DAMAGE BY VOID GROWTH IN TENSILE AND BEND TYPE SPECIMENS

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Ductile fracture can be better described by local considerations of its fundamental mechanisms, for example by micromechanical damage models, which do not meet the problems of geometry dependence as they have to be transferable by definition.
In the present contribution, the local damage by the growth of voids according to the RICE and TRACEY model is investigated numerically. The growth rate is influenced by triaxiality and the change of the plastic equivalent strain. To study these effects finite element calculations simulating crack growth of two different specimens, C(T) and M(T), have been performed, and the near crack tip area is investigated.

INTRODUCTION

One of the essential problems of fracture mechanics is the transferability from specimens to structures. The resistance against ductile tearing is characterized by a J-resistance curve which is obtained from bend type specimen by standard procedures (1). The original idea was that one unique resistance curve would suffice to characterize the material. However, testing of different types of specimens and loading conditions revealed considerable differences in the R-curves, especially in the slopes. Therefore limits and conditions for J-control have been set forth in the standards for fracture testing which define a lower bound estimate of J-capacity in order to obtain a conservative index of material toughness. Many restrictions and requirements for the application of J-R curves have been set up, and many attempts of introducing a "second parameter" (2) to account for the constraint dependence of R-curves have been made, recently.

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There is also some general criticism on the physical meaning of J as a controlling parameter for crack growth. Another interesting approach has been proposed by TURNER (3) who introduced the dissipation rate which describes tearing resistance in a physically more meaningful way (4). But as it is a structural quantity, too, it does not solve the problem of transferability, either.

Ductile fracture can be better described by local considerations of its fundamental mechanisms, which avoid these problems as they have to be transferable by definition. In the present contribution the "local approach" of BEREMIN (5,6) based on the RICE & TRACEY (7) model of the growth of a spherical void in a ductile material will be applied to analyse the ductile crack growth both in a bend and a tensile type specimen.

DAMAGE BY VOID GROWTH

For ferritic steels at temperatures above the brittle to ductile transition temperature plastic deformation is limited by the process of void formation, growth and coalescence (8). In the first stage of this ductile failure process voids nucleate from second phase particles (non-metallic inclusions) by decohesion of the particle-matrix interface at a critical radial stress (9) or even by cracking of the particle.

We suppose that the void formation is influenced by the maximum principal stress, σ_I , and the plastic deformation which can be characterized by the difference of equivalent stress, σ_{eq}, and yield stress, σ_y (5, 6). Then we can state the condition

$$\sigma_I + k\,(\sigma_{eq} - \sigma_y) = \sigma_c \quad , \tag{1}$$

where k is a material parameter which depends on the shape of the inclusions and σ_c is a temperature independent critical stress.

In the present contribution we shall not analyse void formation but growth of voids. RICE and TRACEY (7) derived an equation for the growth rate of a spherical cavity in a perfectly plastic material

$$\frac{\dot{R}}{R} = 0.283\ \dot{\varepsilon}^{pl}_{eq}\ e^{\frac{3\sigma_h}{2\sigma_y}} \quad , \tag{2}$$

where R is the current radius, σ_h the hydrostatic stress and $\dot{\varepsilon}^{pl}_{eq}$ the plastic equivalent strain rate. BEREMIN (5,6) replaced the yield stress, σ_y , by the actual equivalent stress, σ_{eq}, to account for strain hardening. The "time" parameter for calculating the "rate" $\dot{R}$ may be taken as the monotonically increasing crack length, a, for ductile crack extension

$$\dot{R} = \frac{dR}{d\Delta a} = \frac{dR}{da} \quad . \tag{3}$$

A fracture criterion may be derived from equation 2 by integration and comparison with a "critical" ratio of the void radii, $(R/R_0)_c$. An incremental formulation

$$\left(\frac{R}{R_0}\right)_{n+1} = \left(\frac{R}{R_0}\right)_n \left(1 + 0.283\ \Delta\varepsilon_{eq}^{pl}\ e^{\frac{3\sigma_h}{2\sigma_{eq}}}\right) \tag{4}$$

as in the European round robin on local critera (10) is used in the finite element simulations.

RESULTS FOR C(T) AND M(T) SPECIMEN

The finite element (FE) calculations are performed for sidegrooved compact specimens C(T) and centre cracked tensile panels M(T) made of the German standard steel StE 460 (11). Their dimensions are summarized in the following table. The specimens have been tested for large ductile crack growth to investigate "geometry effects", and the numerical simulations follow the experimental records.

StE 460, Bundesanstalt für Materialforschung und -prüfung (BAM 1.34) GEOMETRY				
W (mm)	B (mm)	B_n (mm)	a_0/W	Δa_{max} (mm)
C(T) 50	25	19	0.59	7.6
M(T) 50	20	16	0.49	9.59

All specimens were fully yielded at initiation of crack growth. The FE models are two-dimensional, assuming plane strain conditions, and subject to prescribed displacements. The void growth evaluations are made with a postprocessing routine according to equation 2, 3 and 4. The void growth rate, $\dot{R}/R$, and the total void radii ratio, R/R_0-1, are interesting quantities giving some information about the size and shape of the process zone as a funtion of the specimen geometry.

In Figs. 1 and 2 the void growth rates are plotted in the ligament for five crack extension values. Due to the singularity of the equivalent plastic strain rate, the void growth rate has a high gradient near the crack tip. The "process zone", defined as a zone of significant void growth rate, spreads about 0.4 *mm* into the ligament for both specimens.

The maximum values of the growth rate (Fig. 3) and the local maximum values of total void radii ratio (Fig. 4) are, of course, found at the actual crack tip. They are plotted for all the calculated loadsteps or crack extensions. There is a high numerical scatter of the data as the plastic strain rate is singular at the crack tip and the stress triaxiality enters by an exponential function, equations 2 and 4, which does not allow for a quantitative interpretation. But it may be concluded that no significant differences of the damage quantities between the two specimen types appear though the stress and strain states differ as is well known. This will become more evident in the following Figures where some important quantities which contribute to or measure damage, i.e. triaxiality (Fig. 5), rate of effective plastic strain (Fig. 6), void growth rate (Fig. 7), and void radii ratio (Fig. 8), are plotted in the vicinity of the crack tip for both C(T) and M(T) specimens. Whereas stress triaxiality and plastic strain rate differ remarkably between the two specimen types the shapes of the damaged zones as characterized by some isoline of significant void radii ratio are much more similar.

CONCLUSIONS

- Finite element calculations with von Mises yield criterion and Prandtl-Reuss-flow rule can be analysed with respect to local damage and fracture criteria by the RICE and TRACEY void growth model and the BEREMIN local approach by a postprocessing program.
- The result of the postprocessing procedure is an evaluation of void radii ratio and void growth rate in the integration points of the structure. Size and shape estimation of the process zone at the crack tip can be estimated from these two quantities. Their respective local maximum values are found at the crack tip.
- The total void radii ratio is an accumulated quantity which increases from loadstep to loadstep at every integration point. Its absolute maximum value is staying at the initial crack tip independent of the loadstep.
- The damaged zone can be defined by some critical value of the void radii ratio; the results of the numerical simulations indicate that this zone is not dependent on the specimen geometry.

REFERENCES

(1) ASTM E 1152-87, "Standard test method for determining J-R curves", Annual Book of ASTM standards, Vol. 03.01, American Society for Testing and Materials, Philadelphia.

(2) Brocks, W. & Schmitt, W., "Constraint Effects in Fracture: Theory and Applications", Edited by M.T. Kirk and A. Bakker, ASTM STP 1244, Philadelphia, to be published.

(3) Turner, C.E., "Fracture Behaviour and Design of Materials and Structures", Edited by D. Firrao, Proc. 8th European Conference on Fracture, Engineering Materials Advisory Service, Warley, UK, 1990, Vol. II, pp. 933-949, 951-968.

(4) Memhard, D., Brocks, W. & Fricke, S., Fatigue Fract. Engng. Mater. Struct., Vol.16, 1993, pp. 1109-1124.

(5) Beremin, F.M.: Metallurgical Transactions A, Vol. 12A, 1981, pp. 723-731.

(6) Beremin, F.M., "Advances in Fracture Research", Edited by D. François, Proc. ICF5, Cannes, Vol.2, 1981, 809-816.

(7) Rice, J.R. & Tracey, D.M., J. Mech. Phys. Solids, Vol. 17, 1969, pp. 201-217.

(8) Tipper, C.F.: Metallurgica 39 (1949), 133-137.

(9) Argon, A.S., Im, J. & Safoglu, R.: Metallurgical Transactions 6a (1975), 362-371.

(10) Mudry, F. and Di Fant, M., "A round robin on the measurement of local criteria", Report RE 93.319, IRSID, 1993.

(11) Aurich, D. et al., "Analyse und Weiterentwicklung bruchmechanischer Versagenskonzepte", Research Report BAM 192, Federal Institute for Materials Research and Testing, Berlin, 1993.

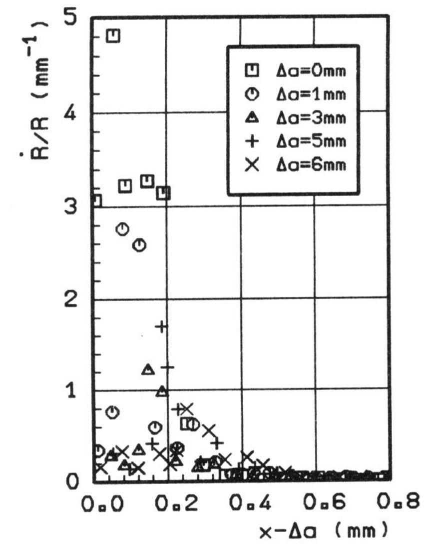


Fig. 1 Void growth rate in the ligament of the C(T) specimen

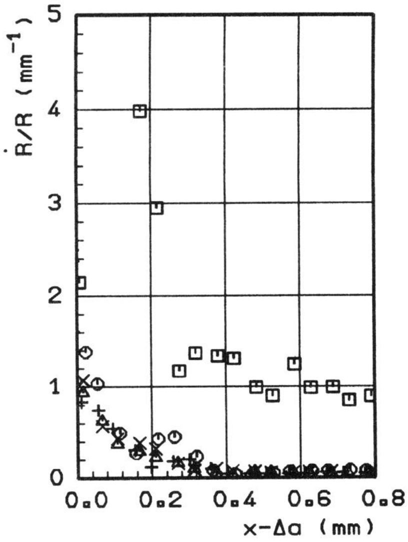


Fig. 2 Void growth rate in the ligament of the M(T) specimen

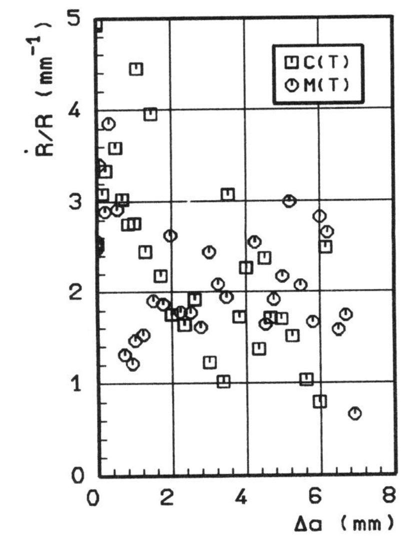


Fig. 3 Void growth rate at the crack tip of C(T) & M(T) specimen

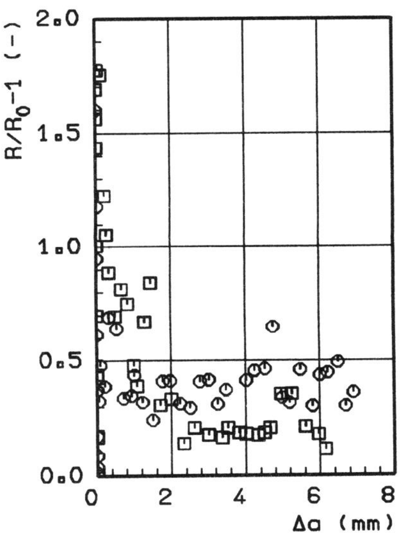


Fig. 4 Void radii at the crack tip of C(T) & M(T) specimen

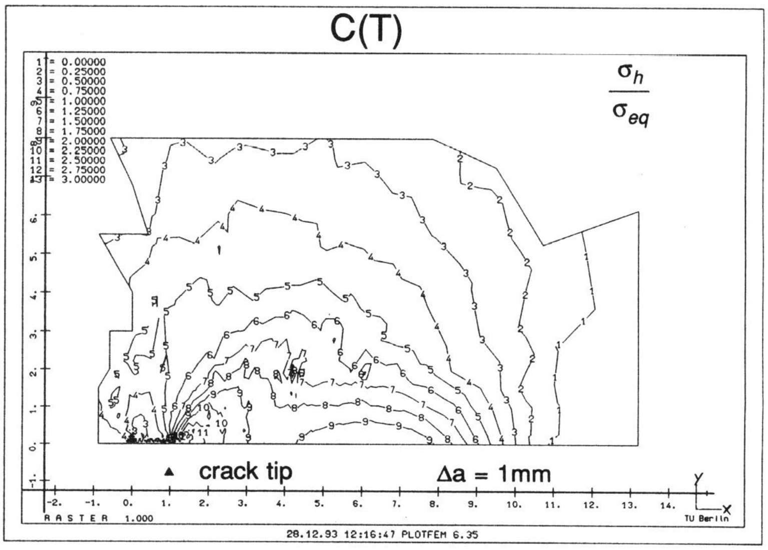
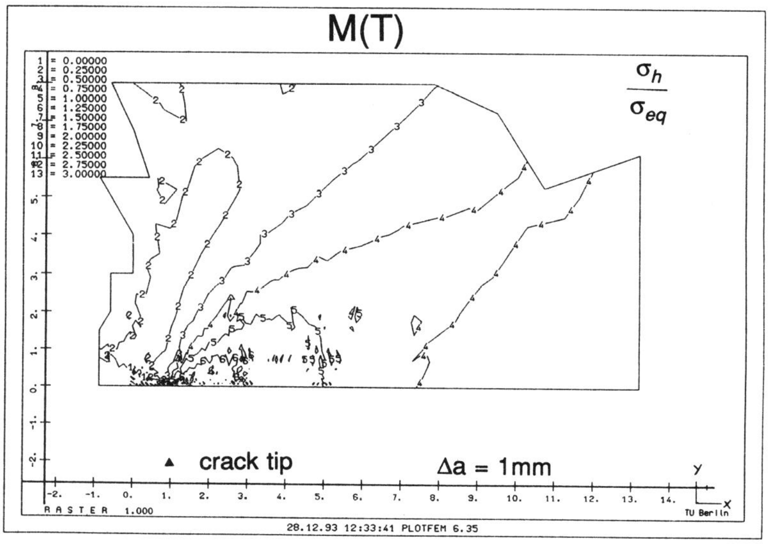


Fig. 5 Isolines of stress triaxiality at the crack tip of C(T) and M(T) specimen for Δa=1mm crack extension



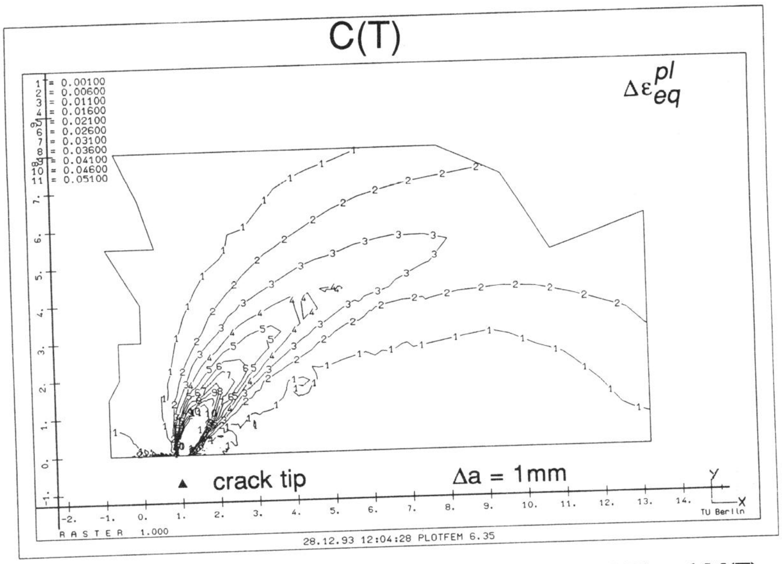
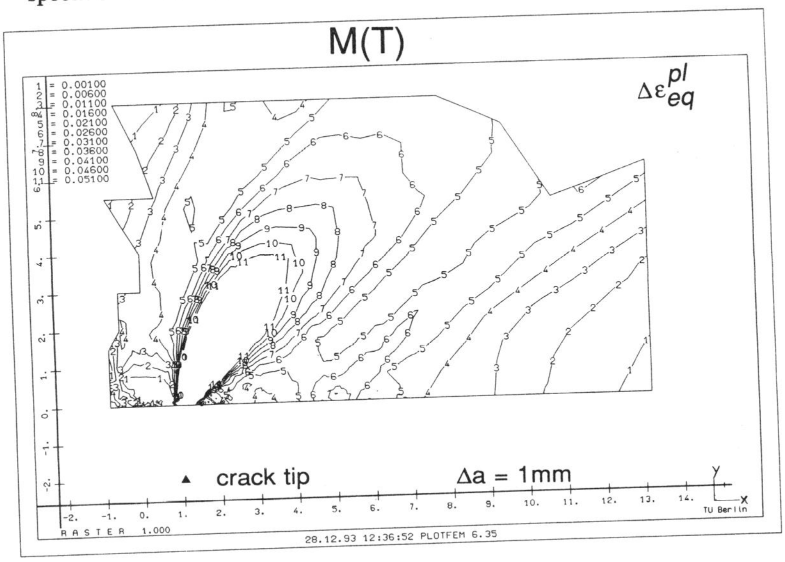


Fig. 6 Isolines of plastic strain rate at the crack tip of C(T) and M(T) specimen for Δa=1mm crack extension



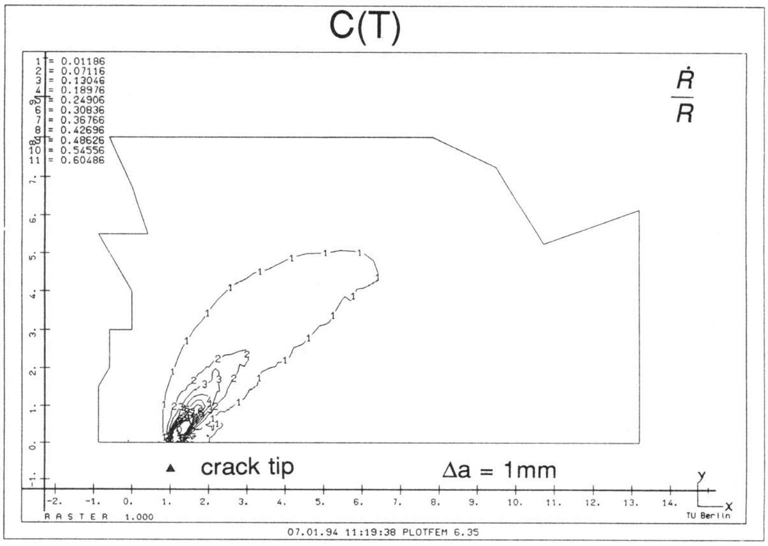
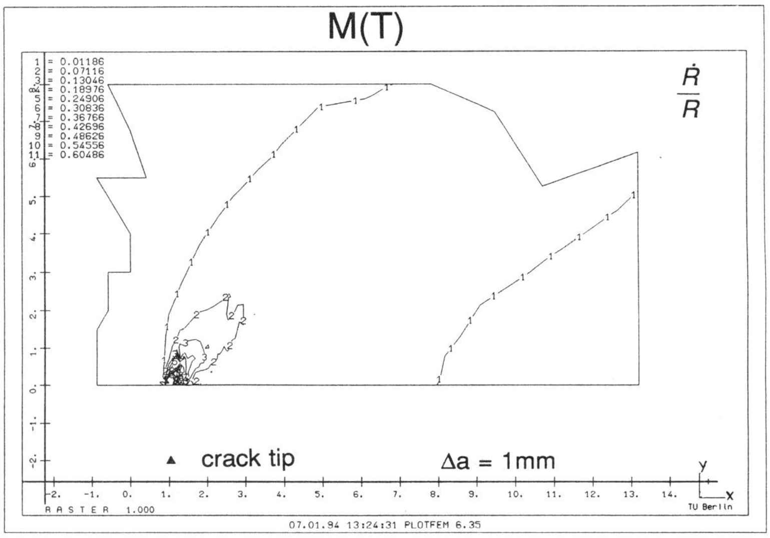


Fig. 7 Isolines of void growth rate at the crack tip of C(T) and M(T) specimen for Δa=1mm crack extension



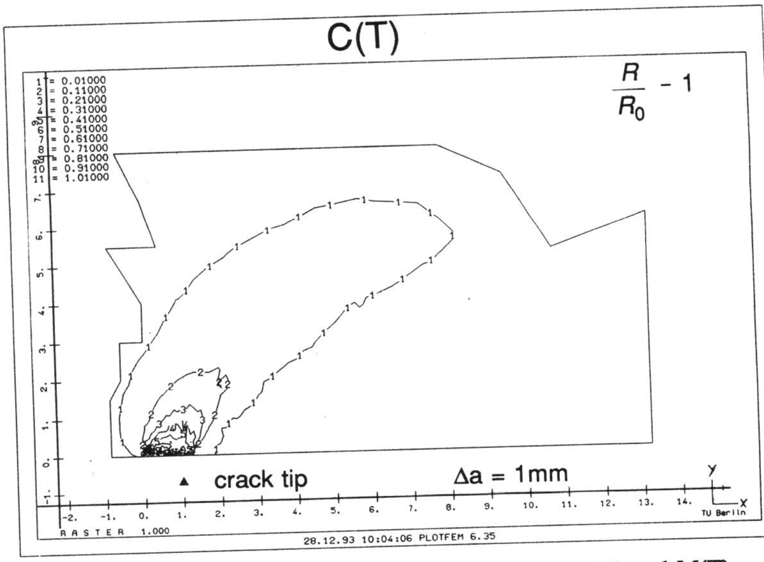


Fig. 8 Isolines of void radii ratio at the crack tip of C(T) and M(T) specimen for Δa=1mm crack extension