SIMULATION OF 3D DUCTILE CRACK GROWTH BY THE GURSON-TVERGAARD-NEEDLEMAN MODEL

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The GURSON-TVERGAARD-NEEDLEMAN model is applied to simulate the ductile crack growth in a DE(T) specimen made of the ferritic steel 20 Mn Mo Ni 5 5. The damage parameters of the model were determined by fitting the numerical to the experimental load vs reduction of diameter curves of round tensile bars. A J_R curve for the DE(T), which agrees quite well with the experimental data, is obtained by a three dimensional FE analysis using the same set of material parameters. The analysis shows that the model can also realistically simulate the local crack growth along the crack front, i.e. its thumb nail shape.

INTRODUCTION

The approach of continuum damage mechanics is a promising way to overcome the numerous problems of size and geometry dependence of the characteristic parameters used in conventional fracture mechanics. The damage model of GURSON, [1] TVERGAARD and NEEDLEMAN [2], the GTN model, is widely and successfully applied to describe initiation and propagation of cracks in ductile materials. The identification and determination of the the parameters require a hybrid methodology of combined testing and numerical simulation. Different from classical fracture mechanics, this procedure is not subject to any size requirements as long as the same fracture phenomena, i.e. ductile tearing, occur in the specimens or components. The present study on ductile crack growth in a DE(T) specimen made of the ferritic steel 20 Mn Mo Ni 5 5 demonstrates the capabilities of the model to handle "geometry effects". Simulations of fracture tests on C(T) and M(T) will follow.

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THE GTN MODEL

The GTN model [1, 2] which is applied in the present study describes the micromechanical processes of void nucleation, growth and coalescence which dominate ductile crack growth. It is based on a modified MISES yield condition

$$\Phi(\mathbf{T}', tr\mathbf{T}, f^*, \sigma) = \frac{3\mathbf{T}' \cdot\cdot \mathbf{T}'}{2\sigma^2} + 2q_1 f^* \cosh\left(q_2 \frac{tr\mathbf{T}}{2\sigma}\right) - \left(1 + q_3 f^{*2}\right) = 0$$

including a second internal variable, f^*, which can be related to the void volume fraction, f. **T** and **T'** are the mesoscopic CAUCHY stress tensor and its deviator, respectively, and $\sigma(\varepsilon^p)$ is the actual flow stress of the matrix material. Evolution equations for f describe the nucleation and growth of voids. Macroscopic crack growth occurs when a certain value of f is exceeded in a material element. This model has been implemented as a user supplied routine [3] in the FE program ABAQUS.

The GTN model contains a total number of nine parameters. Three parameters are used to model void nucleation (f_n, ε_n, s_n), three describe the evolution of void growth up to coalescence and final failure (f_0, f_c, f_f), and the three remaining characterize the yield behaviour of the material (q_1, q_2, q_3). Commonly, it is assumed that $q_2 = 1$ and $q_3 = q_1^2$. q_1 may depend on the hardening of the matrix material and was set to 1.5 in this investigation. The application of micromechanical models to ductile fracture is still a rather new approach and no generally accepted recommendations exist on how to identify and determine these parameters, see e.g. the discussion in [4, 5]. As the model is based on microstructural processes some of the parameters should also be predictable from metallurgical observations. However, ensured quantitative relations are still unavailable and only qualitative hints can be obtained. The determination of the damage parameters is thus a mostly phenomenological fitting procedure which requires a hybrid methodology of combined testing and numerical simulation. NEEDLEMAN and TVERGAARD [6] referred to the phenomenon that the onset of macroscopic fracture of a round tensile bar is associated with a sudden drop of the load. Fitting the numerical results to the experimental data at this point has therefore become a common technique to determine f_c.

Constitutive equations for strain softening behaviour show effects of localization of plastic flow which also means localization of damage. This is the governing physical mechanism of failure but it may cause problems in the numerical simulations as the results become dependent of the size of the finite elements in the damaged zone. This mesh size effect is less significant for tensile specimens but the prediction of ductile fracture resistance is strongly mesh sensitive. The introduction of a new material parameter, i.e. a critical length, l_c, or a critical volume is, hence, required which is related to microstructural features such as the average distance between inclusions. A very straight forward way of handling the problem is to utilize the averaging properties of finite elements themselves, keeping in mind that the respective constitutive relations have been formulated on a "mesoscale". The finite elements in the damaged zone are regarded as "unit cells" and their size as a microsturcturally meaningful parameter [7]. Yet, there is still no way to determine such a parameter from microstructural observations. It has also to be fitted by comparing numerical and experimental results. J_R curves of fracture mechanics specimens are sensitive measures to do this.

EXPERIMENTAL AND NUMERICAL RESULTS

A ferritic steel 20 Mn Mo Ni 5 5 has been studied. Its strength and toughness properties have been characterized by tensile tests on round bars and fracture mechanics tests on C(T), DE(T) and M(T) specimens, respectively. The load, F, vs reduction of diameter, ΔD, curves obtained from the tensile tests have been used to determine the flow curve, $\sigma(\varepsilon^p)$, of the matrix material and to identify f_c as described above, see Fig. 1. The parameters for void nucleation were set to f_n = 0.04 which approximately corresponds to the volume percentage of carbides, ε_n = 0.30, s_n = 0.1, and an initial void volume fraction of f_0 = 0.001 was assumed. An element size of 0.1 mm in the necking section of the tensile bar and the ligament of the DE(T) was assumed as in comparative analyses of similar materials [4, 5]. It is concluded from Fig. 1 that a critical volume fraction of f_c = 0.020 best matches the experimental data. The above parameters are taken for all the following simulations.

As the fracture mechanics specimens were not side grooved three dimensional calculations appeared to be necessary. Due to a threefold symmetry only one eigth of the DE(T) had to be modelled. Fig. 2 shows that the experimental and numerical load (F) vs elongation (ΔL) curves for the DE(T) specimen agree satisfactorily. The crack growth resistance is characterized by J and CTOD (δ_5) vs Δa curves in Figs. 3 and 4, in which the test results show that there is no significant geometry effect for these two specimen types. The resistance curve of the M(T) lies much higher but is not displayed here as the objective of the present study is primarily a comparison of experimental and numerical resistance curves. The numerically predicted curves coincide satisfactorily with the experimental ones even though a rather simple method for estimating the GURSON parameters has been used in this investigation. Simulations of the M(T) will follow to demonstrate that the model can also handle "constraint effects" with one set of material damage parameters independent of the specimen geometry as it was shown in [5].

Fig. 5 displays normal stresses contours in the tensile direction, σ_{33}, in the centre plane of the DE(T), showing that the stress concentration takes place at the actual crack tip. The model can also simulate the thumb nail shape of the crack realistically as Fig. 6 shows by comparing the damage in the ligament obtained by the FE simulation (left) with the experimental crack growth (right). Damage values of $f^* = 1/q_1$ indicate "final fracture" of the corresponding elements.

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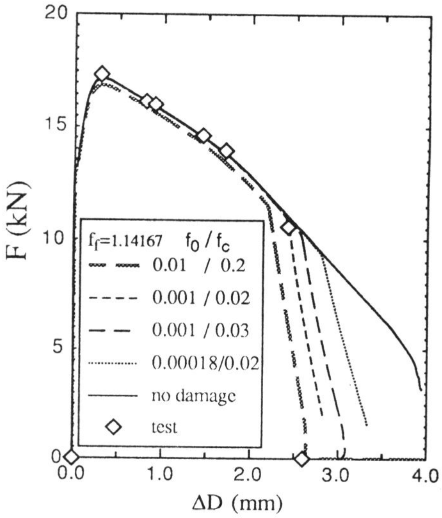

Fig.1 Load vs reduction of diameter of the tensile bar

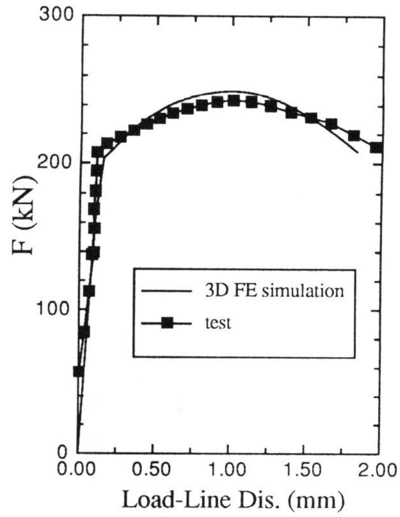

Fig.2 Load vs Load-Line Displacement curve of the DE(T)

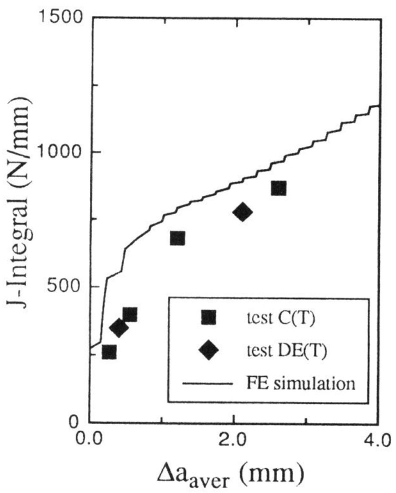

Fig.3 J_R curve of the DE(T)

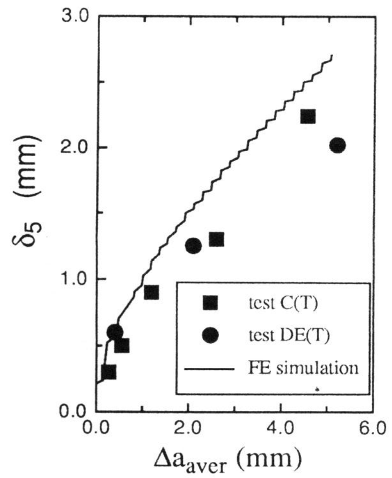

Fig.4 $CTOD_R(\delta_{5R})$ curve of the DE(T)

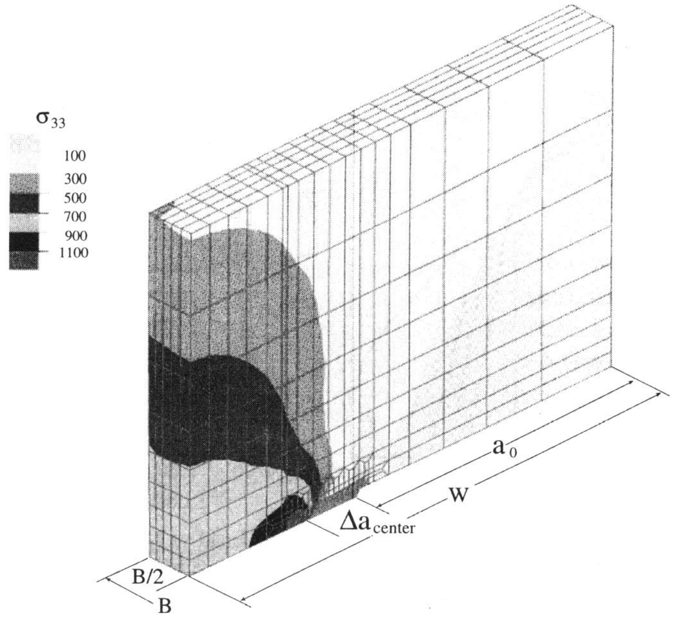

Fig.5 Distribution of tensile stress, σ_{33} , in the DE(T) at $\Delta a_{aver} \approx 4.3$ mm

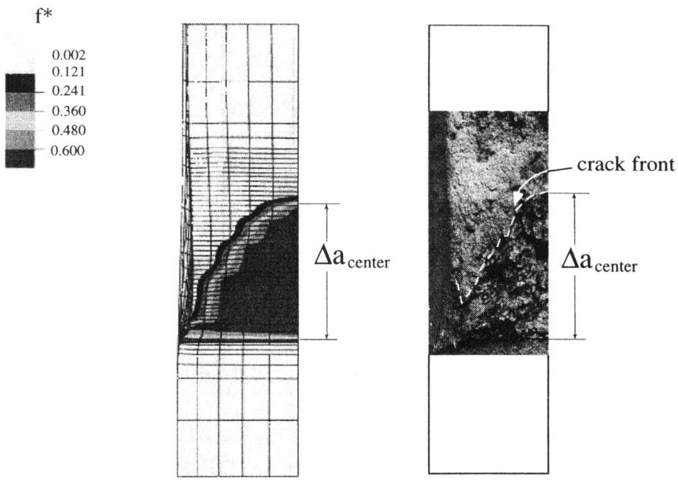

Fig.6 Damage in the ligament (FE simulation) and ductile crack growth (experiment)