MICROSTRUCTURAL EFFECTS ON DAMAGE MECHANICS IN CONSTRUCTIONAL STEEL

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Shear fracture in ductile metals is caused by the micro-mechanisms void nucleation, void growth and void coalescence. To determine ductile failure curves a critical local stress and local strain state is defined which, however, is dependent on the load history. The failure curve is determined by tensile tests using differently notched tensile specimens. The parameters stress triaxiality and equivalent plastic strain are calculated locally at the point of void coalescence, which is determined by metallographic examination. For similar stress states during deformation the failure curves of tensile specimen can be applied to components to assess their safety against failure.

INTRODUCTION

Depending on component specifications different failure criteria apply for ductile material: fracture, instability or exceeding of a given elastic or plastic strain. For the ductile failure of steel various testing methods with different kinds of material parameters for the characterisation of the material are applied. This report deals with ductile fracture due to shear fracture.

DAMAGE MECHANICS

Ductile failure of steel can be divided into three stages: void nucleation, void growth and void coalescense.

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Void Nucleation

There are many criteria to describe the process of void nucleation. Some give 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 centre of an inclusion must be exceeded to cause debonding or cracking of the particle, respectively. Stress criteria consider the macroscopic stress field and a second microscopic stress to derive a critical local stress at the particle.

Most of the strain criteria have been derived from stress criteria. They demand a critical stress caused by dislocation pile up at the interface. The higher the plastic strain of the matrix material around the particle, the higher is the dislocation pile up and the induced interface stresses. Additionally to the critical stress or the critical strain, a sufficient elastic distortion of the matrix is necessary to continue the process of cracking or debonding of the particles. But most calculations show that the critical distortion is already reached in the elastic condition.

Void Growth

The following process of void growth presupposes a plastic deformation of the matrix. The increase of the void volume strongly depends on the state of stress. All experiments and analyses show an exponential increase with the triaxiality, which is the ratio of the mean stress σ_m divided by the von Mises equivalent stress σ_v. A positive triaxialitiy causes an increase, a negative triaxiality causes a decrease of the void volume. A typical growth law for a single void in an infinite matrix was derived by Rice and Tracey (1).

$$\ln\left({}^{R_i}\!/_{R_o} \right) = 0{,}283 * \int_{\varepsilon = \varepsilon_n}^{\varepsilon_i} \exp\left(\frac{3}{2} * \left(\frac{\sigma_m}{\sigma_v} \right) \right) d\varepsilon \qquad (1)$$

The equation shows clearly the influence of the state of stress during the deformation process. Beginning with void nucleation at a certain strain ε_n and ending with void coalescense at the initiation strain ε_i the void growth rate is gouverned by the stress state exponentially. To calculate the void growth rate the strains at void nucleation and coalescense have to be determined in experiments. The disadvantage of this method is the missing consideration of the effect of damage on the plastic deformation of the matrix. The major advantages are that the equations are easy to handle and that the result of a single FE-calculation may be used for many postprocessing-routines.

A second way to calculate the void volume is to modify the von Mises flow law by introducing a damage parameter „f" into the equation representing the void volume fraction. Like the state of hardening the state of damage is now part of the equation and the effect of damage on the plastic deformation can be considered. To change the flow law for the FE-calculations user-defined routines have to be introduced into the common FE-codes. Now the calculated behaviour of a specimen has to be compared with the experimetal one. Several damage parameters in the flow law have to be varied to adjust the calculated curves to experimetal ones. These are the original damage parameters, the additional damage parameter at void nucleation and critical damage parameter at void coalescence and local failure of the specimen. Currently there are two models in discussion, the modified Gurson-(2) and the Rousselier-model (3).

Void Coalescense

The last step of ductile failure is the coalescense of voids representing the initiation of a microcrack. There are several micromechanic models as well as several criteria to describe coalescense. The most common one is the damage parameter or the void volume fraction. Void coalescense occurs, if a critical value is reached. Other influences are neglected. This simple criterion is employed by the modified Gurson (2) - and the Rousselier-model (3). Other criteria are critical stresses, strains and a critical energy density or combinations of these parameters. The combination of triaxiality and equivalent plastic strain leads to the failure curve, which is determined using specimens with similar load history. Failure curves indicate critical combinations of triaxiality and equivalent plastic strain at initiaton. The state of damage needs not to be calculated. To determine an initiation strain of a component only its stress and strain history has to be compared with the one of a similar specimen. If the state of stress is identical during the deformation process, the void volume fraction must be the same and consequently both, the specimen and the component reach the same initiation strain. The missing consideration of the damage and the easy determination of failure curve are the advantages of this method. The influences of the microstructure on the failure curve will be shown in this paper.

EXPERIMENTS AND RESULTS

To vary the stress state in a wide range different notch geometries of tensile bars were tested. All notched specimen were loaded up to crack initiation, and after removal they were cut in the centre plane parallel to the specimen axis. After polishing the specimens were examined microscopically whether loading had been stopped before, precisely at or after crack initiation. By using this method it is possible to determine the critical specimen deformation for each geometry exactly. Depending on the notch radius and the notch depth void coalescence takes place in the centre or in the notch ground of the specimens. If failure occurs inside the specimen, the critical length l_c is given by neighboured microvoids. In case of initiation at the notch tip l_c is given by the distance between the void and the notch ground. l_c is a characteristic material parameter which is independent of the triaxiality and can be determined metallographically (4).

Using FE-calculation it is now possible to determine the local stress triaxiality σ_m/σ_v and the local equivalent plastic strain ε_v^p at the locus of crack initiation. This procedure was carried out for all specimen geometries and the critical parameters σ_m/σ_v and e_v^p are represented as a failure curve. Smooth notch geometries lead to an initiation locus in the middle of the specimen, while sharp notches locate the initiation at the notch ground.

Figure 1 shows the failure curve for a steel S 460 M which was investigated at room temperature with a cross head speed of Q = 0,5 mm/min. The equation of the failure curve is derived from the Rice and Tracey equation for void growth (1) and shows the influence of local strain to local triaxiality at the locus of first initiation:

$$\sigma_m / \sigma_v = 1/A * \ln\left(\varepsilon_v^p / B + C \right) \tag{2}$$

To vary the microstructure a simulation of a microstructure being part of a TIG-weldment was manufactured with a Gleeble machine. So the simulation S2 is a tempered martensit while the original material (S 460 M) consists of ferrit, perlit and bainit. Both microstructures have the same inclusions, inclusion-sizes, inclusion-distances and the same l_c but a totally different stress strain curve. The mechanical properties of both microstructures can be taken from the following table:

TABLE 1- Mechanical properties of the investigated microstructures

	S 460 M, original	simulation S2
Microstructure	ferrit, perlit, bainit	tempered martensit
R_{el} (MPa)	475	
$R_{p0.2}$ (MPa)		524
R_m (MPa)	573	676
σ_f (MPa)		423
TEl	0.31	0.232

Figure 2 shows the failure curves of the two different microstructures which were investigated at the same conditions. It is seen that the failure curve for the tempered martensit is lower than for the original material for specimen geometries which initiate at the notch ground. A higher strength of the matrix material lead to lower local equivalent plastic strain for low local triaxiality to reach void coalescence. The other geometries show a comparable local stress strain conditions at the initiation locus for both materials. Under high local triaxialities there is no influence of the strength of the matrix material.

CONCLUSIONS

Local failure curves describe the load capacity for void coalescence of ductile fracture. They are based on experiments with notched tensile specimens and FE-Calculations. Different microstructures lead to different failure curves. The change of the microstructure from ferrit, perlit and bainit to tempered martensit allows a lower possible local equivalent plastic deformation / strain in fields of low triaxiality to reach crack initiation.

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SYMBOLS USED

R_i = void radius
R_o = original void radius
σ_m = hydrostatic stress
σ_v = von Mises stress
ε_n = void nucleation strain
ε_v^p = local equivalent plastic strain
σ_m/σ_v = local stress triaxiality

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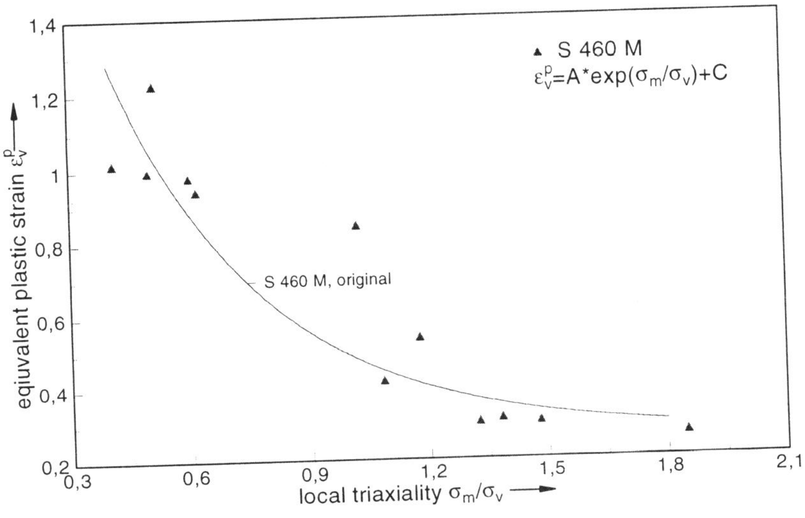

Figure 1 Failure curve of the steel S 460 M

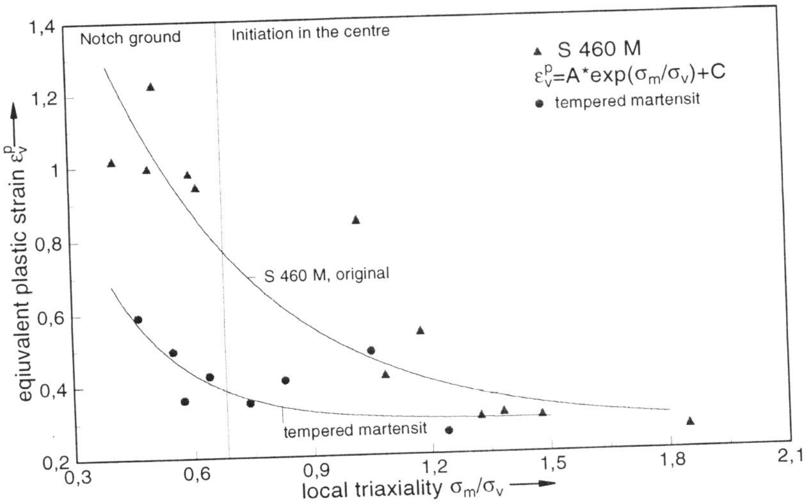

Figure 2 Failure curves for both investigated microstructures