ICF100563OR

DUCTILE FRACTURE ANALYSIS OF STRUCTURAL STEEL USING MICROMECHANICAL MODELLING

M. Rakin[1], A. Sedmak[2], S. Sedmak[1], M. Zrilic[1], S. Putic[1]

[1]Faculty of Technology and Metallurgy, University of Belgrade, Karnegijeva 4, 11000 Belgrade, Yugoslavia
[2]Faculty of Mechanical Engineering, University of Belgrade, 27 Marta 80, 11000 Belgrade, Yugoslavia

ABSTRACT

Modelling of ductile fracture initiation on a precracked geometry, based on knowledge of the behaviour at tension of simple uncracked material, has been done within the scope of micromechanical analysis. Finite element calculation has been applied in two steps: first, on a tensile round smooth specimen and then, on the standard CT specimen. Analysis was performed on low-alloy structural steel as a part of Round Robin on Micromechanical Models, organised by European Structural Integrity Society (ESIS) - Technical Committee for numerical methods (TC8) [1].

Micromechanical model based on a particular criterion of flow in a porous solid has been applied. The model was initially established by Gurson, and later on modified by Tvergaard and Needleman (the GTN model).

The value of critical void volume fraction, f_c, was first determined on a smooth specimen, and then used for modelling of crack growth initiation in standard CT25 specimen. Four-node and eight-node isoparametric finite elements (FE) with reduced integration were used. Crack tip singularity of CT specimen has been modelled only using a rather fine mesh. The large strain analysis with updated Lagrangian formulation has been used in both calculations. Probably the most difficult part of ductile fracture analysis, to present physically void nucleation as accurately as possible, was carried out by quantitative metallographic analysis of size and number of non-metallic inclusions in steel.

The results obtained suggest that the critical values of micromechanical parameters according to GTN model may be used for approximate prediction of ductile fracture initiation on CT specimen for tested steel.

KEYWORDS
ductile fracture of steel, micromechanical modeling, finite element calculation, crack initiation, non-metallic inclusions, void volume fraction

INTRODUCTION

Micromechanism of ductile fracture of most metals and alloys includes void nucleation, growth and coalescence. Application of so-called global criteria of fracture mechanics such as COD and J-integral in characterisation of ductile fracture initiation does not provide satisfactory results for all cases of external loading. The problems arising in solving the phenomenon of severe plastic strain at crack tips and application of the results obtained to account for the behaviour of various structures of different geometry are not insignificant. Micromechanical approach is introduced in an effort to describe the process of fracture in a way close to actual phenomena in a material. It means that it is necessary to define as accurately as possible the stress/strain fields, and at the same time the values of the variables describing material damage.

Micromechanical model based on plastic-flow function as formulated by Gurson [2] and modified by Tvergaard and Needleman [3,4] is most widely used for the analysis of initiation of ductile fracture of the alloys. Unlike traditional flow criteria (e.g. von Mises criterion), this one introduces the void volume fraction, f, variable. Numerical and experimental analysis of the modified Gurson model, most frequently referred to as Gurson-Tvergaard-Needleman (GTN) model, shows that the development of damage at microscopic level and plastic strain as a global, macroparameter affected by external loading can be well-described and determined [1,5,6,7].

In this paper, the round smooth specimen ϕ6 and compact tension specimen CT25 ($a_0/W = 0{,}56$) have been analysed according to ESIS TC8 Numerical Round Robin on Micromechanical Models, Phase II, Task A [1]. Void nucleation around non-metallic inclusions in tested low-alloy steel 22 NiMoCr 3 7 has been examined using quantitative metallographic analysis. Based on this analysis, initial void volume fraction, used as an input datum in FE calculation, was determined.

Criterion of crack initiation based on GTN model - critical void volume fraction, f_c - has been determined on smooth specimen and used in prediction of crack growth initiation on CT25 specimen. Fractography of smooth specimen has been performed and crack initiation site has been determined.

MICROMECHANICAL MODELLING OF DUCTILE FRACTURE USING THE GTN MODEL

Ductile fracture of structural steel is initiated by void nucleation, growth and coalescence around non-metallic inclusions and second-phase particles in metal matrix. Depending on the size, shape and quantity of these particles in steel, several models have been developed in an effort to describe complex micromechanism of void nucleation. The common point for all so far proposed models is the assumption that void nucleates when so-called critical stress within inclusion or at inclusion-matrix interface has been reached [8,9].

In the GTN model, void nucleation is most frequently defined using initial void volume fraction of non-metallic inclusions, f_0, with which so-called primary voids are defined, and using models that may describe their subsequent nucleation (secondary voids) during growth of the primary ones as matrix of material becomes deformed.

Growth of nucleated voids is strongly dependent on stress and strain state. The GTN model was based on the observation that the nucleation and growth of voids in a ductile metal may be described macroscopically by extending the classical plasticity theory to cover the effects of porosity [5]. Thus, void volume fraction variable f is introduced in plastic potential equation [2,3]:

$$\phi = \frac{3\sigma'_{ij}\sigma'_{ij}}{2\sigma^2} + 2q_1 f \cosh\left(\frac{3\sigma_m}{2\sigma}\right) - \left[1 + (q_1 f)^2\right] = 0 \qquad (1)$$

where σ denotes actual flow stress of the matrix of the material, σ'_{ij} is stress deviator, σ_m is mean stress and the parameter q_1 was introduced by Tvergaard [3] to improve the ductile fracture prediction of the Gurson model. It is obvious that material loses its load carrying capacity if f reaches the limit $1/q_1$, because all the stress components have to vanish in order to satisfy Eqn. 1. In order to take into consideration void coalescence mechanism, upon attainment of critical void volume fraction, f_c, the process of material failure should be "accelerated" so that in FE processing the following applies: 1) f for $f \le f_c$ and 2) $f_c + K(f - f_c)$ for

$f > f_c$. Parameter K defines slope of the sudden drop on the load - diameter reduction diagram and often is denoted as "accelerating factor".
Two parts contribute to the increase of the void volume fraction in FE calculation with incorporated GTN yield criterion: one is the growth of the existing voids and the other is the nucleation of new voids during the external loading:

$$\dot{f} = \dot{f}_{nucleation} + \dot{f}_{growth}, \text{ where } \dot{f}_{nucleation} = A\,\dot{\varepsilon}^{p}_{eq} \text{ and } \dot{f}_{growth} = (1-f)\,\dot{\varepsilon}^{p}_{ii} \quad (2)$$

$\dot{\varepsilon}^{p}_{eq}$ is equivalent plastic strain rate and $\dot{\varepsilon}^{p}_{ii}$ is the plastic part of the strain rate tensor. Nucleation of the secondary voids led by strain increase is most frequently tried to be described using two approaches. The first one was defined by Gurland [10], and is determined by the model of continuous nucleation of new voids, so that the parameter A is constant. The second one was proposed by Chu and Needleman [11] and is based on hypothesis that void nucleation follows normal distribution. Although the second one has been much more used in investigation, it has been shown [6] that both approaches give similar results.

RESULTS AND DISCUSSION

Critical value of void volume fraction f_c, corresponding to crack initiation in smooth specimen and crack growth initiation in CT specimen, was determined by combined experimental-numerical procedure. Void nucleation was defined by volume fraction of non-metallic inclusions. Initial void volume fraction f_0 was determined by quantitative metallurgical analysis; nucleation of the secondary voids was not taken into account due to rather low presence of non-metallic inclusions in tested steel. Using optical microscope, three prepared samples of test material were examined; 100 fields of vision were made for each sample.

Initial void volume fraction was determined as an average value of surface fraction of non-metallic inclusions for all fields of vision. For planimetric procedure of determination of volume fraction of non-metallic inclusions, a semi-automatic measuring method was applied. Contouring of inclusion profiles and determination of surface fraction for each of the fields of vision were carried out using computer software. The inclusions were classified according to the procedure described in [12].

Numerical calculations of tension of smooth round and CT specimen were made according to the true stress-strain curve at 0°C and in accordance with ESIS TC8 round robin project [1]. For both calculations the large strain analysis with updated Lagrange procedure was applied. Plastic flow of the material was determined by GTN yield criterion (eqn. 1) with isotropic hardening. FE calculations did not incorporated void coalescence effect. The calculations for smooth specimen were made in two ways: by applying quadrilateral 4-noded and 8-noded FE with reduced integration. CT specimen was modelled only with quadrilateral 4-noded FE; 8-noded FE were not used due to convergence problems. The calculation was made for plane strain conditions. Crack tip was modelled using refined mesh (0.4 x 0.4 mm), without singular FE. Dimensions of tested specimens and FE meshes are shown in Fig. 1.

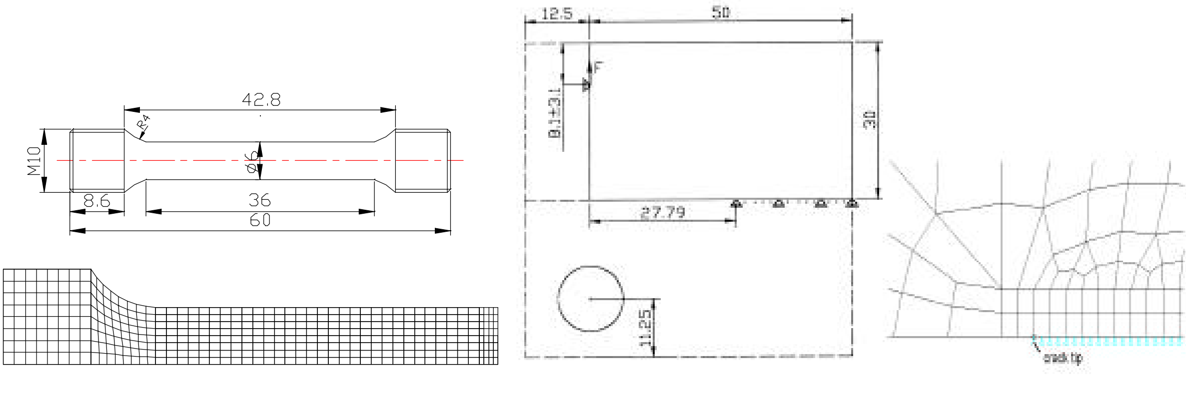

Figure 1: Tested specimens - dimensions and FE meshes

Force-reduction diagram of smooth specimen diameter is shown in Fig 2. Experimental and FE results are in good agreement. Force-specimen elongation curves are also in good agreement. Calculation with 8-noded FE gives somewhat lower position of tensile curve, and immediately in front of the experimental point of fracture, it gives certain further bending of the curve. Having in mind that the void coalescence effect is not used in the calculations and that sudden drop on force-necking diagram was not to be expected, the phenomenon of bending of tensile curve near the spot corresponding to experimental fracture is interesting. The reason for this phenomenon is significant softening of individual FE in the necking area, caused by an increase of void volume fraction f. The application of von Mises criterion does not indicate this phenomenon [13].

Critical void volume fraction f_c, was determined according to the diagram shown in Fig. 3, based on the increase of void volume fraction in finite element in the centre of the specimen and depending on reduction of the diameter of the minimum cross-section (in the region where necking occurred), for both calculations of smooth specimen. Certain difference between the values determined for f_c, is obvious, but the calculation using 4-noded FE gives for f_c a value which is in better agreement with previous researches and recommendations ($f_c = 0.05$ for the same steel [1] and $f_c = 0.045$ for the similar steel A508Cl.2 [7].

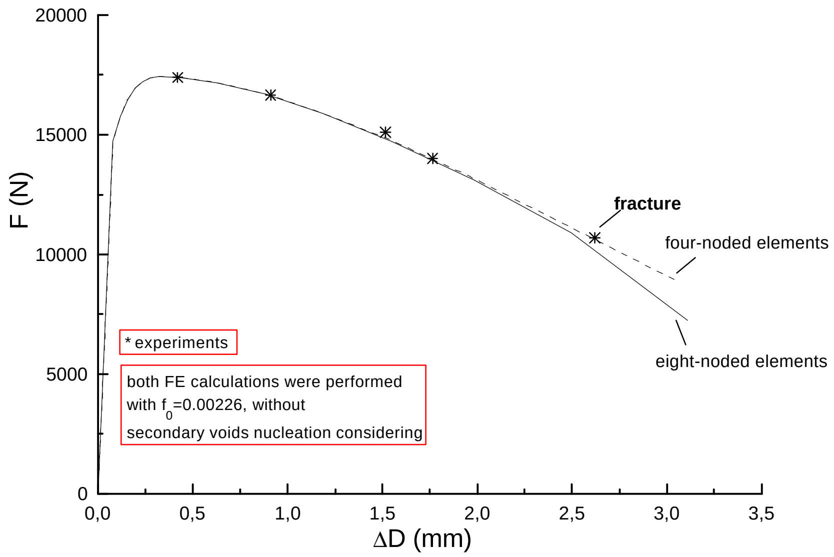

Figure 2: Load vs. reduction of diameter with four-noded and eight-noded FE calculation

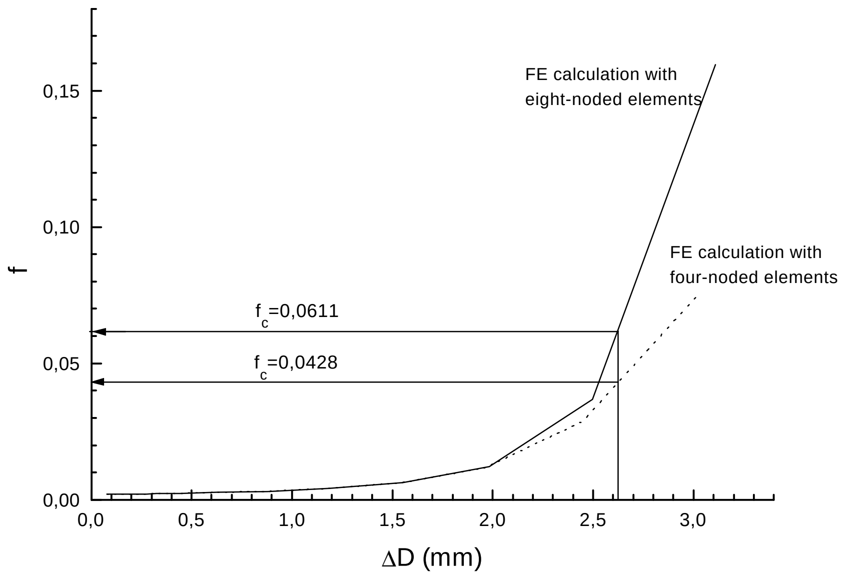

Figure 3: Determination of critical void volume fraction

Change of void volume fraction f (average value from 4 Gauss points) across the smallest cross-section of the specimen is given immediately before and after the fracture of the specimen (Fig. 4) for calculation with 8-noded FE. One can clearly see from the figure that the fracture starts from the centre of the specimen. The change of f at cross-section in the necking area of the specimen obtained by the calculation using 4-noded FE is of the same character.

In Fig. 5 fractography of smooth specimen, obtained by SEM, is given. Crack initiation site in the centre of the specimen is shown in the left micrograph. The crack has initiated from dimple which had nucleated by cavity growth around sulphide, as suggested by its shape. Around crack initiation site, ledges of radial crack growth are noticeable. In micrograph to the right a larger cavity is noticeable, which has nucleated from a broken oxide, as also suggested by its shape.

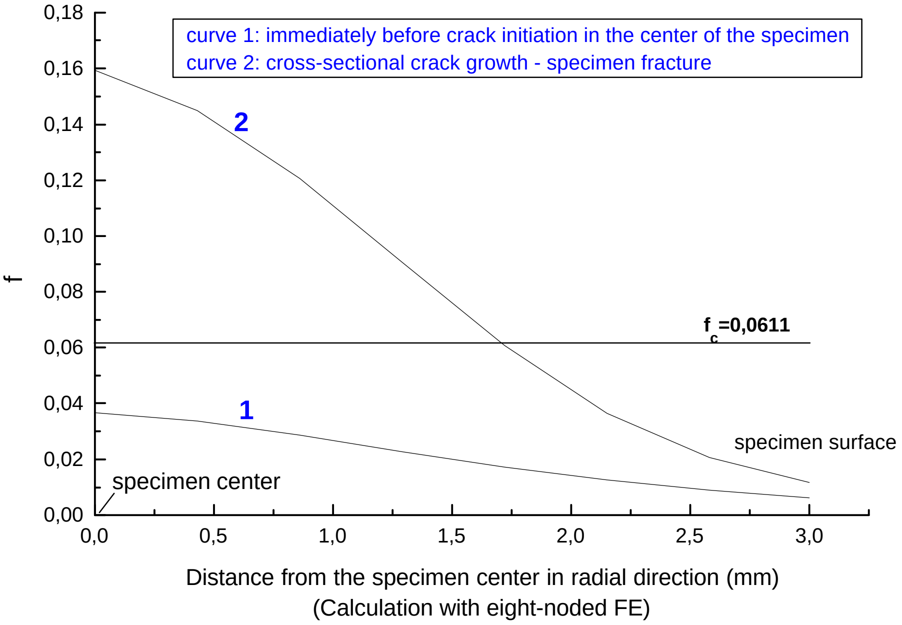

Figure 4: Distribution of void volume fraction f in necking zone

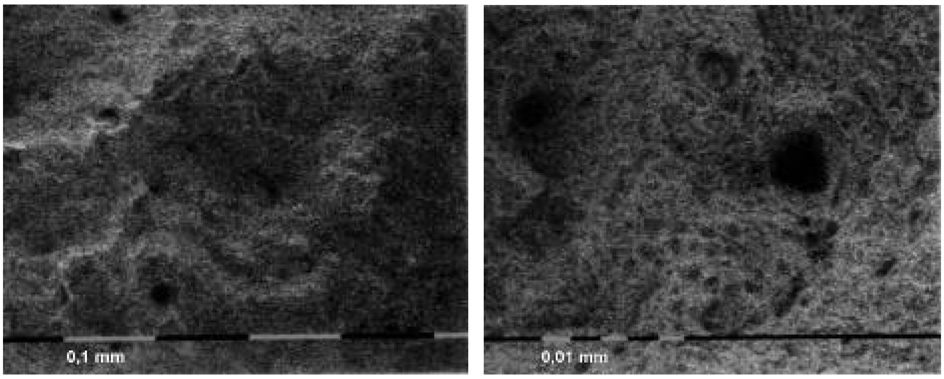

Figure 5: SEM micrographs of crack initiation in the center of smooth specimen

J-integral corresponding to the crack growth initiation in CT25 specimen was evaluated from the external work U according to the numerically obtained load – load line displacement curve [14]:

$$J_0 = \frac{\eta U}{B_n (W - a_0)} \quad \text{and} \quad \eta = 2 + 0.522\left(1 - \frac{a_0}{W}\right) \tag{3}$$

where B_n = 20 mm due to 20% side grooves. Load line displacement v_{LL} at the moment of the onset of crack growth was determined according to to the value f_c determined for smooth specimen. Failure of FE in front of a crack tip was conditioned by $f \geq f_c$. Based on the two values determined for f_c, two J-integrals corresponding to the crack growth initiation were calculated (Tab. 1)

TABLE 1

CALCULATED J_0 VALUES

Calculations of smooth specimen	f_c determined on smooth specimen	J_0 (kN/m) corresponding to the crack growth initiation in CT25 specimen
using 4-noded FE	0.0611	352.1
using 8-noded FE	0.0428	325.8

The values of J_0 determined in this way show certain deviation from the experimental value J_0 = 229 kN/m [1]. Possible reasons for this deviation are: a) use of 4-noded instead of 8-noded FE (the later were not used due to convergence problems); b) insufficient mesh refinement near the crack tip: further calculations should be made so that size of FE in front of a crack tip corresponds to the mean free distance between non-metallic inclusions $\lambda \approx 0.2$ mm determined by quantitative metallurgical analysis.

CONCLUSION

Based on the results of micromechanical modelling of ductile fracture of structural low-alloy steel, the following may be concluded:

- experimental values and results obtained by FE calculation according to GTN model for smooth specimen are in very good agreement; critical value of void volume fraction f_c was determined in the centre of the specimen in both calculations, using both 4-noded and 8-noded FE;
- quantitative metallurgical analysis is necessary for determination of initial void volume fraction f_0 and mean free distance λ;
- the value obtained for J_0 using both values determined for f_c exceeds experimental value and may be used for approximate prediction of ductile fracture initiation in CT specimen for tested steel; the calculations should be updated by more refined mesh and higher degree of FE interpolation functions.

REFERENCES

1. Bernauer G. and Brocks W. (2000). *Numerical round robin on micro-mechanical models - Results*, ESIS TC8, Institute for Materials Research - GKSS Research Center, Geesthacht
2. Gurson A.L. (1977). *Journal of Engineering Materials and Technology*, 99, 2.
3. Tvergaard V. (1981). *International Journal of Fracture*, 17, 389.
4. Tvergaard V. and Needleman A. (1984). *Acta Metallurgica*, 32, 157.
5. Zhang Z. L. (1996). *Fatigue & Fracture of Engineering Materials and Structures*, 19, 561.
6. Zhang Z. L. and Niemi E. (1994). *Engineering Fracture Mechanics*, 48, 529.
7. Sun D-Z., Kienzler R., Voss B. and Schmitt W. (1992). In: *Fracture Mechanics - Twenty - Second Symposium*, ASTM STP 1131, II, pp. 368-378, Atluri S.N., Newman J.C., Raju Jr.I. and Epstein J.S. (Eds.), American Society for Testing and Materials, Philadelphia.
8. Thomason P.F. (1990). *Ductile Fracture of Metals*, Pergamon Press, Oxford.
9. Argon A.S. and Im J. (1975). *Metallurgical Transactions*, 6A, 839.
10. Gurland J. (1972). *Acta Metallurgica*, 20, 735.
11. Chu C.C. and Needleman A. (1980). *Journal of Engineering and Materials Technology*, 102, 249.
12. Underwood E. E., (1970). *Quantitative Stereology*, Adison-Welsey, Reading, Mass.
13. Rakin M., Sedmak A., Matejic P., Zrilic M., and Sedmak S. (2000). In: *Proceedings of the ECF 13 'Fracture Mechanics: Applications and Challenges'*, printed on CD, M. Fuentes et al. (Eds.), ESIS Publication, Elsevier Science Ltd, Oxford.
14. ESIS P2/92 (1992), *Procedure for Determining the Fracture Behaviour of Materials*, ESIS Procedure