Micromechanical Approach - Transferability of Ductile Fracture Parameters

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ABSTRACT: *Major advantage of micromechanical models for prediction of two basic types of fracture, ductile fracture and cleavage fracture, should be non-dependence of model parameters on geometry. In this way it is possible to determine fracture parameters on limited quantity of material using small specimens. In this paper, ductile fracture of structural steel has been analysed on specimens without initial crack and precracked specimens. A part of investigation was carried out through participation in "Numerical Round Robin on Micro-Mechanical Models" organised by European Structural Integrity Society (ESIS). Additional quantitative metallurgical analysis was made in order to determine volume fraction and mean free path of non-metallic inclusions in tested steel. Finite element calculations on different geometries were performed.*

Based on non-coupled (the Rice-Tracey model) and coupled (modified Gurson model) micromechanical approaches, crack initiation and onset of growth on tensile specimens have been analysed. Simplified procedure for determination of critical values of model parameters corresponding to ductile fracture initiation was proposed. Good transferability of parameters determined on simple geometry to the analysis of behaviour of precracked geometry in ductile fracture condition was established. End goal of investigations that are in progress is analysis of actual precracked structure by applying micromechanical approach and simplified method of determination of ductile fracture parameters.

INTRODUCTION

In past decade, a number of Round Robin projects [1,2,3] were organized with the aim to develop and apply micromechanical approach to the analysis of ductile and cleavage fracture of steel. It is more than 20 years now since the development of micromechanical model was initiated by investigations of Gurson [4] and Beremin's [5] research-group. So far none of proposed procedures has been standardized, although several procedures and recommendations have been published [6,7]. Last Round Robin project third phase of which is in progress [3], has contributed to consideration of transferability of damage parameters from geometries without initial crack to precracked geometries according to the micromechanical approach.

Should the problem of parameter transferability to various geometries be successfully solved, it would be possible to prove more than once repeated assumption that micromechanical damage parameters are not geometry- but only material-dependant. This would immensely improve analysis of integrity of real precracked structure, based on laboratory results obtained by testing of a series of specimens.

It is well-known that so far developed and standard-recommended parameters of classical elastic-plastic fracture mechanics (such as COD and J-integral) cannot reliably describe and predict behaviour of the materials affected by external loading under all conditions. The problems are particularly prominent in case of severe plastic strain at the crack tip that may occur in ductile fracture initiation.

Therefore, as a convenient one, a micromechanical approach is introduced in an effort to describe the process of fracture in a way close to actual phenomena in a material. This approach is based on a large number of models dealing with material damage and fracture from the microscopic point of view. According to the model of Rice-Tracey [8], void growth in ductile fracture micromechanism is strongly dependent on stress-field multiaxiality. Similar applies to the model of Huang [9] As these are uncoupled models, damages are calculated subsequently, by post-processing routines, based on knowledge of the stress and strain fields determined experimentally and using FE analysis.

In past decade, more and more attention has been paid to and research efforts directed to the so-called coupled models of damage, where the damage parameter has been "built into" numerical procedure and is estimated by processing during the very FE elastic-plastic evaluation. One of such models for description of ductile fracture has been developed by Tvergaard and Needleman [10,11], based on constitutive equations suggested by Gurson [4]. In this model plastic flow of a material depends on growing porosity developed by void nucleation and growth. An effort has been made to describe the whole process with the fewest possible number of parameters. Main variable parameter - void volume fraction f - is directly incorporated in plastic flow criterion.

In present paper, criterion of crack initiation based on both uncoupled and coupled micromechanical approach has been determined on smooth specimen and used in prediction of crack growth initiation on CT specimen. Numerical analysis was carried out through participation in the Round Robin project [3].

BASIC THEORETICAL CONSIDERATIONS

In the paper, as uncoupled approach to the ductile fracture initiation, Rice-Tracey equation for spherical void growth was used, taking into account material hardening proposed by Beremin [5]:

$$\ln\left(\frac{R}{R_0}\right)_c = \int_{\varepsilon_0}^{\varepsilon_c} 0.283 \exp\left(\frac{3\sigma_m}{2\sigma_{eq}}\right) d\varepsilon_{eq}^{p} \tag{1}$$

where R stands for the actual mean void radius, R_0 is its initial value, the ratio σ_m/σ_{eq} represents stress state triaxiality, and $d\varepsilon_{eq}^{p}$ is the equivalent plastic strain increment. Eq. (1) is integrated from strain corresponding to the crack initiation to critical value ε_c when void coalescence initiates a crack in material. According to the applied model, it is considered that porosity effect on material constitutive equations is very low, so that the damage parameter is not represented in the yield criterion, while Eq. (1) is applied in post-processing calculation.

The Gurson-Tvergaard-Needleman (GTN) model assumes that material porosity in ductile fracture in progress should be taken into account in material flow criterion using the following form:

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

where σ denotes actual flow stress of the matrix of the material, σ'_{ij} is stress deviator and the parameter q_1 was introduced by Tvergaard [10] to improve the ductile fracture prediction of the Gurson model. f* is a function of the void volume fraction [11]:

$$f^* = \begin{cases} f & \text{for } f \le f_c \\ f_c + K(f - f_c) & \text{for } f > f_c \end{cases} \tag{3}$$

f_c is the critical value at which void coalescence occurs. Parameter K defines slope of the sudden drop on the load - diameter reduction diagram and is often referred to as 'accelerating factor'. For f* = 0, the plastic potential (Eq. 2) is identical with that of Von Mises.

TESTED STEEL AND METALLURGICAL OBSERVATIONS

Low-alloyed ferritic steel was tested: 22 NiMoCr 3 7 according to DIN designation. Chemical composition of steel is given in Tab. 1. Tested temperature was 0°C (R_e = 468 MPa, R_m = 619 MPa) [3].

TABLE 1: CHEMICAL COMPOSITION IN WEIGHT PERCENT

C	Si	Mn	P	S	Cr	Mo	Ni	Al
0.22	0.21	0.86	0.018	0.011	0.42	0.83	0.92	0.015

In the GTN model, void nucleation is most frequently defined using initial volume fraction of non-metallic inclusions, f_0, with which so-called primary voids are defined, and using some models that may describe their possible effect on subsequent nucleation (mostly around ferrite carbides - secondary voids) during growth of the primary ones. Fig. 1 shows two micrographs obtained by optical microscope. On the left measurement field one can clearly see whole series of sulphides and one large oxide.

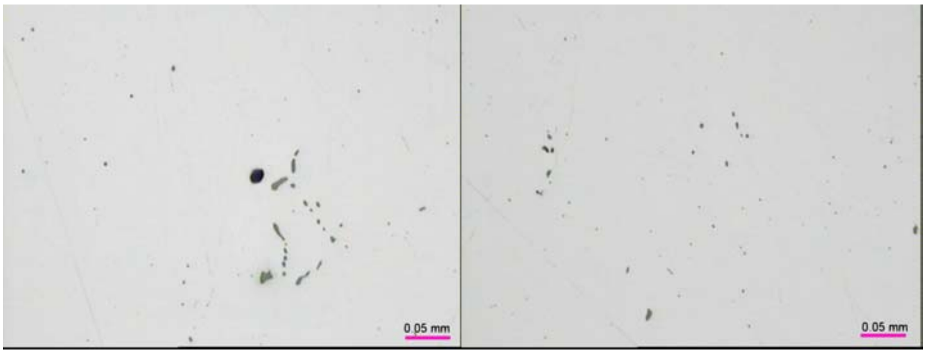

Figure 1: Two optical micrographs of non-metallic inclusions

Initial void volume fraction f_0 was determined by quantitative analysis as a mean value of surface fraction of non-metallic inclusions for all measurement fields, according to [12]:

$$f_0 = \overline{V}_V = \overline{A}_A = \frac{\Sigma A_i}{n} \qquad (4)$$

where n = 100 is a number of measurement fields. In this way, the value of initial volume fraction of non-metallic inclusions f_0 = 0.00226 was determined. Nucleation of so-called secondary voids was not taken into account as it has been found [13] that its application would lead to premature softening of this steel.

DETERMINATION OF DUCTILE FRACTURE PARAMETERS AND ANALYSIS OF THEIR TRANSFERABILITY

FE elasto-plastic calculations of smooth $\phi 6$ and precracked CT25 (W= 50 mm, $a_0/W \approx 0.56$) specimens were performed according to ESIS Round Robin TC8 Project, Phase II, Task A [3]. Isoparametric quadrangular eight-node finite elements with reduced (2x2) integration were used. The large strain formulation with updated Lagrange procedure was applied. Material non-linearity was taken into account by using the true stress-true (logarithmic) strain curve. Von Mises (in uncoupled modelling) and GTN (in coupled modelling) yield criteria were used. Diagram load F - reduction of the smallest diameter ΔD in necking section is shown in Fig. 2. For both calculations a very good agreement with experimental values was obtained. According to the diagram, small influence of tested steel porosity is obvious.

Void growth ratio R/R_0 was evaluated according to Eq. (1) adopted for postprocessing calculation. The crack initiates when the critical value of damage parameter has been reached, and its location can be identified according to the critical value $(R/R_0)_c$ in uncoupled calculation and f_c in coupled calculation. For both damage parameters, similar distribution was obtained in the smallest cross section in necking section. Critical values $(R/R_0)_c$ and f_c were calculated in the centre of smooth specimen. In Fig. 3 increase of f in FE in the specimen centre is shown versus reduction of diameter in necking region. Critical value f_c=0.0611 was determined using bisection of formed curve and straight line corresponding to the value ΔD = 2.63 mm. This value of diameter reduction was experimentally determined (see Fig. 1). Same procedure was used in $(R/R_0)_c$=3.045 determination.

With this procedure, determination of critical values of damage parameters was simplified and necessity to use Eq. (3) in coupled calculation avoided, which means that f_c value need not be prescribed and subsequently fitted with experimental results but could be defined according to the diagram in Fig. 3.

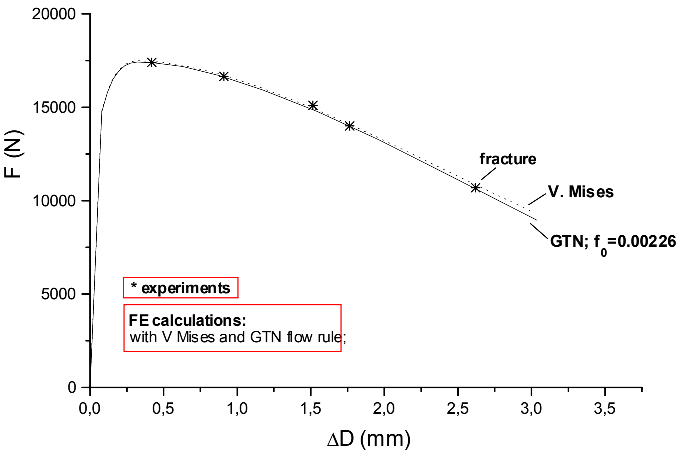

Figure 2: Load F vs. reduction of specimen diameter ΔD

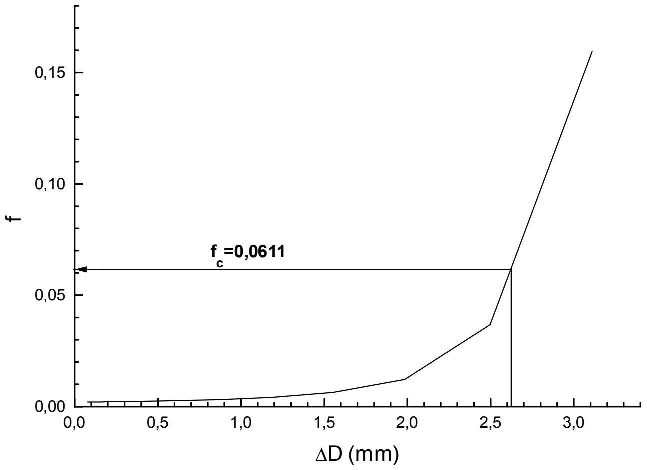

Figure 3: Determination of the critical void volume fraction f_c

Thus determined $(R/R_0)_c$ and fc values were used for prediction of the onset of crack growth on standard CT25 specimen. 2D FE calculations were performed under plain strain conditions. Crack tip was modeled only by mesh refinement; no singular finite elements were used. It has been established [14] that FE size at the crack tip significantly affects J_i values (J-integral on crack initiation), and it is assumed that it depends on the distance between non-metallic inclusions in steel. The mean free path λ, as the mean edge-to-edge distance between inclusions, was determined as follows [12]:

$$\lambda = \frac{1 - A_A}{N_L} \tag{5}$$

where N_L is the number of interception of oxides or sulphides per measurement line unit and A_A is the area fraction of inclusions as defined above. Average value of $\overline{\lambda}$=219 μm was determined using Eq. (5) on all 100 fields of measurement. Considering that it has not been confirmed that mean free path depends on orientation, 0.2 x 0.2 mm was adopted as FE size ahead the crack tip. This size was used for both calculations: by application of Von Mises yield criterion and Rice-Tracey void growth model, and by application of GTN model.

The criterion of the onset of crack growth was $R/R_0 \geq (R/R_0)_c$ i.e. $f \geq f_c$ at Gauss point closest to the crack tip. Calculation of J_i corresponding to crack initiation was made according to the procedure proposed in [15]. Values of J_i determined both experimentally and numerically are given in Tab. 2.

TABLE 2: J_i VALUES

	J_i (N/mm)
experimental [3]	230
the Rice-Tracey model; FE = 0.2 x 0.2 mm at the crack tip	249.2
the GTN model; FE = 0.2 x 0.2 mm at the crack tip	220.4

CONCLUSION

Based on the results obtained for J_i it is obvious that both uncoupled and coupled method of micromechanical modelling can be applied to describe ductile crack initiation in tested low-alloyed ferritic steel. Good transferability of $(R/R_0)_c$ and f_c parameters determined on smooth specimen for prediction of the onset of crack growth on CT specimen was achieved. For determination of critical values of these parameters a simplified procedure was applied that proved to be good; prescription of f_c value in coupled modelling and fitting of numerical with experimental results were avoided. Considering the effect of FE size at a crack tip on prediction of the onset of crack initiation, quantitative metallurgical analysis is necessary.

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