DIFFERENT CDM-MODELS AND THEIR ABILITY TO DESCRIBE THE DAMAGE DEVELOPMENT AT DUCTILE FRACTURE OF STEEL

R. Schiffmann, W. Dahl, W. Bleck

Department of Ferrous Metallurgy, RWTH Aachen University of Technology
D - 52072 Aachen, Intzestraße 1, Germany

ABSTRACT

Ductile fracture of materials is caused by micromechanical damage developing during the plastic deformation and finally leading to the initiation and propagation of a crack. Continuum damage mechanics (CDM) can be used to describe this process. Local stress and strain properties are calculated by FEM-models to serve as input for the computational determination of the damage indicators. These output properties should be able to characterise fracture or crack initiation behaviour independent of stress state (stress triaxiality) or loading history (change of stress triaxiality).

Technical metallic materials usually show one dominating damage mechanism: micro-void growth. This growth starts at the yielding point of the material where existing voids or newly formed voids start expanding and ends at the initiation point where voids unify to form a microcrack finally leading to fracture. This micromechanism can be described by different models more or less directly:

1. Geometric models: a) The void growth model of Rice&Tracey for a spherical void
   b) The Dung-McClintock-model of three-dimensional void growth
2. Energetic model: The damage work model proposed by Chaouadi
3. Formal models: The damage accumulation model proposed by Wang

Experimental data to check the models exist for a high-strength structural steel. Differently notched tensile specimens were deformed until crack initiation occurred to produce different stress triaxialities. By varying the notch radius during deformation stress triaxiality could be changed in a wide range. Observation of fracture surfaces of broken specimens by SEM can give an estimation of final void sizes which can be compared with calculated sizes.

1. INTRODUCTION

The investigation of fracture processes and the conditions of component failure play an important role in engineering sciences. Fracture mechanics has become an indispensible part of material sciences. In order to know more about fracture behaviour in the last years the way of the "local approach" is gone in order to describe the damage accumulation finally leading to fracture.

The discipline "continuum damage mechanics" builds the bridge between classical destructive testing and the new possiblities offered by nowadays computers to test recent models working on the basis of continuum mechanics to be able to better calculate structural integrity and predict lifetime.

2. DUCTILE FRACTURE

For the investigated material ductile behaviour is found which leads to the typical dimple covered fracture surfaces produced by slide fracture. The micromechanism of damage accumulation is the growth of micro-voids generated by second phase particles always present in engineering materials. Failure occurs by the coalescence of these voids which leads to the initiation and propagation of a crack finally fracturing the material.

3. MODELLING

In order to model the material degradation by void growth the finite element method (FEM) is used, which supplies data based on continuum plasticity. Data gained in specimen testing serve to calibrate the modelling, micromechanical important properties such as stresses and strains achieved from FE-calculation serve as input parameters for damage model calculation modules.

Models used in this contribution are:

A) geometric models - void growth equations

-) the Rice-Tracey-model for the growth of a single spherical void in an infinite matrix [1],[2]

$$\ln\frac{R}{R_0} = 0.283\cdot\int_0^{\varepsilon}\exp\left(\frac{3}{2}\cdot\frac{\sigma_m}{\sigma_V}\right)\cdot d\varepsilon \tag{1}$$

R ... void radius

σ_m/σ_V ... stress triaxiality

σ_V ... von Mises equivalent stress

ε ... equivalent plastic strain

σ_m ... hydrostatic stress

R_0 ... original void radius, inclusion radius

-) the three-dimensional void growth model proposed by Dung based on McClintock's void growth equation the void is regarded as ellipsoidally-shaped [3],[4]

$$\ln \frac{R_1}{R_0} = \int_0^{\varepsilon} \left\{ \left[\frac{\sqrt{3}}{(1-n)} \sinh\left(\frac{\sqrt{3}\cdot(1-n)}{4} \cdot \frac{3\cdot\sigma_m}{\sigma_V} \right) \cdot \cosh\left(\frac{\sqrt{3}\cdot(1-n)}{4} \cdot \frac{\sigma_2-\sigma_3}{\sigma_V} \right) \right] + \frac{6}{4} \cdot \frac{\sigma_1-\sigma_2-\sigma_3}{\sigma_V} \right\} d\varepsilon \qquad (2)$$

R_1 ... void semi-axis in straining direction R_2, R_3 ... void semi-axes perpendicular to straining direction

σ_1 ... stress in straining direction σ_2, σ_3 ... stresses perpendicular to straining direction

n ... strain hardening exponent of the material

B) energetic model

The damage work model as proposed by Chaouadi based on the Huang-modification [5] of the Rice-Tracey void growth equation [1] which can be correlated to J-Integral considerations [6],[7]

$$W_d = \int_0^{\varepsilon} \left[1 + 3\cdot 0.427 \cdot \frac{\sigma_m}{\sigma_V} \cdot \exp\left(1.5 \cdot \frac{\sigma_m}{\sigma_V} \right) \right] \cdot \sigma_V \cdot d\varepsilon \qquad (3)$$

W_d ... damage work density

C) formal damage accumulation model proposed by Wang

Derived from elastic strain energy density considerations of classical creep damage mechanics [8] a damage evolution model is proposed which incorporates the accumulation coefficient k as a crucial constant that has to be found by fitting procedures and should characterise the behaviour of the material:

$$WSP_i = \int_{\varepsilon_0}^{\varepsilon_i} k \cdot f\left(\frac{\sigma_m}{\sigma_V} \right) \cdot (\varepsilon - \varepsilon_0)^{k-1} d\varepsilon \qquad (4)$$

$$f\left(\frac{\sigma_m}{\sigma_v} \right) = \frac{2}{3}(1+\nu) + 3\cdot(1-2\cdot\nu)\left(\frac{\sigma_m}{\sigma_v} \right)^2 \qquad (5)$$

WSP_i ... damage parameter according to Wang at crack initiation ν ... Poisson’s constant

k ... damage accumulation coefficient

ε ... equivalent plastic strain: ε_0 ....in undamaged state ε_i ....at crack initiation

4. MATERIAL TESTED

The material investigated was the high strength structural steel FeE690. Its chemical composition is given in **TABLE 1**, its mechanical properties are shown in **TABLE 2**.

TABLE 1

CHEMICAL COMPOSITION (mass-%)

steel	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Ni**	**Mo**	**Cu**	**Ti**	**V**	**Al**
FeE 690 (L)	0.17	0.65	0.90	0.012	0.006	0.86	0.027	0.41	0.015	0.017	0.01	0.033

TABLE 2

MECHANICAL PROPERTIES (tensile test)

steel	**R_{eL} [MPa]**	**R_m [MPa]**	**A_5 [%]**	**Z [%]**
FeE 690 (L)	695	818	23	74

5. EXPERIMENTS

The material was tested in standard axisymmetric tensile specimens which were differently notched to produce different stress states. Stress state was strongly varied by applying the two-step method for tensile tests proposed by Marini et al. [9] in order to produce different loading histories. Specimen geometries and loading histories investigated are given in TABLE 3, denominations of ESIS P6-94D draft procedure on local approach [10] were applied.

TABLE 3

SPECIMEN GEOMETRIES AND LOADING HISTORIES

according to ESIS P6 - 94 D

one-step experiments:	two-step experiments:	prestraining (ε_V^p):		
NT 1 - 5	unnotched→NT 1 - 5	55%	76%	95%
NT 2 - 5	unnotched→NT 2.5 - 5	“	“	“
NT 2.5 - 5	unnotched→NT 4.3 - 5	“	“	“
NT 4 - 5	NT 1 - 5→NT 4.3 - 3.5	13%	17%	22%
NT 8 - 5	NT 2 - 5→NT 8 - 3.5	15%	27%	35%
unnotched	NT 4.3 - 5→NT 8 - 3.5	46%	55%	62%

first value: notch radius [mm], second value: minimal diameter [mm], e. g. “NT 2 - 5 → NT 8 - 3.5 prestraining 35%“ means: notched axisymmetric tensile specimen, prestrained with a notch radius of 2 mm and a specimen diameter (notch) of 5 mm to a true strain of $\varepsilon_v^p = 0.35$ in the center, afterwards machined to a notch radius of 8 mm and a specimen diameter (notch) of 3.5 mm and strained in a second step

Metallographic investigations allowed for the detection of crack initiation and thus the determination of initiation strains which served as stop-mark for FEM-modelling.

The final damage state at initiation could be estimated in terms of dimple sizes observed on the fracture surfaces which were compared to final void sizes determined by void growth models.

6. RESULTS OF MODELLING

a) Rice-Tracey; pure void expansion

Figure 1 shows the void growth from yielding to crack initiation of all loading histories as a funtion of stress triaxiality. The void sizes at crack initiation are given as dots or rings and the paths of stress states are given as (dotted) lines from yielding to initiation. It can easily be seen that the void size at initiation is not constant but decreases with stress triaxiality. This shows clearly the competition between void growth and deformability which has already been reported [7],[11]. Furthermore it shows that the asumption of a constant void size at initiation as used in the Beremin-criterion [2],[10] can only be a rough approximation.

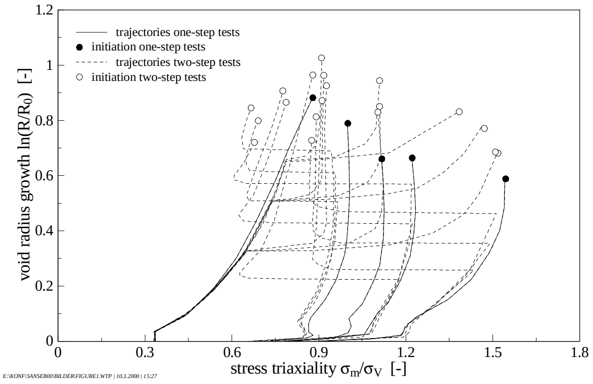

Figure 1: void radius growth according to the model of Rice and Tracey [1] as a function of applied stress triaxialitiy from yielding to initiation

b) Dung-McClintock; void shape change

In order to get data of void cross sections this model is used to calculate void growth. The voids are regarded as ellipsoidally-shaped and interacting. Results are given in **Figure 2**. Additionally results from fracture surface measurement by scanning electron microscope (SEM) have been added (right y-axis). It can be seen that the void cross sections are decreasing with stress triaxiality, for model calculations as well as for measured dimple sizes. The model seems to unterestimate the absolute values of void growth. Underestimation has been reported for the Rice-Tracey model, too [5].

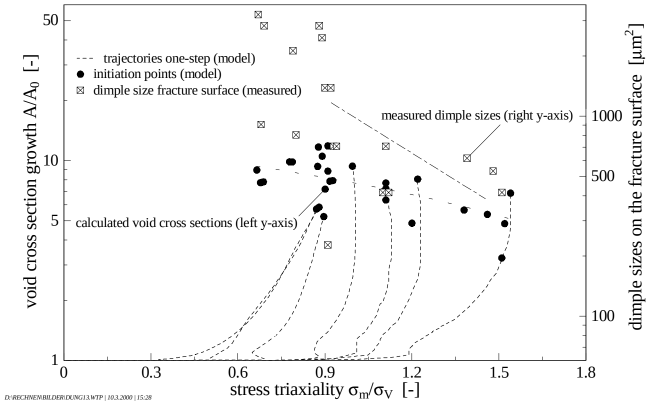

Figure 2: void cross section growth according to the model of Dung / McClintock [3] compared to dimple size measurement on fracture surfaces

c) Chaouadi; damage work model

Figure 3 gives the results of the damage development expressed in terms of energy densities according to the damage work model. The initiation values for all stress states and histories hit a common level of W_{di}=4100 mJ/mm^3 with good accuracy. Therefore this property W_{di} can be regarded as a physically meaningful material property.

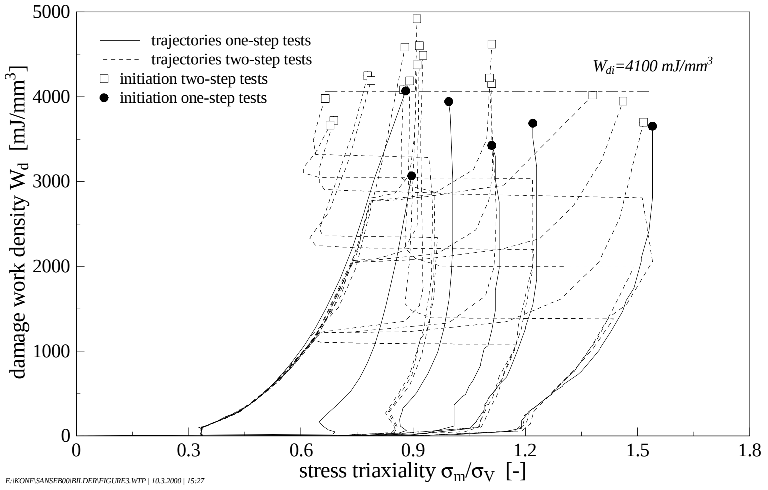

Figure 3: damage work density development according to the model of Chaouadi [6] as a function of applied stress triaxiality from yielding to intiation

d) Wang; degressive damage accumulation function

Results of model calculations according to the Wang model from yielding to crack initiation are given in **Figure 4** as a function of stress triaxiality. The critical damage parameters at initiation decrease with higher triaxiality and hit values of about 1.0 to 1.7 what means a relatively high scatter. The accumulation coefficient k is found to be 0.67, if all loading histories are used. For only one-step loaded specimens with only slightly changing stress triaxialities a value of k=0.53 is found by data analysis calculations. These k-values are in the range of engineering materials found in literature [12].

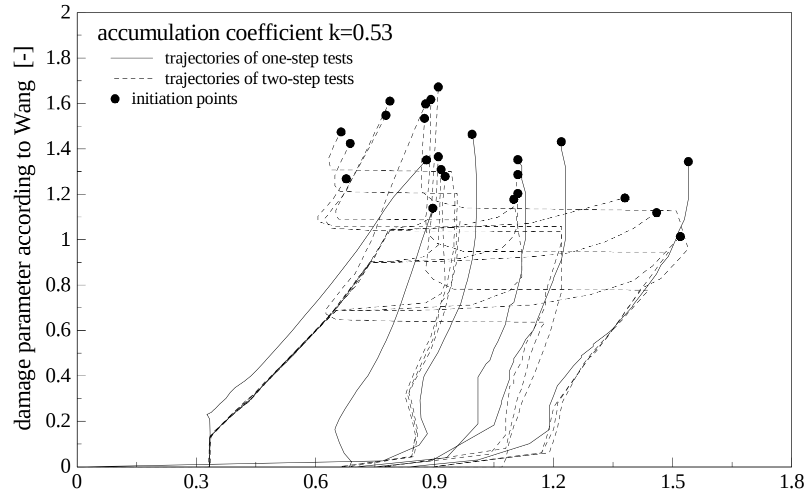

Figure 4: evolution of the damage paramter according to Wang [12] as a function of applied stress triaxiality from yielding to initiation

7. DISCUSSION

a) *Void growth equations* have the big advantage of supplying properties which can be measured experimentally, these are void radii or void cross sections. On the other hand void growth models can be proven or rejected or just be modified on basis of experimantal data. More sophisticated models as for example the Dung equations are preferable but the limits of applicability have to be obeyed. Void size parameters are generally not constant at crack initiation and therefore cannot be used without correction to formulate an initiation criterion independent of stress state.

b) *Energetic models* seem to be based physically and should be able to offer an initiation criterion. The applied damage work model gives a good example. The critical material property W_{di}=4100 mJ/mm^3 is within the range of similar materials (RPV-steels). Scatter is remarkably low. As the relation to the J-Integral is given [7] this should be the extension or the successor of the classical elastic-plastic fracture mechanical approach. A disadvantage of this model is that the damage variable cannot as easily be determined experimentally as for example void sizes. Nowadays computer technology offers ways to apply the model in the framework of the finite element method (FEM).

c) A *new model* proposed by Wang [12] shows that opposite from the other models a *degressive damage accumulation law* also can offer modelling possibilities leading to acceptable results. But it has to be doubted, that damage accumulation is stronger at the first deformation steps than in the last steps shortly before crack initiation, because this would mean a new access in the understanding of ductile damage processes. Nevertheless accumulation coefficients in the range of 0.5 to 1 can be found for most engineering materials as it was the case for this contribution, too. A big disadvantage seems to be that the accumulation coefficient k, which should be a kind of material property in its own way, is determined by fitting procedures and cannot be derived analytically.

d) *Conclusion:* As an initiation criterion the critical damage work density W_{di} seems to be most promising as the model is physically meaningful and the calculations supply results of convincing accuracy.

e) *Future work:* Two free-cutting steels of similar chemical composition and mechanical properties but different inclusion sizes are tested. Inclusion fractions and therefore void volume fractions are quite high which should allow to easily observe void growth due to plastic deformation and check void growth models.

8. REFERENCES

[1] Rice, J.R., Tracey, D.M.
On the Ductile Enlargement of Voids in Triaxial Stress Fields,
J. Mech. Phys. Sol. 17(1969), S. 201-217

[2] Beremin F.M.
Study of the fracture criteria for ductile rupture of A 508 steel
Advances in Fracture Research - 5th International Conference on Fracture (D. Fracois Editor)
Pergamon Press, March 1981

[3] Dung, N. L.
A simple model for the three-dimensional growth of voids/inclusions in plastic materials
Int. Journ. of Fracture 53 (1992) R19-R25

[4] McClintock, F.A.
A criterion for ductile fracture by the growth of holes, J. Appl. Mech. 35 (1968), S. 363-371

[5] Huang, Y.
Accurate Dilatation Rates for Sperical Voids in Triaxial Stress fields
Transactions of ASME, Journal of Applied Mechanics, Vol. 58, December 1991, p. 1084-1086

[6] Chaouadi, R., De Meester, P., Scibetta, M.
Micromechanical modelling of ductile fracture initiation to predict fracture toughness of reactor pressure vessel steels, Euromech-Mecamat ‘96 Fontainebleau
Journal de Physique IV, C6-53/64, Vol. 6, Oct. 1996

[7] Chaouadi, R.
Micromechanically-based damage modelling of crack initiation in reactor materials
Dissertation (doctoraat in de toegepaste wetenschappen), D/1996/7515/3, Katholieke Universiteit te Leuven, Feb. 1996

[8] Kachanow, L. M.
On the time to failure under creep conditions (in Russian)
Izvestija Akademij Nauk SSSR, Otdelenie Tekhnicheskikh Nauk 8, 1958, p. 26 -31

[9] Marini, B., Mudry, F., Pineau, A.
Ductile rupture of A508 steel under nonradial loading
Eng. Frac. Mech. 22 (1985) No. 3, S. 375-386

[10] ESIS P6-94D, Draft procedure to measure and calculate local approach critera using notched tensile specimens, version 4.0, March 1997

[11] Hancock, J.W., Mackenzie, A.C.
On the Mechanisms of Ductile Failure in High-Strength Steels Subjected to Multi-Axial Stress-States, J. Mech. Phys. Solids 24 (1976), p. 147-169

[12] Wang, T.-J.
A new ductile fracture theory and its applications
Acta mechanica sinica, Vol.11, No.1, February 1995, p. 83-93

Acknowlegdement:

The tests described in this publication were performed in the framework of a series of projects funded by the German Society of Research (DFG). Support under the project number Da58/79-1 is gratefully acknowledged.