6) and Mäntylä et al (7). In most cases, the location of cleavage initiation sites could be determined with sufficient accuracy, by tracing back the tear ridges and river patterns present on the fracture surface. The co-ordinates of the potential cleavage initiation sites were measured, and microstructural features associated with the assumed cleavage initiation site were classified. It was detected that cleavage initiation is often associated with the presence of small spherical or large elongated inclusions. EDAX analysis confirmed that in majority these inclusions are composed of manganese sulfide. The large elongated inclusions are often arranged in clusters.

It is important to note that the contribution of large inclusions in triggering cleavage significantly increased with temperature, and was much less pronounced in CT specimens, where a strong stress gradient is present. The probability of finding large inclusions in the small highly stressed zone ahead of the crack tip is small. This is in sharp contrast to the observations conducted on the smoothly notched AE4 tensile specimens tested at -90 °C. In this case, a ductile crack with an average radius of 300 µm emanating from a cluster of large inclusions was found to have induced cleavage in *all* specimens, see Renevey (6). Fractography indicates that small inclusions directly trigger cleavage, whereas (clusters of) large inclusions rather indirectly contribute to cleavage initiation, presumably by raising stresses in their vicinity.

All the specimen geometries were modelled by FEM analysis. For the tensile specimens an axisymmetric element formulation was used, whereas the CVN and CT specimens were modelled in 3-D. A mesh size of 100 µm in the expected direction of the crack growth was chosen. In order to account for ductile damage and crack initiation, the GTN model (8,9,10) was employed, in a rate dependent formulation, the parameters of which were determined in a similar way as described in a preceding study (11). The constitutive equations can be found in detail in Mühlich et al (10). The parameters describing porosity were determined following the chemical composition (initial void volume fraction $f_0 = 0.0005$ as given by to Franklin's formula, strain-induced void volume fraction $f_N = 0.006$), and fitting the global response of smooth tensile tests (nucleation strain $\varepsilon_N = 0.3$, critical void volume fraction $f_c = 0.06$). However, it shall be noted that a better fit for the CVN data could have been obtained with $f_c = 0.04$. The Beremin (1) model was applied in post-processing. The failure probability is given by

$$P_F = 1 - \exp\left[-\left(\frac{\sigma_W}{\sigma_u}\right)^m\right] \qquad (1)$$

with

$$\sigma_W = \sqrt[m]{\int_{PZ} \sigma_1^m \frac{dV}{V_0}} \qquad (2)$$

where the Weibull stress σ_W is computed over the plastic zone. σ_1 was not taken the current but the *maximum* value of the largest principal stress in respect to time (loading history). The Weibull parameters m and σ_u were determined by the maximum likelihood method, as proposed by ESIS TC 1.1 (2). V_0 was chosen $(50\,\mu m)^3$, as in Beremin (1).

RESULTS AND DISCUSSION

The numerical analyses served to compute the local stresses at the assumed cleavage initiation sites, which had been identified by fractography. This procedure allowed to define some 'failure locus' for cleavage fracture for the material examined. However, a certain scatter of the 'local' variables has been diagnosed, linked to the local metallurgical features of the initiation site. Figure 1 shows the local fracture stresses and strains at cleavage initiation. Since the co-ordinates of the sites have only been determined on the fracture surface (in the nominal crack plane), but not normal to the crack plane, actual stresses and strains may be slightly different. The apparent stresses are slightly lowered due to the softening effect of the GTN model. Most stress values are in the range of 1500 to 1900 MPa, whereas the strain values spread from almost zero for CT specimens up to some 40% for smoothly notched tensile specimens (AE4). In the latter specimen geometry, stresses are distributed almost homogeneously over the notched section, and increasing specimen elongation induces only a weak increase in local stress. This situation yields a low scatter of the fracture stress, resulting in a high m-value when applying the Beremin model (Figure 2 and Table 1).

Table 1 sums up the parameters obtained. They are found to be far from unique. The term $\sigma_u V_0^{1/m}$ is included for better comparison, since m and σ_u are interdependent. It has to be stated that this term is too high for the CT specimen. This is attributed to the relatively coarse mesh composed of linear elements, yielding a global response that is overly stiff. It can be assumed that a finer mesh would allow a better description of strain localisation, and modify the local stress at the crack tip and consequently the Weibull stress.

The fractographic findings call for a modification of the Beremin model, in order to describe the change with load history of the defect population inducing cleavage, i.e. the impact of ductile damage on cleavage initiation. One possibility would be introducing a random distribution of the initial and/or nucleating porosity fraction in the FEM model. Highly voided cells would fail very early in the loading history, increasing stresses in their neighbourhood, and thus the Weibull stress (fracture probability). This approach could be very useful for studying the competition between cleavage and ductile fracture mechanisms in the ductile-to-brittle transition region, but appears rather cumbersome in practical application. Another approach would be the coupling of 'pure' cleavage and ductile fracture probabilities, as proposed by Renevey (6).

Finally, another possibility is the introduction of some 'effective' stress in an approach similar to continuum damage mechanics. We define an 'effective' maximum principal stress $\tilde{\sigma}_1$ as the 'mesoscopic' maximum principal stress σ_1 in the element, modified by a term that compensates the softening effect of the GTN model, and accounts for the stress rise with the increasing size of defects with load history. This term could contain the equivalent plastic strain, the effective surface or the volume fraction of voids, or still other variables that describe ductile damage. Note that the original strain modification as proposed by Beremin *lowers* the Weibull stress with strain, whereas the present model leads to an *increase*. Of course a more appropriate approach would call for a tensor formulation of this variable, which would allow to introduce the influence of specimen orientation. However, in this approach we have tested a very simple formulation

$$\tilde{\sigma}_1 = \sigma_1 \cdot (1 + const \cdot f) \qquad (3)$$

where *const* is a parameter to be determined by a fit between different specimen geometries and/or temperatures, and f the void volume fraction as computed with the GTN model.

Table 1 and Figure 3 (note the different scale on the abscissa in Figure 3 as compared to Figure 2) show the effect of the modification for the entire set of specimens, taking e.g. a parameter of $const = 8$. The agreement between the parameters is significantly improved, as compared to the original Beremin model. However, the CT specimen seems still poorly described, for the reasons discussed above.

TABLE 1 - Weibull parameters obtained by original and modified Beremin model.

			Beremin original			Beremin modified		
Specimen type	T (°C)	Nr. of spec.	m	σ_u	$\sigma_u V_0^{1/m}$	m	σ_u	$\sigma_u V_0^{1/m}$
AE2	-150	35	19,7	3143	1990	19,1	3231	2017
AE4	-90	20	44,5	2080	1700	19,0	3101	1934
CVN	-90	28	17,0	3284	1936	16,7	3341	1952
CVN	-60	27	28,5	2658	1938	20,7	3147	2040
CT	-90	24	18,2	3601	2196	16,6	3880	2255

CONCLUSIONS

In a previous fractographic study, the cleavage sites (type and co-ordinates) in a A508 steel had been identified, in different specimen geometries. It had been found that inclusions play a dominant role in cleavage initiation. FEM analyses allowed to associate the local fracture stress and strain with each of the sites. Based on the fractographic findings, a simple modification of the Beremin model is proposed, that significantly improves the transferability of parameters between different specimen geometries.

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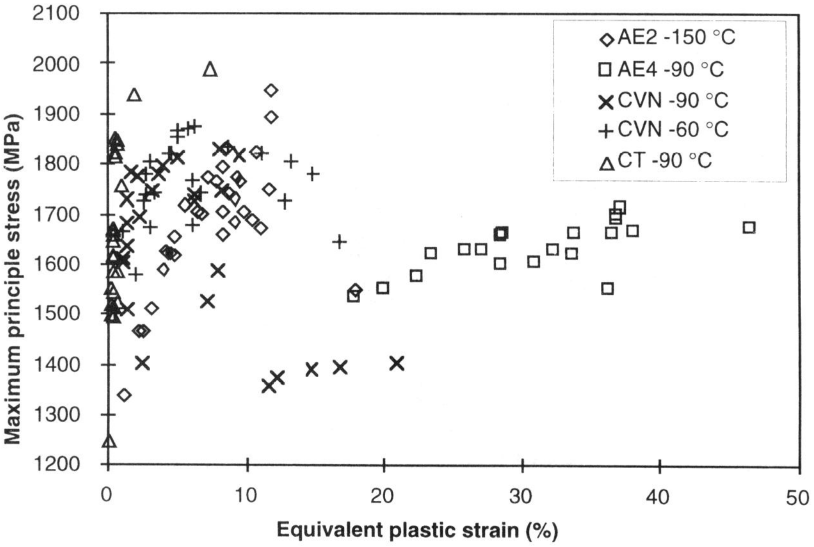

Figure 1 Maximum principal stress and equivalent plastic strain associated with each of the cleavage initiation sites.

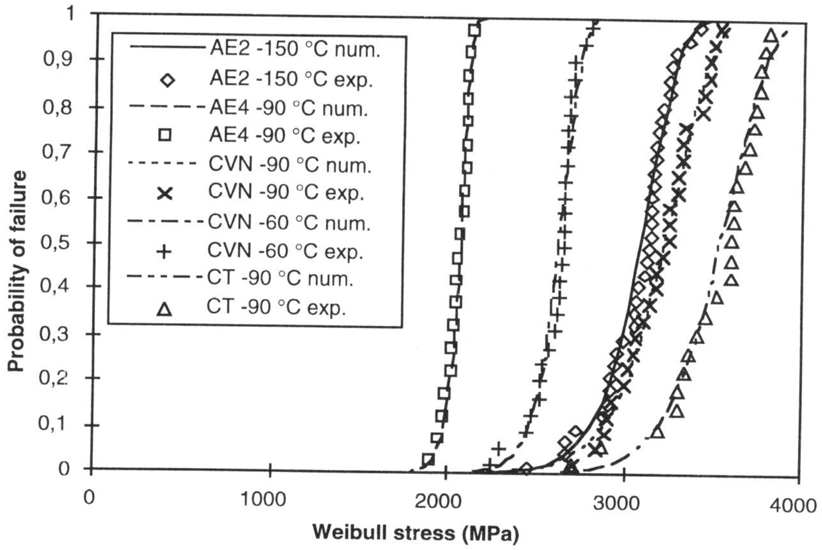

Figure 2 Application of the Beremin model to different specimen geometries.

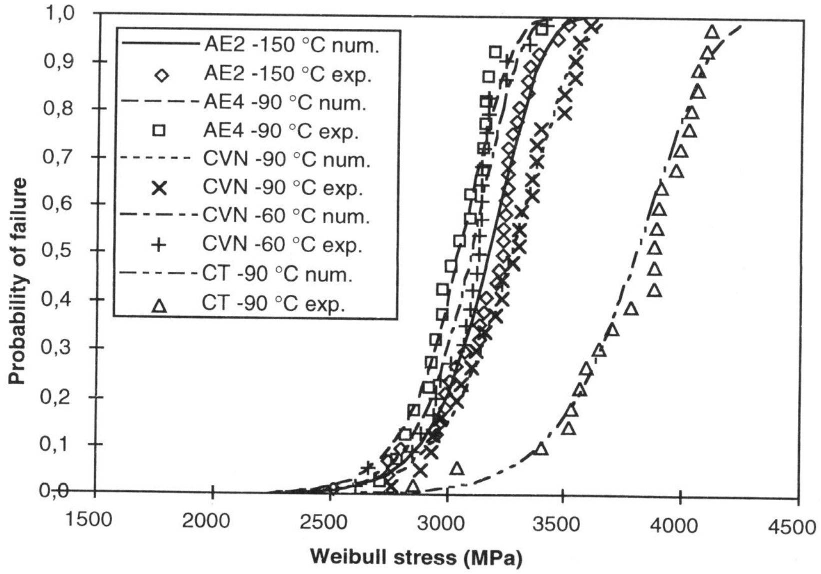

Figure 3 Application of the void volume fraction modified Beremin model to different specimen geometries.