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MICROMECHANISM OF DUCTILE FRACTURE INITIATION - VOID NUCLEATION AND GROWTH

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Abstract. *Micromechanism of ductile fracture of most metals and alloys includes void nucleation, growth and coalescence. The voids nucleate at the second phase particles and non-metallic inclusions. Application of so-called global criteria of fracture mechanics such as COD and J-integral in characterization of ductile fracture onset 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 describe behaviour of various structures of different geometry are not insignificant. In present paper 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. Unlike traditional flow criteria (for instance, with metals widely applied Von Mises criterion), established flow criterion introduces volume fraction (f) variable. Through application of this model, by combining experimental and numerical procedures, an effort is made to predict ductile fracture of metals. In present paper fracture initiation of smooth specimen has been analyzed; described model was incorporated into finite element (FE) program, so that one of the results for each Gauss point may be void volume fraction as well. Probably the most difficult part of such a characterization of ductile fracture is to present physically void nucleation as accurately as possible. An approach to void nucleation, suggested by Chu and Needleman, has been discussed in this paper; the model is based on hypothesis that void nucleation follows a normal distribution of void formation predominantly around coarser non-metallic inclusions in steel. It is particularly problematic to examine secondary voids nucleation around smaller non-metallic inclusions and second phase particles, and to realize their effects on further growth of the existing (primary) voids, and especially on their coalescence resulting in fracture. This has been accompanied by adequate metallographic analysis of non-metallic inclusions and their volume fraction, which represents starting results for elastic-*

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plastic analysis of a porous solid using FE method. The results obtained suggest that applied micromechanical model can be used for characterization of initiation of ductile fracture in steel on geometries without precracks, and that metallurgical analysis is necessary to describe physically the first phase - void nucleation. Special contribution should represent application of the results obtained with a simple geometry to the precracked structures, which should be confirmed in work to follow.

INTRODUCTION

The process of ductile fracture of most metals and alloys includes void nucleation, growth and coalescence. First phase of ductile fracture takes place around the non-metallic inclusions and second-phase particles. In materials in which the particles that might initiate void nucleation are tightly bound with the matrix, already first phase may lead to fracture. In materials of distinct plastic behaviour, fracture occurs following all three phases specified. However, it is not possible to set clear boundaries between brittle and plastic materials, as one and the same material under certain circumstances may behave as a brittle one, while under some other circumstances it may behave as plastic one. Main characteristic of ductile fracture is that throughout the process of fracture energy is consumed, until finally the whole becomes separated in two parts.

So far developed and standard-recommended parameters of elastic-plastic fracture mechanics cannot reliably describe and predict behaviour of the materials affected by external loading under all conditions. Therefore, as a convenient one, a local approach is introduced that has been simultaneously developed in theoretical, experimental and numerical sense. This 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 of microscopic damages in an effort to explain and predict macroscopic failure. At the same time, it is necessary to define as accurately as possible the stress/strain fields and values of the variables describing material damage. According to the model of Rice-Tracey [5], void growth is strongly dependent on stress-field multiaxiality. Similar applies to the models of Huang [6] and Chaouadi *et al.* [7] as well. 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 few years, more and more attention has been paid to and research efforts directed to the so-called uncoupled 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 [3], based on constitutive equations suggested by Gurson [2]. In this model plastic flow of a material depends on void nucleation and growth, that are tried to be presented with the fewest possible number of parameters. Main variable is void volume fraction that is directly incorporated in flow criterion. Numerical and experimental tests of this modified Gurson model, most frequently referred to as Gurson-Tvergaard-Needleman (GTN) model, show that the development of damage at microscopic level and plastic strain as a global, macro-parameter of behaviour of material affected by external loading, can be well-described and determined. In spite of imperfections of the model that are tried to be reduced by growing scope of investigations [9,10], it seems that it is possible to predict the values of macroscopic ductile toughness based on microscopic aspects [11].

In present paper a calculation of standard-specimen tension has been made and criterion of initiation of ductile fracture according to GTN model (critical void volume fraction, f_c) established. Flow criterion with additional variable is incorporated in FE programme. The results obtained have been compared to the experimental data and numerical values determined by traditional Von Mises flow criterion. Void nucleation around non-metallic inclusions in tested steel has been particularly examined using quantitative metallographic analysis.

MICROMECHANISM OF DUCTILE FRACTURE INITIATION AND MODELS OF DAMAGE

Onset of ductile fracture is initiated by void formation around non-metallic inclusions and second-phase particles in metal matrix that is subjected to plastic strain under influence of external loading, and is one of the most complex processes of micromechanism of fracture of this type. Size of the second phase particles and non-metallic inclusions in engineering alloys may range from ≈0.01 μm to values that by far exceed 1 μm [1]. Their shape varies from spherical to lamellar or even irregular form [12]. Depending on the size, shape and quantity of these particles as possible spots for initiation of ductile fracture, numerous models have been developed in an effort to describe this complex micromechanism. Some models evaluate a critical stress, others use a critical strain. Both types of criteria are based on the fact that a critical stress at the interface of an inclusion or in the center of an inclusion must be exceeded to cause debonding or cracking of the particle [13]. 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 subsequent nucleation (secondary voids) during growth of the primary ones as matrix of material was deformed.

Growth of nucleated voids is strongly dependent on stress and strain state. Most of experiments and analyses show an exponential increase with the stress triaxiality which is defined as the ratio of the mean stress σ_m and equivalent stress σ_{eq} [5,7,13]. These investigations represent the basis of uncoupled approach to the material damage in micromechanical analysis. In that case Von Mises criterion is most frequently used as a flow criterion. Coupled approach to the material damage and ductile fracture initiation considers alloy as a porous medium where the influence of voids on plastic flow cannot be avoided. Gurson [2] has analysed plastic flow in porous materials supposing that the material behaves as continuum. The existence of voids is taken into account indirectly, through their average value [4]. It has been experimentally shown that the Gurson model describes initial phase of fracture adequately, but that it is not adequate for actual behaviour of the material in subsequent phases of fracture initiation. Tvergaard and Needleman have started from the Gurson model and, after certain modifications (by introducing the coefficient of correction), established the model that is more in accordance with the experimental results. According to this modified (GTN) model, plastic potential is given by [3]:

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

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 and Needleman [3] to improve the ductile fracture prediction of the Gurson model. Thus, plastic flow in porous material does not only depend on the equivalent plastic strain ε^p_{eq} in the matrix material, but according to this model, also on a second variable, the void volume fraction f. f^* is a function of the void volume fraction:

$$f^* = \begin{cases} f & \text{for } f \le f_c \\ f_c + K(f - f_c) & \text{for } f > f_c \end{cases} \tag{2}$$

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 often it is denoted as 'accelerating factor'. For $f^* = 0$, the plastic potential (eqn. 1) is identical with that of Von Mises.

According to Needleman and Tvergaard, the nucleation of the new - secondary voids and the growth of the existing voids were introduced into Gurson constitutive relationships by the following definition of the growth rate of f:

$$\dot{f} = \dot{f}_{nucleation} + \dot{f}_{growth} \tag{3}$$

$$\dot{f}_{nucleation} = B\,(\dot{\sigma} + \dot{\sigma}_m) + D\,\dot{\varepsilon}^p_{eq} \tag{4}$$

$$\dot{f}_{growth} = (1 - f)\,\dot{\eta}^p_{ii} \tag{5}$$

where $\dot{\eta}^p_{ii}$ is the plastic part of the strain rate tensor. According to Chu and Needleman [14] parameters B and D are chosen under assumption that void nucleation follows a normal distribution. For strain controlled void nucleation parameter D is given by:

$$D = \frac{f_N}{S_N\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{\varepsilon^p_{eq} - \varepsilon_N}{S_N}\right)^2\right], \; B = 0 \tag{6}$$

with f_N denoting volume fraction of void forming particles, ε_N is mean strain at void nucleation and S_N is corresponding standard deviation.

DETERMINATION OF CRITICAL VALUE OF DAMAGE PARAMETER IN DUCTILE FRACTURE INITIATION

The GTN model without void coalescence mechanism (lower part of eqn. 2) was integrated into finite element program. The results were obtained with the structural, low alloy steel (used mainly for manufacture of pressure vessels) 22 NiMoCr 3 7. Initial void volume fraction f_0 was determined by quantitative optical microscopy according to [18]. Fig. 1 shows two visual fields on the sample prepared for metallographic analysis. On the left visual field one can clearly see whole series of sulphides and one large oxide. Initial void volume fraction is determined as a mean value of surface fraction of non-metallic inclusions for all visual fields, which is $f_0 = 0.00226$.

Numerical calculation was carried out on the standard smooth specimen of 6 mm diameter. Due to symmetry, FE mesh was formed for one quarter of the specimen. Initial imperfection was not used for neck formation. Loading was introduced using prescribed displacements of specimen edge in a number of steps. Four- and eight-noded quadrangular finite elements with reduced integration were used. Size of finite elements in the centre of the specimen was 0.3 × 0.125 mm. Material non-linearity was modeled by true stress - true (logarithmic) strain curve. The large strain (updated Lagrangian) FE formulation was used.

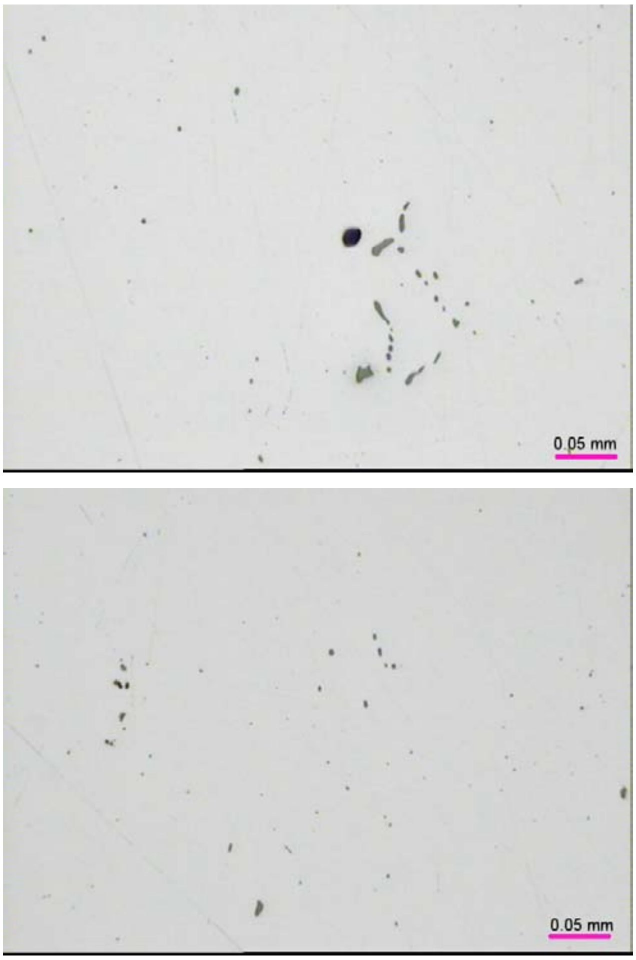

Fig. 1. Two photos of non-metallic inclusions obtained using optic microscope

Elastic-plastic FE calculations were carried out with Tvergaard-Needleman parameter value $q_1 = 1.5$ according to [3], both, with and without secondary void nucleation. When secondary void nucleation was taken into account, parameter D according to the Chu-Needleman model was determined for $\varepsilon_N = 0.3$, $S_N = 0.1$ and $f_N = 0.04$. These are literature, for steel most frequently used, values [11,15].

Fig. 2 shows a diagram load F, vs. reduction of cross-section of a round specimen for FE calculation using four-noded finite elements. Calculation in which initial void volume fraction was taken into account using f_0 and calculation in which traditional Von Mises criterion was used gave approximate results. Moreover, the differences between the Von Mises law and the GTN model are negligible almost up to the initiation of damage. FE calculation in which secondary void nucleation under tension is taken into account gives more severe deviation from experimental data after maximum loading has been reached and neck formed on the specimen. Selection of parameters of the Chu-Needleman model must probably be based on the experimental investigations of tested steel, which means that optic microscopy should be used for determination of possible points of secondary voids nucleation, i.e. of smaller particles in the material "following" plastic strain of the matrix at the beginning of loading, that only later - with significant increase of plastic strain - may influence the increase of damage as initiators of new voids. This point of view may not be *a priori* correct as, judging by the initial void volume fraction, it is a rather "pure" steel, so that it may happen that the influence of secondary voids nucleation should be very small or even negligible.

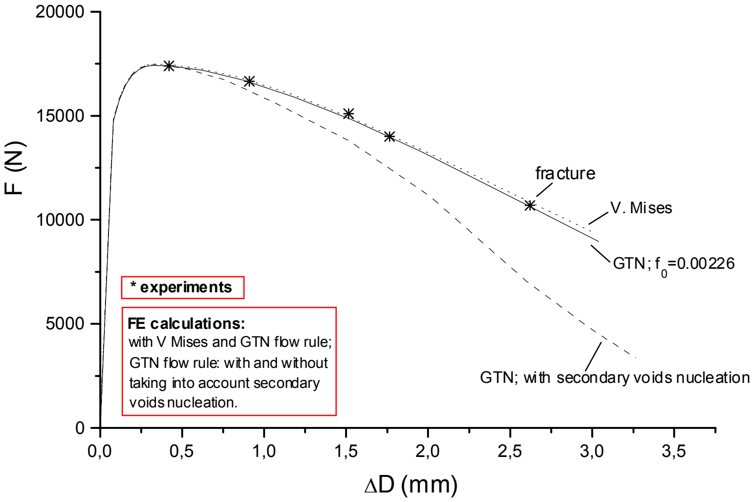

Fig. 2. Load vs. reduction of diameter with four-noded FE calculation

The influence of FE analysis was taken into account by carrying out calculation with eight-noded finite elements with reduced integration as well. The results for *F*-Δ*D* diagram with that calculation, together with the previous one (both made with f_0 taken into account, but without consideration of possible nucleation of secondary voids) are shown in Fig. 3. Calculation with eigth-noded FE gives somewhat lower position of tensile curve, but the interesting thing is that, immediately in front of the experimental point of fracture, it gives certain further bending of the curve.

Having in mind that the fracture criterion given by the lower part of the expression for function $f*$ (eqn. 2) is not used in the calculation and that sudden drop on force-necking diagram was not to be expected in both calculations, this phenomenon seems very interesting. That practically means that, in a way, the fracture was still suggested by the point of last lapping of the curve, which may be of great significance in simplification of this complex procedure. Of course, when the whole eqn. 2 is taken into account, sudden drop could be expected exactly at that point or close to it, but that means further sophistication of already complex numerical analysis, which makes its commercial exploitation more difficult. It remains to investigate this phenomenon more thoroughly through further work, and to give recommendations for the simplest and yet sufficiently accurate performing of the numerical procedure.

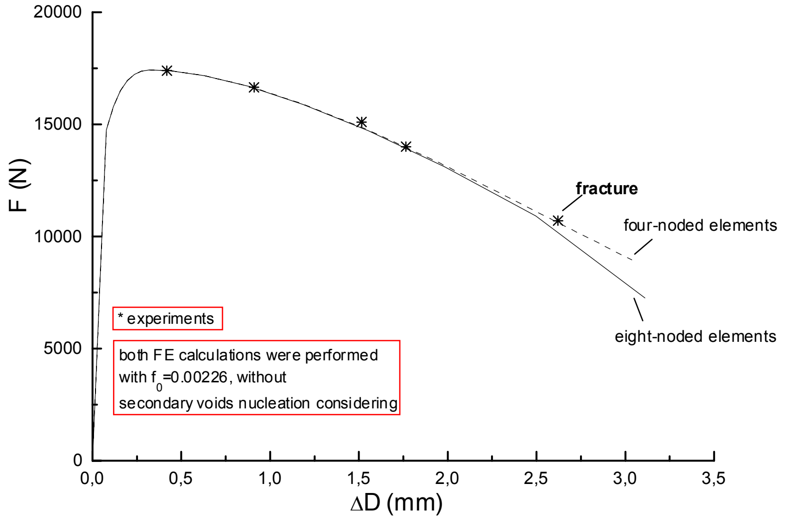

Fig. 3. Load vs. reduction of diameter with four-noded and eight-noded FE calculation

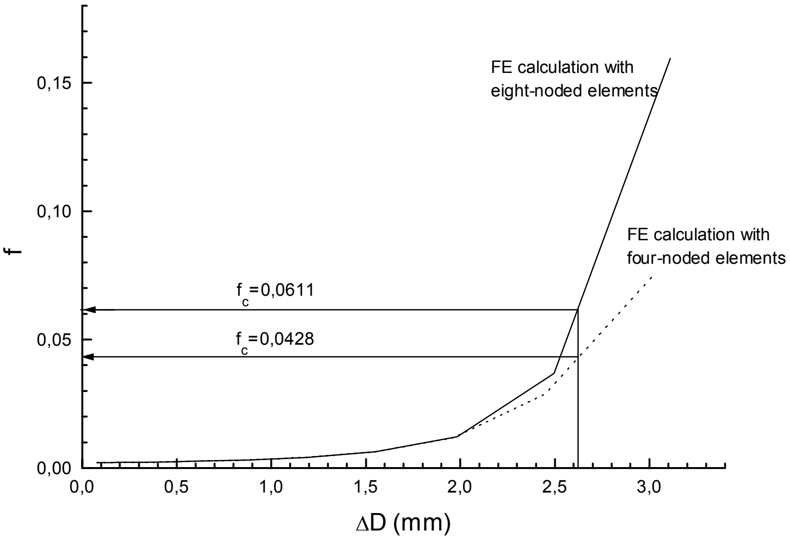

Fig. 4. Determination of critical void volume fraction

Critical void volume fraction, f_c, was determined according to the diagram shown in Fig. 4, from the increase of void volume fraction in finite element in the centre of the specimen, depending on cross-section reduction at the point at which the neck appeared on the specimen – minimum cross-section – for both FE calculations (for the calculation with eight-noded elements, mean value of void volume fraction at Gauss points was taken). For determination of f_c value experimental result [10] for the necking $\Delta D \approx 2.63$ mm was used, at which sudden drop of force occurs, which is caused by coalescence of voids in the material. The values obtained are in good agreement with so far recommended values [9,10] for this steel ($f_c = 0.05$) and steel that is most similar to it according to American standard A508Cl.2 ($f_c = 0.045$) [16].

The values obtained should be verified through their application in an analysis of the onset of crack growth on the precracked geometries, all that in order to establish an experimental and numerical procedure that would make parameters of the model applied geometry-independent, i.e. dependent on tested material only.

CONCLUSION

Based on the results obtained by numerical analysis using elastic-plastic calculations on standard round specimen of low-alloy steel for pressure vessels, the following may be concluded:

- the difference between the GTN model with void volume fraction incorporated in the flow criterion and traditional Von Mises flow criterion is small: both calculations give the results very close to the experimental ones;
- FE calculation using eight-noded elements makes it possible to determine approximately void coalescence point on the load vs. reduction of diameter diagram, without considering previously prescribed critical void volume fraction, f_c in calculation;
- determined value for f_c is in accordance with former recommendations;
- the procedure should be verified on geometries with precracks.

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MIKROMEHANIZAM INICIJALIZACIJE DAKTILNIH FRAKTURA - NUKLEACIJA PRSKOTINA I NJIHOV RAST

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U radu su, polazeći od rezultata dobijenih numeričkim putem, koristeći pretpostavku o elastično-plastičnom telu, na standardnom kružnom uzorku od nisko legiranog čelika za sudove pod pritiskom, izvedeni sledeći zaključci:

- razlika između GTN modela sa udelom zapreminske poroznosti uključenim u kriterijum strujanja i tradicionalnog Von Mises-ovog je mala: oba proračuna daju rezultate bliske eksperimentalnim

- FE proračun koji koristi elemente sa osam čvorova omogućuje da se približno odredi dijagram zavisnosti tačke koalescencije pora od smanjenja prečnika

- određivanje zapreminskog kritičnog udela poroznosti f_c

- procedura bi se trebalo proveriti kod oblika sa predprskotinama.