APPLICATION OF LOCAL APPROACH TO THE CLEAVAGE FRACTURE BEHAVIOUR OF F82HMOD FERRITIC-MARTENSITIC STRUCTURAL STEEL

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In the framework of the European Fusion Blanket Programme, the ductile-to-brittle transition behaviour of reduced activation ferritic-martensitic steels is investigated using methods based on local fracture criteria. The numerical analysis of experiments with notched tensile specimens of various shapes performed at selected temperature levels yield the basis for the transferability of predictions of fracture parameters to different conditions of geometry and temperature. A fractographic analysis of fracture surfaces is essential for the confirmation of the appropriate modelling and for the identification of competing fracture mechanisms. The present paper gives first results on the characterization of the Japanese F82Hmod steel in the brittle (low temperature) regime.

INTRODUCTION

Ferritic-martensitic (FM) steels are candidate structural materials for a future fusion reactor. Reduced activation (RA) materials have been developed within the framework of the European Blanket Programme by specific reduction of radiologically unfavourable impurity elements. Additionally, radiologically critical alloying elements (e.g. Mo, Nb) which promote long term activation following neutron irradiation have been substituted by elements with favourable radiological properties (like W, V, Ta) and the Ni content was kept at a low level.

The ductile-to-brittle transition behaviour is of special concern in design considerations because of the observed considerable shift of the ductile-to-brittle transition temperature (DBTT) towards higher temperatures under neutron irradiation.

A fracture mechanics concept based on mechanisms of ductile or brittle failure behaviour is indispensable for the assessment of size and geometry effects, irradiation effects, and effects due to complex mechanical as well as thermal loading conditions. In particular, there is the problem of transferability of results from laboratory experiments to component design as well as the problem of the interpretation of results from small specimen testing under irradiation conditions.

The Local Approach (developed during the last decades mainly in France [1] and now subject to first attempts of standardization [2]) combines a precise description of the initiation mechanisms of unstable crack propagation and an exact description of the stress field in the material for the description of fracture behaviour. In the cleavage regime, which is

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addressed in the following, appropriate statistical treatment of the experimental data and its numerical evaluation is essential. Fractography is needed for an appropriate interpretation of the applied model and also to ensure that the basic assumptions of the model with respect to the fracture mechanism are justified.

One heat of the specific RAFM steel termed F82Hmod (see Table 1) was provided by NKK, Japan and its metallurgical and mechanical characterization is currently subject of a comprehensive investigation programme in different European laboratories under the auspices of the IEA. The material is available in a reference heat treatment condition of 1040° C/38min + 750° C/1h with a DBTT observed in Charpy V tests of about -70 to $-50°$ C [3]. The structure is fully martensite with a grain size of about 70μm and no significant difference in LT, LS and TS orientation.

In the sequel, the first steps towards an application of local fracture criteria for the description of F82Hmod steel are presented: stress-strain relation, notched tensile bar design and experiments and Weibull stress analysis. Up to now, three different notch geometries have been tested at a temperature level of $-150°$ C, which is well below the transition temperature observed in Charpy V tests.

EXPERIMENTS

The experiments were conducted in close agreement with the proposed ESIS Draft [2].

Stress-strain relation

A detailed knowledge of the stress-strain relation up to fracture of the material is required for the calculation of the Weibull stress at fracture. Tensile tests with cylindrical bars were conducted at $-150°$ C, $-75°$ C and ambient temperature. Young's modulus E and true stress-strain curves were obtained from load vs. extensometer longitudinal displacement measurements up to necking of the specimens. An elastic-plastic material law with a hardening exponent of $n = 0.07$ and temperature dependent parameter K (see Table 2) was fitted to the true plastic strain range of $[.1, \ldots, 10\%]$ according to [4]

$$\sigma = K\varepsilon_{\mathrm{pl}}^{n}. \tag{1}$$

Design of notched tensile specimens

The results of the elasto-plastic characterization were used to select suitable notch geometries. Criteria for the selection of the final geometries were that the axial stress in the plane perpendicular to the notch root attains its maximum inside the specimen and the course

C	Si	Mn	P	S	Cu	Ni	Cr	Mo
0.09	0.11	0.16	0.002	0.002	<0.01	0.02	7.66	<0.01
V	**Nb**	**B**	**T.N**	**Sol. Al**	**Co**	**Ti**	**Ta**	**W**
0.16	<0.01	0.0002	0.005	0.001	<0.01	0.001	0.02	2.00

Table 1: Composition (wt-%) of F82Hmod; Heat No. 9741

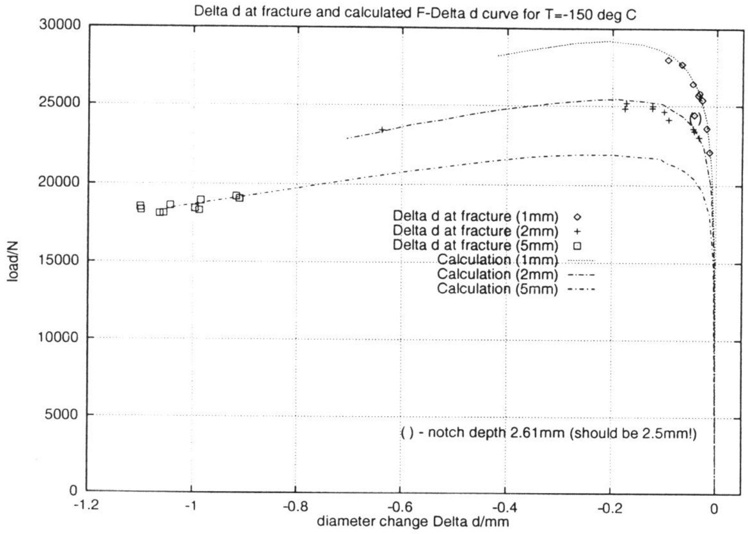

Figure 1: Calculated $F - \Delta d$-curves and experimental Δd at fracture.

of the axial and circumferential stresses as well as the degree of multiaxiality in that plane is different for the various geometries.

Large strain deformation plasticity calculations with the ABAQUS Finite Element code [5] with a Ramberg-Osgood material law equivalent to eqn. (1) indicate that cylindrical notched bar specimens with 10mm diameter, notch depth 2.5mm and notch radii of 1, 2, and 5mm fulfil the criteria.

Experiments with notched tensile bars

Cylindrical notched bar specimens with a raw diameter of 10mm and a minimum diameter of $d_0 = 5$mm were fabricated from plates of 15mm thickness. The orientation of the specimen axis was perpendicular to the main rolling direction. Notches of 1, 2, and 5mm radius were introduced and surface finish of the notches was achieved by polishing in axial direction.

The tests were performed under displacement control with a crosshead speed of .5 mm/min and continuous optical recording of the minimum notch diameter d.

For the numerical evaluation of the tests, the load (F) vs. reduction of diameter (Δd)

RT			$-75°$ C			$-150°$ C		
K	σ_0	E	K	σ_0	E	K	σ_0	E
820	520	214000	950	570	240000	1200	810	220000

Table 2: Material parameters K, σ_0 (0.2% offset yield strength), E (unit is MPa).

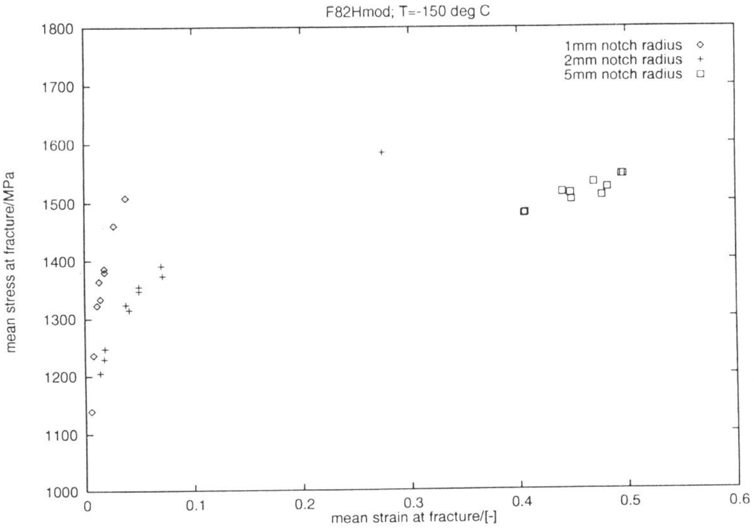

Figure 2: Mean stress σ_M and mean strain ε_M at fracture [6].

curve was used. Fig. 1 shows the calculated curves together with the values of the specimens at fracture. For the sharp (1mm) notched specimens, the fracture occured before maximum load within a relatively small Δd range, whereas for the 2mm notched specimens a larger range of Δd at fracture was observed and some doubt on the homogeneity of the data is caused by one specimen fracturing at a considerable larger Δd than the rest [6]. This has to be confirmed by future fractographic investigations. For the 5mm notched specimens, Δd at fracture attained considerable larger values and excessive plastic deformation occured. Surprisingly, the experimentally obtained values were still met with good accuracy by the calculated $F - \Delta d$-curve despite the fact that no ductile damage was contained in the constitutive Ramberg-Osgood model. As fractographic results are not yet at hand it is currently not possible to characterize this behaviour which is also reflected in the results of the observed mean stress $\sigma_M = 4F/(\pi d^2)$ and strain $\varepsilon_M = 2 \ln d_0/d$ at fracture given in Fig. 2.

WEIBULL STRESS ANALYSIS

The Weibull stress at cleavage fracture is a random variable that characterizes the fracture resistance of the material against cleavage (brittle) fracture. The Weibull stress σ_W is defined by

$$\sigma_W^m = \frac{1}{V_0} \int_{V_{pl}} \sigma_1^m \, \mathrm{d}V \tag{2}$$

where m is the so-called Weibull slope, V_0 is a reference volume introduced for dimensional purposes only and set to 1mm^3, V_{pl} is the volume of the plastic zone, and σ_1 is the first principal stress.

The statistical distribution of its critical value i.e. the value at cleavage fracture is given by $F_{\sigma_W}(\sigma_W) = 1 - \exp\left(-\left(\frac{\sigma_W}{\sigma_u}\right)^m\right)$. The distribution parameters σ_u and m of the Weibull stress σ_W at fracture are material parameters (i.e. independent of the stress state if no steep stress gradients exist) and may depend on temperature.

For the analysis, the Weibull stress at fracture was determined from the diameter reduction Δd of the notched tensile specimens at fracture which is used in the present analysis as experimental loading parameter.

For numerical reasons, the integration of the Weibull stress according to eqn.(2) is performed after normalizing σ_1 by a suitably chosen reference stress, e.g. the flow stress. The Weibull stress is integrated element-by-element. In case of the present 2D axisymmetric model, we have

$$\begin{aligned} \sigma_W &= \sigma_{\text{ref}} \left[\frac{1}{V_0} \sum_{\text{el}} \sigma_{W_{\text{el}}} \right]^{\frac{1}{m}} \qquad \text{with the auxiliary quantity} \\ \sigma_{W_{\text{el}}} &= \sum_{i=1}^{k_i} w_i \sum_{j=1}^{k_j} w_j \left(\frac{\sigma_1(r_i, s_j)}{\sigma_{\text{ref}}} \right)^m (\det J(r_i, s_j)) \end{aligned} \tag{3}$$

where k_i, k_j are the number of integration points in each dimension and w_i, w_j the respective weights for the Gauss quadrature. For $k_i = k_j = 2$, we have $w_i = w_j = 1$ and r_i, $s_j = \pm 1/\sqrt{3}$.

The integration domain is the plastic zone defined by a von Mises yield criterion. With this procedure, only the stress values at the integration points, are used and averaging procedures within the elements are avoided.

For each load step, the first principal stress value is checked against the value of the previous step and a stress envelope is defined in order to avoid artefacts in the calculated Weibull stress values caused by locally decreasing stresses due to effects of stress redistribution.

RESULTS AND CONCLUSIONS

The two Weibull parameters m and σ_u are determined using an iterative Maximum Likelihood procedure [7]. Fig. 3 shows the Weibull diagram of the 1- and 2mm samples together with the fitted Weibull distributions and indications of the 90% confidence intervals for σ_u. The 90% confidence intervals for m are [5.2, 14.6] for the 1mm notches and [5.7, 13.9] for the 2mm notches, respectively.

The results for the 1mm and 2mm notched specimens agree very well. The results of the 5mm specimens are not included in the graph. They show a very high value of the Weibull modulus ($m = 92$) whereas the value of $\sigma_u = 1900$MPa is quite similar. This behaviour is accompanied by very large plastic strains at fracture (see Fig. 2). It is quite obvious from these

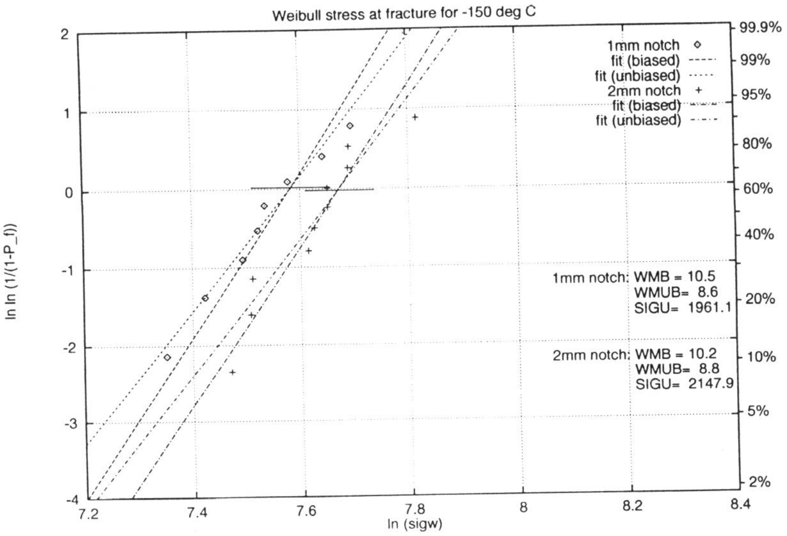

Figure 3: Maximum Likelihood results of σ_W for two notch geometries at -150° C.

results, that a different fracture mechanism is activated in this case. It was already observed in preliminary fractographic observations on unnotched specimens that at some temperatures axial cracking is visible on the fracture surface. Apparently a certain combination of temperature and stress state promotes this fracture mechanism.

The future fractographic investigations will have to clarify this aspect and the numerical analysis has to be modified accordingly, if necessary.

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