# EFFECT OF STRAIN RATE ON DUCTILE FAILURE BEHAVIOUR OF FeE 460 TM STEEL

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The aim of the experiments is to determine failure curves to show the effect of strain rate on ductile fracture. Quantitative results concerning the influence of the stress triaxiality and the plastic strain in the case of crack initiation for two different strain rates were examined on notched tensile specimens of the steel FeE 460 TM.

## INTRODUCTION

For safety and economic reasons, it is required to know the mechanical-technological properties and the fracture behaviour of materials. In ferritic steels cleavage or ductile failure occurs depending on strain rate and temperature. While the mechanism of cleavage fracture is understood, the micromechanical processes of ductile fracture are more complicated. Ductile fracture is a mode of material failure in which voids nucleate during deformation and grow until they coalesce to form a continuous fracture path. Void nucleation occurs at inclusions by decohesion of the particle-matrix interface or particle fracture. Afterwards, the voids grow depending on the plastic strain and the stress mode and finally they coalesce if a critical condition is reached. The last step is equivalent to the failure of specimens or components and is defined as crack initiation.

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## MICROMECHANISMS OF DUCTILE FAILURE

In order to get a better understanding of the mechanisms of ductile fracture it is required to analyse the nucleation, growth and coalescence of voids more carefully. In literature numerous experimental investigations and models exist to characterize ductile failure in metallic materials.

### Void nucleation

Experimental examinations of different steels show that voids nucleate at particles according to two different mechanisms. Particle fracture is observed, if the inclusion size reaches a critical value whereas particle-matrix decohesion takes place for smaller particles and weaker interfacial bonding. Moreover, void nucleation is influenced by the mechanical properties of the matrix, the inclusion´s shape and the stress triaxiality. There have been many attemtps to model void nucleation. The models can be divided into stress controlled, strain controlled and energy controlled ones.

### Void growth

After nucleation, the voids will expand to a characteristic volume and shape, which is determined by material properties and test conditions. The void growth is strongly influenced by the stress triaxiality during the plastic deformation and by the particle size and shape. Knowing that voids nucleate at very small plastic deformations, the ductile failure behaviour is characterized especially by void growth up to initiation. Therefore, the predictions of the void growth rate are particularly important for the micromechanical understanding of ductile fracture.

The models for describing the void growth can be distinguished as models, which take into consideration the interaction of material behaviour and of void volume fraction, and as models, which assume the influence of void volume fraction on the plastic flow to be so small that it can be neglected, as presented by McClintock (1) and Rice/Tracey (2).

The macroscopic behaviour of the material is described according to the flow rules of von Mises. The void growth rate is analysed with a separate equation. An idealized cylindrical or spherical void within an infinite matrix is assumed.

Therefore an exponentially increasing void growth rate with the triaxiality of stress is found.

## Void coalescence

In this stage the growing voids link together according to different mechanisms. The first mode consists of the growing of voids until they impinge. Another possibility for crack initiation is the formation and propagation of fine cracks between the holes nucleated at inclusions. The third mode of coalescence is characterized by the formation of secondary smaller voids in the bands of intense shear localized between larger inclusion-nucleated voids. In literature there is no agreement in predicting the state of void coalescence whether a critical stress, a critical strain, a critical void volume fraction or void size is required to initiate material failure. However most of the criteria are still based on a critical void volume fraction or a certain void size. The models containing a critical void size are based on the void growth predictions of McClintock (1) or Rice/Tracey (2).

It can be concluded that the predictions of void coalescence correspond with the void growth models in which the maximum limit is defined by a critical void size $R_c$ or a critical void volume fraction $f_c$.

## Failure curve

Hancock and Mackenzie (3) developed a failure criterion based on the void growth model of Rice and Tracey. This criterion allows the evaluation of the local plastic equivalent strain $\varepsilon_v^p$ as a function of the stress triaxiality $\sigma_m/\sigma_v$ for the damage state of crack initiation. On the assumption of constant triaxiality during plastic deformation, Hancock and Mackenzie integrated the equation of Rice and Tracey and provided that the void nucleation strain $\varepsilon_n$ is negligible. Void coalescence occurs if a critical void size $R_c$ is reached, independent of the stress triaxiality:

$$\varepsilon_V^p = \frac{\ln\dfrac{R_c}{R_0}}{0{,}283} \cdot \exp\left(-\frac{3}{2}\frac{\sigma_m}{\sigma_V}\right) \tag{1}$$

The function $\varepsilon_v^p = f(\sigma_m/\sigma_v)$ represents the failure curve. It is important to point out that the critical local strain $\varepsilon_v^p$ must be reached within a defined material volume fraction $V_c$ or over a critical distance $l_c$ . Underneath the failure curve, the material behaviour is influenced by void growth. Every locus on the failure curve shows the critical combination at initiation. Therefore, the failure curve represents the border line between safe and unsafe behaviour of structural components.

To predict crack initiation under proportional loading by reaching a critical void size $R_c$ the model of Rice and Tracey was modified in the following way:

$$\varepsilon_V^p = A\exp(B\frac{\sigma_m}{\sigma_V}) \tag{2}$$

It is recognizable that the presented model contains material constants A and B in contrast to the origin model of Rice and Tracey, which works with the constant parameters 0,283 and 3/2 for all materials. The consideration of material constants seems reasonable because the failure mechanisms in ductile materials are very complex and cannot be characterized by a constant parameter combination for all materials.

## EXPERIMENTAL PROCEDURES AND NUMERICAL CALCULATIONS

To vary the stress state in a wide range different notch geometries of the tensile bars were manufactured. All notched specimens were loaded up to crack initiation, and after stress removal they were cut in the centre plane, parallel to the specimen axis. After polishing the specimens were checked with an optical microscope wether they had been stopped before, precisely at or after crack initiation. When a microcrack was found in the microsection, the deformation of the next specimen with the same geometry was reduced and the specimen was examined. By using this method it is possible to determine the critical specimen deformation at initiation for each geometry exactly.

Depending on the notch radius ($\rho_0$= 0,25; 0,5; 1,1; 2 mm) and notch depth ($t_0$= 0,5; 1,5; 4,0 mm) 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 defined by the distance between two neighboured microvoids. In case of initiation taking place at the tip of a notch $l_c$ is given by the distance between the void and the notch ground. The evaluation of the characteristic length $l_c$ with respect to the specimen geometry shows no influence of stress triaxiality. An average value of $l_c$=57μm was found. Moreover metallographical investigations of more than 1000 inclusions led to a statistical distance between the inclusions of about 120µm and an average inclusion diameter of $D_{inc}$=2,3µm. By EDX-analysis, the inclusions could be identified as Al- and Ca-oxides.

For those specimens which were loaded to crack initiation the actual notch radii and diameters were measured. These parameters were used as a stop criterion for the necessary finite-element calculations with the FE-programme ABAQUS to determine the local stress triaxiality $\sigma_m/\sigma_v$ and the local equivalent plastic strain $\varepsilon_v^p$ at the locus of crack intiation. This procedure was carried out for all twelve specimen geometries and the critical parameters $\sigma_m/\sigma_v$ and $\varepsilon_v^p$ for void coalescence are represented as a failure curve. For the determination of the critical void size $R_c$ at crack initiation, which is involved in the introduced models, SEM-investigations were done. The average value of $R_c$ is 6,5µm.

The modified Rice and Tracey model offers a good agreement with the experimental results. Therefor this model was taken to compare the experimental data for two different strain rates (Q=0,5 and 5 mm/min). Figure 2 shows the experimental data for all specimen geometries and the critical parameters $\sigma_m/\sigma_v$ and $\varepsilon_v^p$ for void coalescence according to the strain rate. It can be said that there is no measurable influence of the strain rate on the failure behavoiur in steel FeE 460 TM.

## CONCLUSIONS

Local failure curves describe the load capacity for void coalescence of ductile fracture. They are based on experiments with notched tensile specimens and finite-element calculations. The evaluation of the microscopic investigations shows no influence of the specimen geometry on the characteristic length $l_c$. There is no influence of the strain rate on the failure behaviour in the steel FeE 460 TM.

## REFERENCES

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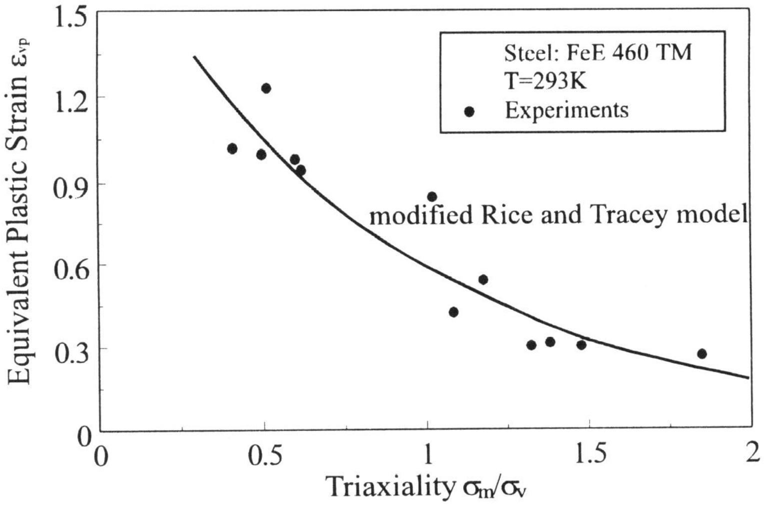

Figure 1. Failure curve for the steel FeE 460 TM under proportional loading

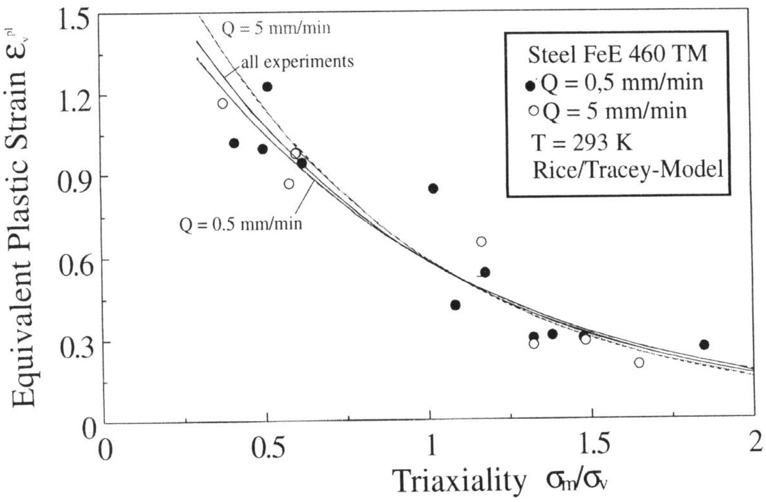

Figure 2. Failure curves for the steel FeE 460 TM for two different strain rates