THE INFLUENCE OF THE TRIAXIALITY IN THE STABLE CRACK GROWTH MODELLING USING GTN MODEL

L. Vlcek[1] and V. Kozák[1]
[1] Institute of Physics of Materials, AS of CR, Brno, Czech Republic

ABSTRACT

Micromechanical models of ductile tearing based on the damage mechanics have showed themselves as a perspective way to implement some characteristics of microstructure into the material modelling. The GTN model is described by nine parameters: three parameters are used to model void nucleation; three describe the evolution of void growth up to coalescence and the last three parameters characterize the yield behaviour of the material. The first two sets of parameters can by determined experimentally, for the last set of parameters (q_1, q_2, q_3) the recommended values are used in a general way. In particular, q_1, depends on the hardening and is set to 1.5, $q_2=1$ and $q_3=q_1^2$. But q_2 parameter can depend on the triaxiality and recommended values can give non-realistic results. The ductile fracture of forged steel 42CrMo4 is simulated by 3D FEM using WARP3D and Abaqus. Crack extension is based on the element extinction algorithm and real elastic-plastic material behaviour has been taken into account. Determination of the micromechanical parameters required a hybrid methodology, which has been done by combination of numerical calculations, experimental tests and microscopic observation. The base micromechanical parameters have been determined from the real tensile tests combined with finite element calculation. The R-curve has been determined using the three point bend specimens and for the supposed crack propagation the vanishing elements were used. The coincidence of the predicted curve and experimental one is very good; numerical simulation has proved the last set of parameters is necessary to calibrate and the influence of the triaxiality on the J initiation parameter has been found.

1 INTRODUCTION

The general aim of this work can be found in explanation of some questions which are related to problems with transferability of an experimentally measured data into real construction if the Gurson - Tvergaard – Needleman model (GTN) is being applied. Within the framework of the damage mechanics, the GTN (Gurson [1], Tvergaard [2], Tvergaard and Needleman [3]) model is thought of as a micromechanical process like initiation, growth and coalescence of voids. A major item of GTN model is the yield criterion which extends von Mises yield criterion and can be expressed as:

$$\Phi = \frac{2}{3}\frac{S_{ij}S_{ij}}{\sigma_{YS}^{2}} + 2q_1 f^{*}\cosh\left(\frac{3}{2}\frac{q_2\sigma_m}{\sigma_{YS}}\right) - \left[1 + q_3 f^{*2}\right] = 0 \qquad (1)$$

$$f^{*} = \begin{cases} f & f_c \geq f \\ f_c - \dfrac{f_u^{*} - f_c}{f_F - f_c}\left(f - f_c\right) & f_c \leq f \end{cases} \qquad (2)$$

The parameters q_1, q_2, q_3 are used to adjust the model, σ_m is hydrostatic stress, σ_{YS} is yield stress, f^* is void fraction, f_c is the critical void fraction for coalescence, f_F is the final value of f, $f_u^*=1/q_1$. The void volume fraction, f, which is defined as the total volume of all cavities to the volume of the body, is introduced as an internal variable to characterize the damage. Its equation consists of two terms due to nucleation and growth:

$$df = df_{growth} + df_{nucl} \quad \text{with} \quad f(t_0) = f_0 , \tag{3}$$

with f_0 as the initial void volume fraction. The void growth rate is proportional to the plastic volume dilatation rate and an empirical approach for nucleation of void was proposed by Gurland [4]. Chu and Needleman [5] suggested a normal distribution for void nucleation (for strain-controlled nucleation) and then we can write:

$$df_{nucl} = A d\varepsilon_p, \tag{4}$$

where A represents the intensity of nucleation and ε_p is equivalent plastic deformation and A is given by

$$A = \frac{f_N}{S_N \sqrt{2p}} \exp\left[-\frac{1}{2} \left(\frac{e_p - e_N}{S_N} \right)^2 \right], \tag{5}$$

ε_N is the mean strain for nucleation, S_N is its standard deviation, f_N is the volume fraction of void nucleating particles.

2 EXPERIMENTS AND DETERMINATION OF THE GTN PARAMETERS

Determination of micro-mechanical parameters is based on combination of tensile tests and microscopic observation. The standard cylindrical specimens with a diameter of 6 mm have been tested at room temperature at crosshead velocity of 2 mm.min^{-1}. From the reason for the numerical simulation the following data have been measured: force vs. elongation and force vs. contraction using optical method. Then true stress-strain curves and a set of pictures of the contracted area have been received. R-curve has been obtained using a standard 25 mm thick specimen with a/W ratio of 0.5 loaded in the 3-point bending on the base of the multi-specimen method. An additional sensor for COD measurement has been used.

The tensile specimens have been analysed as a first. The methodology for the assessment of the micromechanical parameters requires the metallographic observation not only in the area of the local change of the diameter but in the area of non-affected by the plastic deformation. Half of the tensile specimen has been bisected and a die head has been separated. The two samples for optical microscopy have been prepared. Received photos have been analysed using image analysis. Void distribution in the neck area of the round tensile bar can be seen in Fig. 1.

f	0,0049	0,0073	0,0073	0,0083	0,0126	0,0131	0,0349

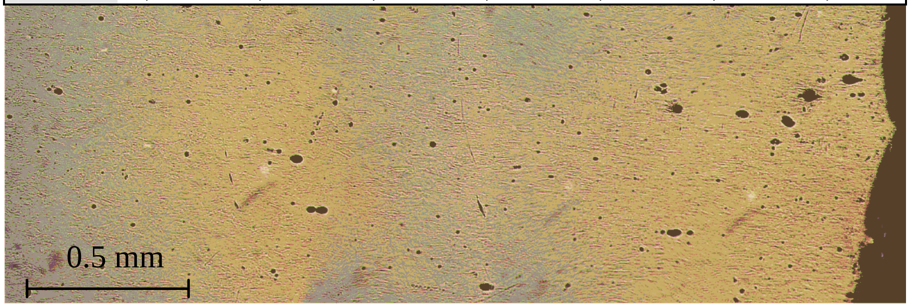


Figure 1: Void distribution in the neck area of the round tensile bar

On the base of the received photos recording contracted area it is possible to submit that in this case of ductile process the coalescence of cavities is minimal. Then the value of f_c is very close to value of f_F and the critical conditions for ductile damage is being received only by combination of growth and nucleation. One can see in Fig. 1 that the f_F close to fracture surface nearly reaches the value equal 0.034 and f_0 the value 0.005.

3 NUMERICAL MODELLING

The results following from the metallographic observation in question of the absence of the coalescence stadium have been verified on the base of the finite element calculation too. An important query for the applicability of the model is whether or not the micro-mechanical parameters are dependent on the mesh size. Material affection was given by the true stress-strain curve, f_N=0.04 and the statistical model of nucleation with recommended values ε_N=0.3 and S_N= 0.1 was chosen (see Needleman and Tvergaard [6]) for all computations. As can be seen in Fig. 2, where the number of elements in the neck area is varying, one can observe the discrepancy between Fig. 2a and 2b. Next computations for more elements than 14 are giving the same curves as in Fig. 2b.

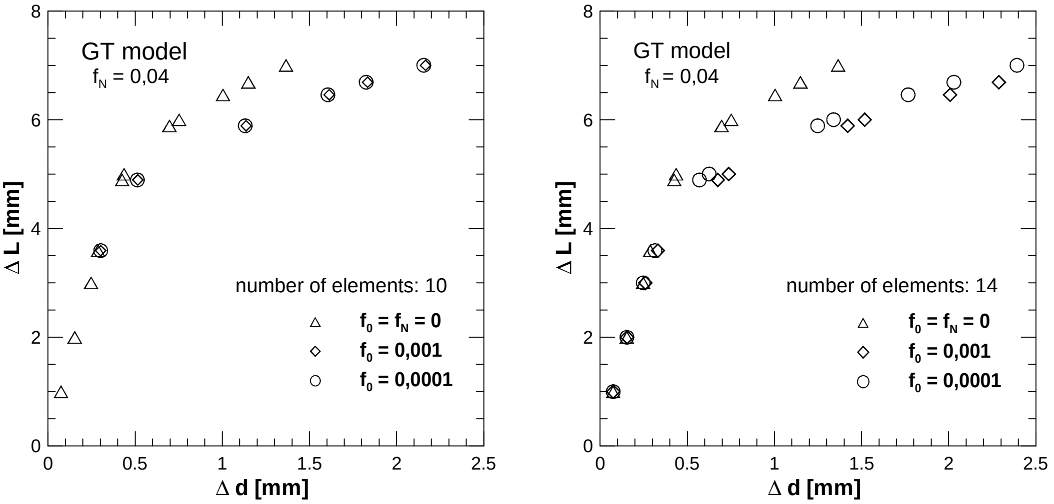
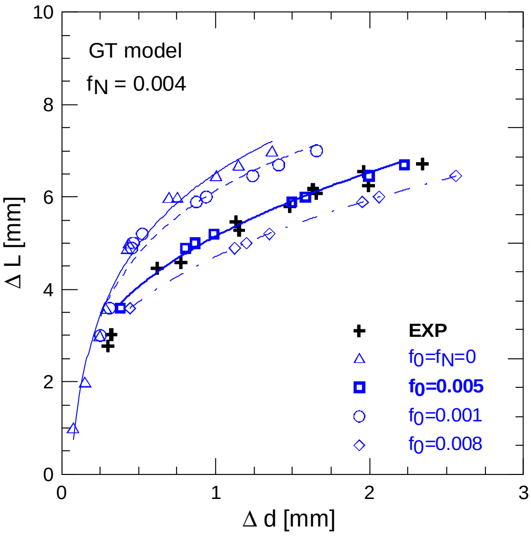

a)
b)

Figure 2: The influence of the mesh size on the curve elongation-contraction

The influence of the initial volume fraction on the slope of elongation-contraction curve has been tested; it can be seen in Fig. 3. It is evident that the increasing value of f_0 implicates the increasing of the value of the plastic deformation in the neck area. Reciprocally the volume fraction of void nucleating particles, f_N, has been tested and it is presented in Fig.4. Both pictures are completed by the experimentally received values.

In the framework of the stable crack growth modelling the 3D model of the standard specimen for three point bend test was created. Using two planes of symmetry only one fourth of the real body was modelled. The problem of determination of the proper mesh size ahead the crack tip was solved on the base of comparison experimentally determined force-COD curve and numerically received one (see Vlcek [7]). The characteristic mesh size was initially determined to 0.5 mm, but the coincidence between experiment and the numerical data was not good. Having been used the mesh where the characteristic mesh size for crack growth area had been selected to 0.1 mm the agreement between experiment and numerical model has been markedly increased.



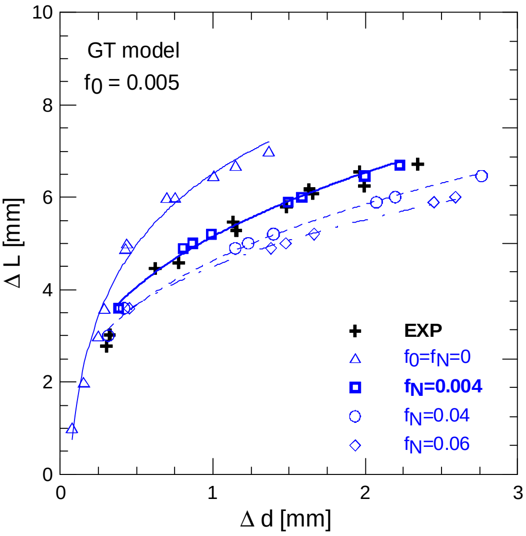


Figure 3: The dependence of the elongation-contraction curve on the varying value f_0
Figure 4: The dependence of the elongation-contraction curve on the varying value f_N

Using above mentioned micromechanical data and FEM software WARP3D [8] the dependence of J-integral on the ductile crack length has been received. As can be seen in Fig. 5 the computed curve and the experimental curve are nearly the same, but the good correlation has been found due to varying of q_2 parameter. The values q_1=1.5 and q_2=1 have been accepted for a long time as constants non-dependent on the material behaviour. Faleskog in work [9] as the first referred to difficulties following from the consideration of the independence of these parameters on the material. The new method of calibration q_1 and q_2 parameters is being discussed in the latest work presented by Kim [10].

In our calibration the q_1 parameter is fixed and the dependence of q_2 (representing the local triaxiality) on the slope of the R-curve is tested. In connection of the slope the attention has been paid on the ductile crack initiation. From physical-mechanical point of view the value of J_i is appeared to be independent on the geometry of the body. This value can be regarded as a material characteristic and it has been determined numerically as the value when the first element vanished. This value can be denominate as a pseudo-physical and its dependence on the q_2 parameter (in Fig. 6) and on the triaxiality factor h (in Fig. 7) has been determined. As can be seen the decreasing of the local stress triaxiality leads to the increasing of the initial value of $J_{i\ FEM}$ and for our experimental steel this initiation value was markedly higher then for recommended value of q_2. The value of J_i is dependent on the geometry of the body (from the engineering approach) and this finding in necessary to take into account in the case of transferability of the experimentally determined data to the real components.

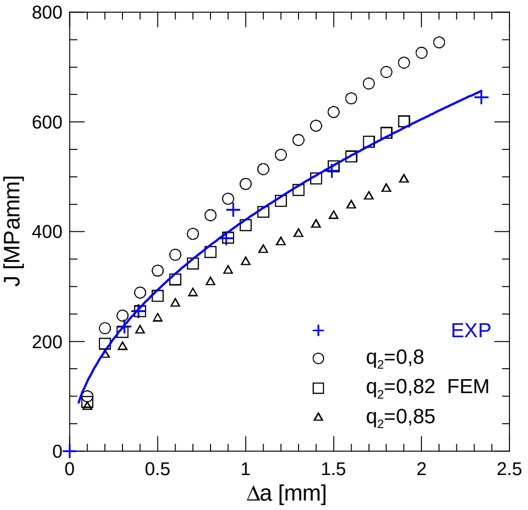
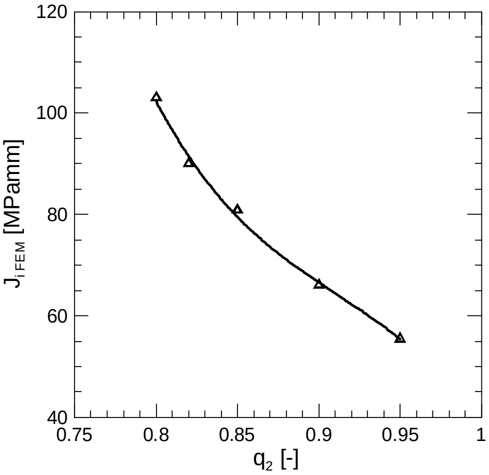


Figure 5: R -curve



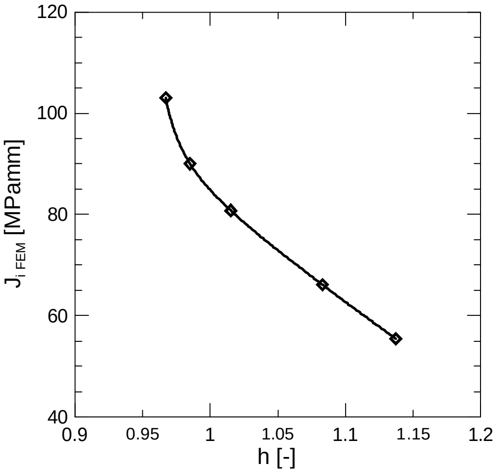


Figure 6: The dependence of $J_{i\ FEM}$ on the q_2 parameter
Figure 7: The dependence of $J_{i\ FEM}$ on the stress triaxiality factor

SUMMARY

- On the base of hybrid procedure the parameters of GT model were determined.

-Using of the „vanishing elements" the ductile crack growth was simulated and R-curve was predicted. The coincidence of the predicted curve and experimental curve is very good due to partial calibration of q_2 parameter.

- The dependence of the initial value of $J_{i\ FEM}$ integral on the stress triaxiality factor has been determined.

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