ON THE APPLICABILITY OF DAMAGE MODELS FOR THE DESCRIPTION OF THE FAILURE BEHAVIOUR OF DUCTILE STEELS

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ABSTRACT

The reliable calculation of the admissible maximum load is of great importance in the evaluation of the load bearing capacity of thick-walled components. One possibility for the calculation of the maximum load is to describe the whole ductile failure of the material by means of so-called damage models. These models try to describe numerically the process developping microscopically and finally leading to fracture by means of continuum mechanical approaches in order to calculate the macroscopical failure behaviour.

Experimental, metallographical and numerical investigations were carried out using the reactor pressure vessel steel 20 MnMoNi 5 5 (similar to A 533 B Cl 1). A comparison of experimental and numerical results demonstrates in how far it is possible to predict the microscopical and macroscopical behaviour of specimens of different size and geometry.

KEYWORDS

A 533 B Cl 1, damage models, ductile failure, finite element calculation, fracture mechanics, local approach, 20 MnMoNi 5 5

INTRODUCTION

For the safety-relevant assessment of thick-walled components it is of great importance to know about the deformation behaviour, the maximum load and the failure mechanism. The deformation behaviour can be described within certain boundaries by means of the conventional structural theorie but this theory will fail as soon as the material behaviour is influenced by stable resp. instable crack growth. In the case of cracks or postulated cracks, methods of the elasto-plastic fracture mechanics are applied to assess the failure process. However, these methods have one disadvantage of only being applied if there is already a crack. Also the crack growth laws used for these methods (commonly on the basis of the J-integral) depend on the geometry and size, [1, 2]. They are either not or only conditionally transferable.

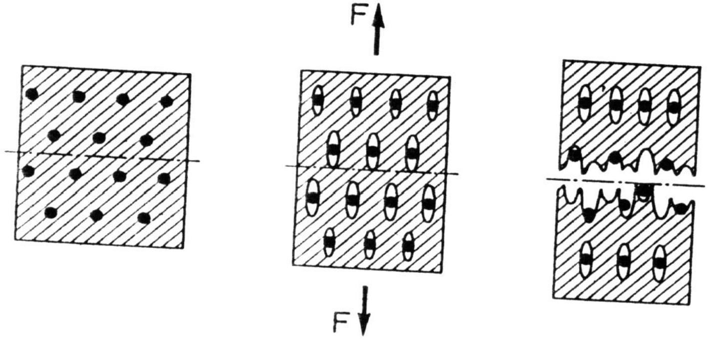
Due to these inadequacies new methods of describing the ductile fracture are increasingly used. One example is represented in the description of the ductile fracture with the help of so-called damage models (local approach). These models try to describe locally the micromechanical processes leading to fracture with mathematical relations. By means of the local consideration it is then possible to determine the location of crack initiation as well as crack growth. Owing to their local formulation, damage models may be used for the calculation of cracked as well as notched or smooth specimens and components.

MATERIAL

The material used for the following investigations is a melt of high purity and toughness of the reactor pressure vessel steel 20 MnMoNi 5 5. This material is very common in Germany and corresponds largely to the American steel A 533 B Cl 1. The material reaches a charpy notch impact energy of $C_v = 200$ J on the upper shelf of toughness on which the tests discussed in this paper were performed. At the testing temperature of 80°C the yield strength amounts to 395 N/mm^2 and the tensile strength to 519 N/mm^2.

MICROMECHANICAL MODELLING

Various work [3, 4, 5] shows that the micromechanical processes leading to ductile fracture can be devided into three successive phases, Fig. 1:



1. void nucleation at second phase particles
2. void growth
3. void coalescence

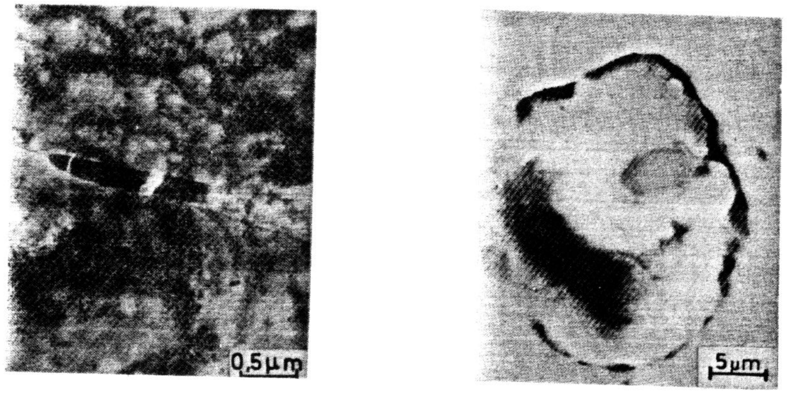
Fig. 1: The three elementary stages in ductile rupture

- Formation of voids on nonmetallic inclusions and precipitations
- Growth of voids with increasing deformation
- Coalescence of cavities ⟹ macroscopic fracture

These three phases can be observed for almost every ductile metal or alloy.

In searching for possibilities of describing ductile fracture numerically numerous material models, in the following called damage models, were developed to describe mathematically the three phases of failure. The aim of such a damage model is to describe one or more of the phases leading to fracture by means of size- and geometry-independent characteristic values. Damage models are almost exclusively used in finite element (FE) programs because of their local approach. However finite element programs need continuum mechanics material models for the description of macroscopic structures. So the aim of a damage model must be to describe the extremly discontinuous stress and deformation state in the area of inclusions and voids with a continuum mechanics approach. Numerous continuum mechanics approaches are known from the literature [6, 7, 8, 9, 10]. For the calculations discussed hereafter, the following models have been chosen to describe the three phases of crack initiation:

Formation of voids. It can be assumed that, for ductile fracture, cavities form essentially at inclusions and precipitations. They are formed either by the cracking of particles or by decohesion of particles and matrix, Fig. 2. Metallographic investigations [11] for the material 20 MnMoNi 5 5 show essentially long iron carbide Fe_3C and needle-shaped Mo_2C precipitations as well as nonmetallic inclusions such as aluminium oxide Al_2O_3, silicon oxide SiO and manganese sulphide MnS. Examinations show also that the voids initiate mainly at the manganese sulphides by decohesion of inclusion and matrix.



a) b)

Fig. 2: Void formation by a) cracking of a Fe_3C-carbide
b) decohesion of MnS-inclusion and matrix

Beremin suggested a model [7] which assumes that void formation only depends on the current state of stress. If, at a point of the structure, a certain critical equivalent stress σ_c is reached, void formation has to be expected at this point. The equivalent stress σ_c is calculated by the following equation:

$$\sigma_c \leq \sigma_{max} + k \cdot (\sigma_v - R_e)$$

k $\widehat{=}$ function of inclusion shape
R_e $\widehat{=}$ yield stress
σ_c $\widehat{=}$ critical equivalent stress
σ_{max} $\widehat{=}$ maximum principal stress
σ_v $\widehat{=}$ von Mises equivalent stress

Growth of voids. Cavity growth follows directly from cavity formation provided the deformation continues to increase. If now the material contains voids, the volume constancy under plastic deformation is inevitably lost. However, the von Mises material model which is generally used to calculate ductile materials assumes a homogeneous material and subsequently volume constancy. In the von Mises model the portion of plastic deformation therefore only depends on the deviatoric stresses. There is no dependence on the hydrostatic stress. If a material contains voids, plastic deformation may occur in that area despite pure hydrostatic loading of the material volume, since at most a two-axial stress state is possible on the void surface which allows the material to yield.

A yield function taking into account void formation and growth is given by G. Rousselier [9]:

$$\phi = \frac{\sigma_v}{1-f} + \sigma_k \cdot D \cdot f \cdot e^{\left(\frac{\sigma_m}{(1-f)\sigma_k}\right)} - \sigma_0 = 0 \tag{2}$$

f $\widehat{=}$ void volume
σ_k, D $\widehat{=}$ constants
σ_m $\widehat{=}$ hydrostatic stress
σ_v $\widehat{=}$ von Mises equivalent stress
σ_0 $\widehat{=}$ present yield stress

In the case of a void volume of zero, i.e. a material without voids, Rousselier's and von Mises yield functions are identical. However with increasing void volume f, the second term of equation 2 becomes larger and the dependence of the yield strength on the hydrostatic stress grows.

Coalescence of voids. The growth of voids is terminated through reduction of area or the fracture of the ligaments between the voids. In the case of the investigated steel it was observed that the ligaments break up due to the formation of shear bands and small secondary voids. Rousselier's yield function considers this process of breaking up of the material bridges (coalescence of voids). The void volume grows exponentially under large plastic deformation causing the stresses to slump despite increasing strains. These phenomena and the related disadvantages shall be illustrated by calculating a notched round tensile specimen with a minimum diameter of 10 mm. The stresses in the centre of the round tensile specimen were determined by a finite element calculation. Figure 3 represents the stresses in loading direction versus the reduction of area of the specimen. In a conventional finite element calculation, i.e. a calculation disregarding the declining material strength caused by void formation, the stress in the centre of the specimen rises continuously. If, however, the calculation is made with Rousselier's material model, a maximum stress with a subsequent steep drop of stress is observed, Fig. 3. This drop of stress is to simulate the coalescence of the voids. In this procedure it is disadvantagieous that the stresses do not decline completely to zero and that the drop is not very steep in contrary to what would have been expected in the case of a fracture of the ligament. In order to obtain a better approach of the calculated course of stress to the real one, a critical void volume f_c was introduced [12]. If the void volume f calculated under the yield conditions proposed by Rousselier reaches the critical value f_c in a specified material volume, then the material stiffness is put to zero at this point. With this additional coalescence parameter f_c a very steep fall in stress down to zero is calculated, Fig. 3.

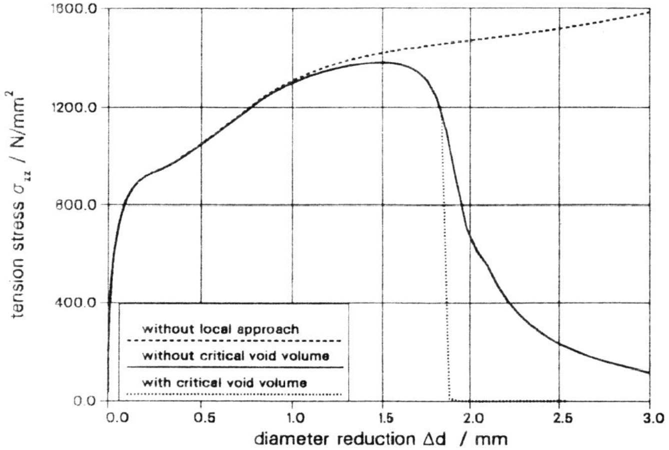


Fig. 3 Calculated tension stress in the center of a smoothly notched tension specimen

RESULTS

The approaches discussed in the preceding chapter allow a numerical simulation of the entire deformation and fracture process. The parameters needed for the damage models were determined on a notched round tensile specimen with a notch radius of $\rho = 2$ mm [13]. The results presented in the following shall show if and in how far the parameters may be transferred to specimens of different size and geometry.

First it was verified whether it is possible to calculate the behaviour of unnotched and notched round tensile specimens with a minimum diameter of 10 mm. Figure 4 shows the experimental and calculated load - diameter reduction behaviour of the different specimens. The results confirm that independent of the notch radius the deformation behaviour of the specimens can be well calculated.

In a second step it was verified to what extent the damage models are transferable to fracture mechancis specimens. For this purpose three CT25-specimens with crack depth ratios

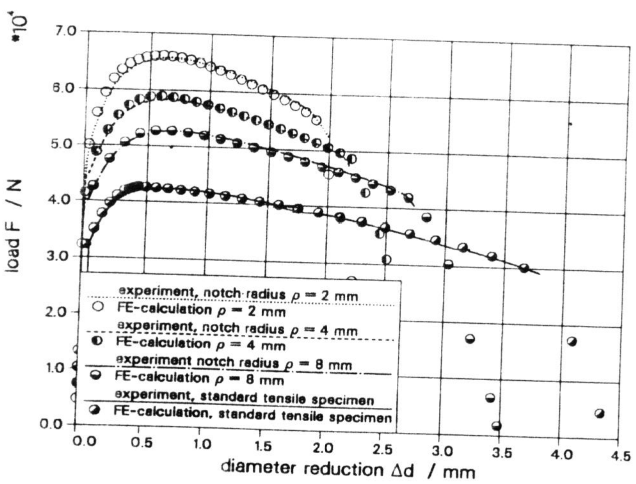


Fig. 4: Comparison of measured and calculated load - diameter reduction of unnotched and notched tensile specimens ($D_{min} = 10\,\mathrm{mm}$)

of a/W = 0,59, a/W = 0,70 and a/W = 0,79 were calculated. This type of specimen which is frequently used in fracture mechanics was side-grooved to 20%. Owing to the transversal strain hindrance caused by the side grooves, the specimen behaviour could be determined under the assumption of plain strain state. In figure 5 the experimentally observed and the calculated load - load line displacement behaviour of the CT25-specimens is illustrated. The calculations using the damage models coincide well with the experimental behaviour. Also crack growth can be well predicted with this approach, Fig. 6.

A DENT-[1]specimen was calculated with the damage models in order to quantify a possible influence of size. The CT-specimens discussed in the preceding paragraph had a thickness of B = 25 mm and a width of W = 50 mm; the DENT-specimen had a thickness of B = 300 mm and a width of 2W = 200 mm. Although the large-scale specimen was not side-grooved, plain strain state was again assumed for the calculation. The damage models required small element size in the crack area. Therefore a 3D idealization was not possible. Figure 7 shows the calculated and experimentally [14] measured load - elongation behaviour of the large-scale specimen. The loads calculated with the damage models overestimate the experiment in the entire course by approximately 10 - 15%. This deviation is attributed to a too stiff idealization of the specimen caused by the assumption of plain strain state. If compared with a conventional finite element calculation which disregards crack growth, the elongation behaviour and the maximum load can be much better calculated with this procedure, Fig. 7. Contrary to the conventional finite element calculation, crack growth can be well predicted by means of the damage models, Fig. 8.

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[1] DENT $\widehat{=}$ double-edge notched tension

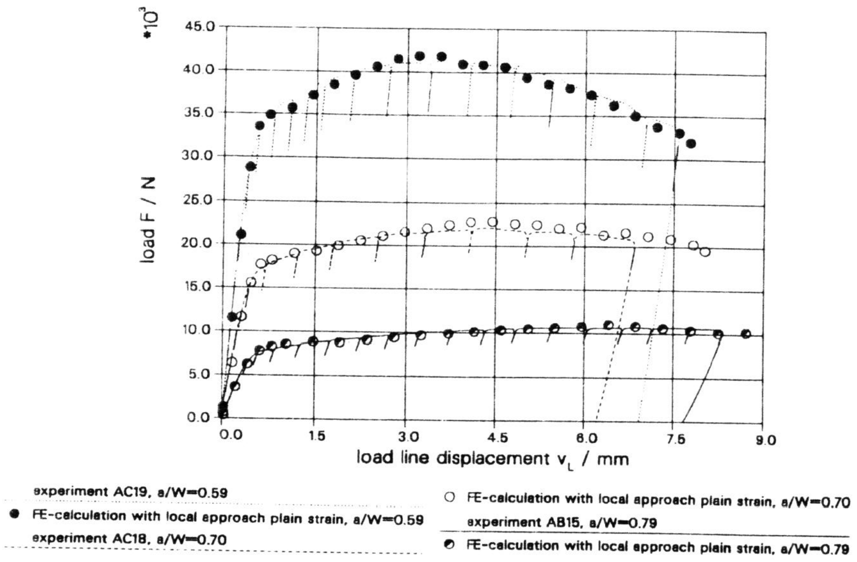

Fig. 5: Comparison of measured and calculated load - displacement behaviour of CT-specimens (B = 25 mm, W = 50 mm)

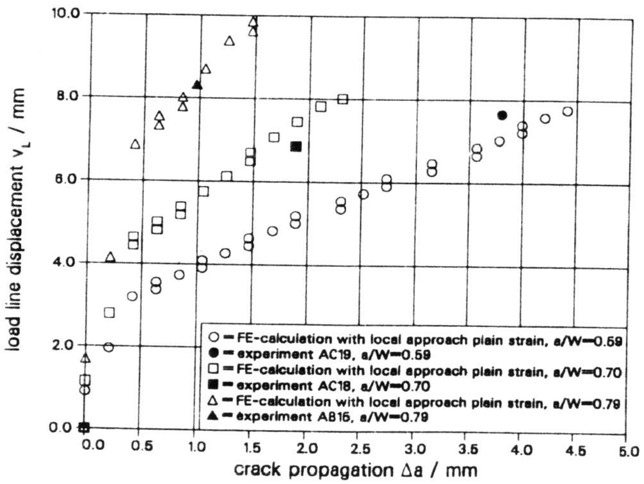

Fig. 6: Comparison of measured and calculated displacement vs. crack propagation curves of CT-specimens (B = 25 mm, W = 50 mm)

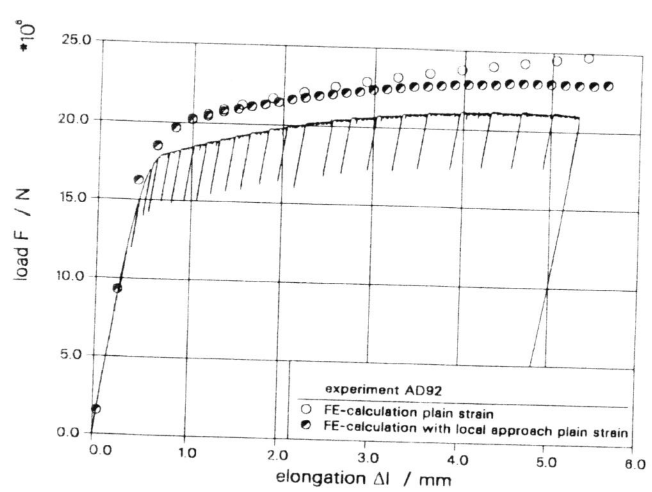

Fig. 7: Comparison of measured and calculated load - elongation behaviour of a DENT-specimen (B = 300 mm, 2W = 200 mm)

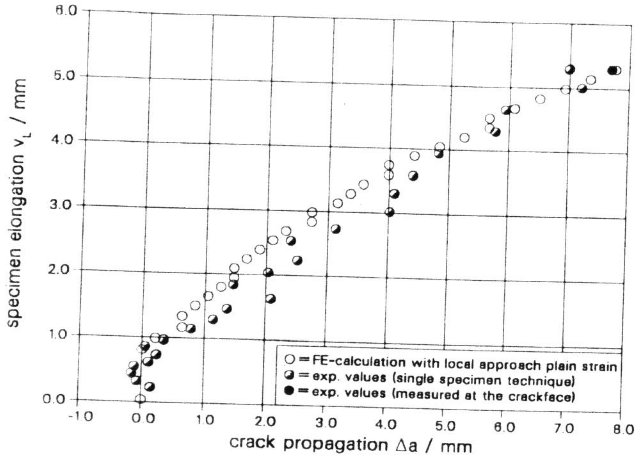

Fig. 8: Comparison of measured and calculated elongation vs. crack propagation curves of a DENT-specimen (B = 300 mm, 2W = 200 mm)

SUMMARY

The following conclusions can be drawn from the calculations of specimens of most different sizes and geometries described in the preceding chapter:

- With the damage models the deformation behaviour and the moment of fracture of unnotched and notched round tensile specimens can be predicted correctly.
- The deformation behaviour and the observed crack growth of fracture mechanics specimens of different sizes and geometries can also be well predicted.
- The parameters necessary for the damage models are determined by means of a notched round tensile specimen. The calculations show that these parameters are transferable to specimens of highly different sizes and geometries.
- What hinders a broad application of damage models is the partly time-consuming and non-standardized determination of the necessary parameters.

In conclusion it can be said that the damage models represent a very promising method for the calculation of the deformation and failure behaviour of specimens and components. Further investigations are in demand to find out whether the approaches described in this paper are transferable to other material groups (austenites, aluminium alloys etc.) and to materials of low toughness.

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