INFLUENCE OF STRAIN HISTORY ON DUCTILE FAILURE OF STEEL

J. Arndt, F. Grimpe and W. Dahl*

Notched tensile bars of a high strength structural steel were loaded to different strains. The process zones between the notches clearly exhibited one area with and one without voids. FE-calculations were carried out to determine stresses and strains along the borderline between both areas. All stresses except the von Mises equivalent stress vary in a wide range. So the von Mises stress or the equivalent strain was chosen as the nucleation criterion. Further specimens were loaded to void coalescense. The results show that the damage curve determined using radially loaded specimens is not valid for specimens under non-radial loading. Examinations of the void growth rate show a dependence of the value at initiation on stresses and strains.

INTRODUCTION

Ductile failure of steels can be divided into three stages: void nucleation, void growth and void coalescense. There are many criteria to describe the process of void nucleation. Some give a critical stress (hydrostatic stress, equivalent stress or main stresses). Others use a critical strain (plastic equivalent strain). Both 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 use the macroscopic stress field to derive a microscopic stress at the particle, strain criteria demand a critical stress caused by a dislocation pile up at the interface. Additionally, a sufficient elastic distortion of the matrix is necessary to continue the process of cracking or debonding. Most calculations show that the critical distortion is already reached in the elastic condition.

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. Allexperiments and analyses show an exponential increase with the triaxiality,

* Institute of Ferrous Metallurgy, Technical University Aachen, Germany

which is the ratio of the mean stress σ_m divided by the von Mises equivalent stress σ_v.

A positive triaxiality causes an increase, a negative triaxiality causes a decrease of the void volume. There are two ways of calculating the actual void volume fraction in FE-calculations. The first way is to use the common FE-codes and calculate the stress and strain history for every single gaussian-point. In a further step these values of stresses and strains are the basic values to calculate the change of void volume using a postprocessing routine (1). The second way is to modify the von Mises flow law by introducing a damage parameter f representing the void volume fraction into the equation. The advantage of this method is the consideration of the effect of damage on the plastic deformation of the matrix. User defined routines have to be introduced into the common FE-codes and the damage parameters have to be varied to adjust the calculated curves best to the experimental ones. These are the major disadvantages.

The last step of ductile failure is the coalescense of voids representing the initiation of a microcrack. There are several micromechanisms as well as several criteria to describe the coalescense. The most common one is the critical damage parameter or void volume fraction. Others 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 combinations of triaxiality and equivalent pastic strain for the safe operation of specimens with similar load histories (2). The influence of the load history on the failure curve will be shown in this paper.

EXPERIMENTS AND RESULTS

Void Nucleation

For the analysis of the process of void nucleation of the high strength structural steel FeE 690 round tensile bars were loaded to different plastic strains. Different notch radii were chosen to change the state of stress in the process zone. After unloading the specimens the process zones between the notches were cut longwise and prepared metallographically. A scanning electron microscope was used to examine the inclusions. They were divided into two groups. The first one contained the inclusions, which were already loosened from the matrix or broken, i.e. which had already nucleated voids. The second group contained inclusions which were still fixed to the matrix and kept their stress carrying capability. The upper diagram in figure 1 gives the result for a quarter of a specimen representing the FE-model. The border line between the areas of both groups can be drawn easily. Along this line the stresses and strains were calculated. These values are given in figure 1 as well. While axial stress σ_l and hydrostatic stress σ_m decrease from the specimen centre to the surface, the equivalent stress σ_{eq} is nearly constant at about 700MPa. Figure 2 gives the same values for a specimen of the same notch geometry but with a different loading as well as for a specimen with a different notch geometry. While axial stress and hydrostatic stress still vary along the borderline and from one specimen to the other, equivalent stress lies at 700MPa. Thus the void nucleation criterion for this individual steel is to reach an equivalent stress of 700MPa, which is only 6MPa higher than the yield strength. This criterion corresponds to an attainment of a certain equivalent plastic strain.

Void Growth and Coalescense

For the study of the influence of the stress state on void growth and coalescense notched tensile bars were loaded in two steps. By an interruption of the test at certain plastic strains and a change of the stress-state by machining notches with different radii from the original ones, the state of stress was varied in a wide range. These specimens were loaded to the coalescense of voids, which was proved metallographically. By using the options "*DLOAD" and "*TYPE=OLDMESH" of the FE-code ABAQUS, the process of unloading and the change of geometry was duplicated in a simulation. The load histories of the centre of the radially loaded specimens are given in figure 3. The connecting line between these points represents the failure curve, which gives triaxiality and plastic strain at initiation for all specimens with similar load histories. Additionally the load histories of the non-radially loaded specimens and the initiation points are given. These specimens have different load histories. Thus their initiation points do not meet the failure curve. Predeformation at lower triaxiality leads to an increasing plastic strain at initiation while predeformation at higher triaxlity leads to a decreasing plastic strain.

In further investigations the actual void radii of all specimens were determined by using the modified equation of Rice and Tracey. In the original equation (1) the triaxiality is kept constant. The modified equation considers the change of triaxiality caused by the change of geometry during deformation and due to the machining of the new notch. Following the criterion that initiation takes place at a critical void growth rate the integral

$$\ln(R_i / R_0) = 0{,}283 * \int_{\varepsilon=0}^{\varepsilon_i} \exp\left(\frac{3}{2} * \frac{\sigma_m}{\sigma_{eq}}\right) d\varepsilon \tag{1}$$

should be constant for all specimens. Figure 4 shows the void growth rate for the radially and non-radially loaded specimens, respectively. The values of the radially loaded specimens at initiation are marked by filled dots. They increase with increasing plastic strain at initiation. Thus the unnotched specimens and those with mild notches seem to have a higher void volume fraction than the specimens with the smaller notch radii. Due to the increasing triaxiality at initiation there is a strong dependence of the void growth rate at initiation on the triaxiality as well. The higher the triaxiality the lower is the void volume fraction necessary to cause initiation. This dependency can be explained by the increase of the local tensile stresses at the locus of initiation with increasing void volume fraction. The same effect has been shown by FE-calculations using cell models (3).

Furthermore, there is a marked influence of prestraining on the void growth at initiation. The initiation values are marked by open dots. There is no correspondence to the values of the radially loaded specimens, neither with respect to strain nor with respect to triaxiality.

This fact leads to the assumption that there are influences of both, plastic strain and triaxility. The influence of triaxiality can be explained by the fact that predominating tensile stresses increase the local tensile and shear stresses between the voids and in this way promote the coalscense. The influence of plastic strain may be caused by the different shapes of the voids. While plastic strain at high triaxialities leads to almost spherical voids, plastic strain at lower triaxialities causes a more elliptical shape. Provided that the volume of both is the same, the perpendicular distance to the maximum tensile stress of the elliptical ones is higher than the distance between the spherical ones. Thus the elliptical ones must be enlarged to cause initiation by failure of the ligament between them. The results of about 30 different experiments (radial and non-radial) show an increase of the required void volume with decreasing initiation triaxiality and with increasing plastic initiation strain.

REFERENCES

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SYMBOLS USED

σ_m	= hydrostatic stress	d	= diameter
σ_{eq}	= von Mises equivalent stress	t, ρ	= notch depth and radius
σ_l	= axial stress	ε_l	= axial strain
f	= damage parameter	ε^p_{eq}	= equivalent strain

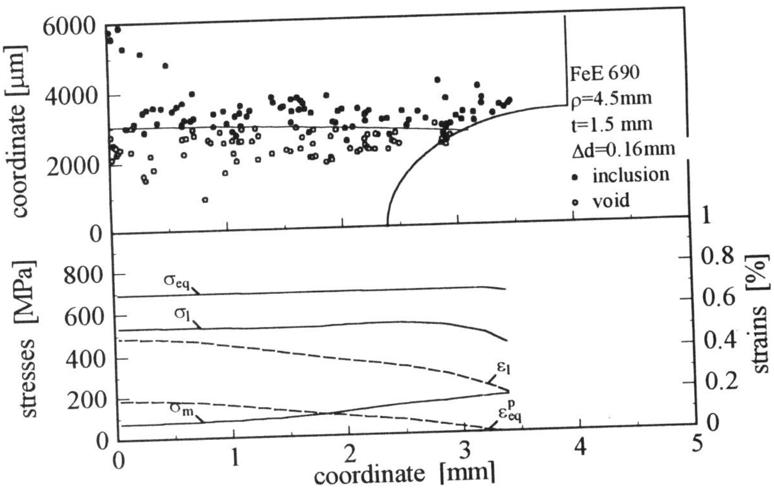

Figure 1. Distribution of voids in the process zone

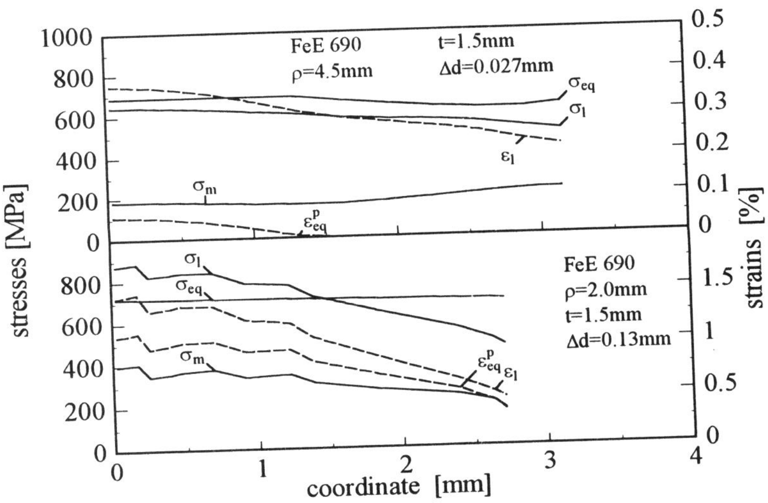

Figure 2. Stresses and strains at void nucleation

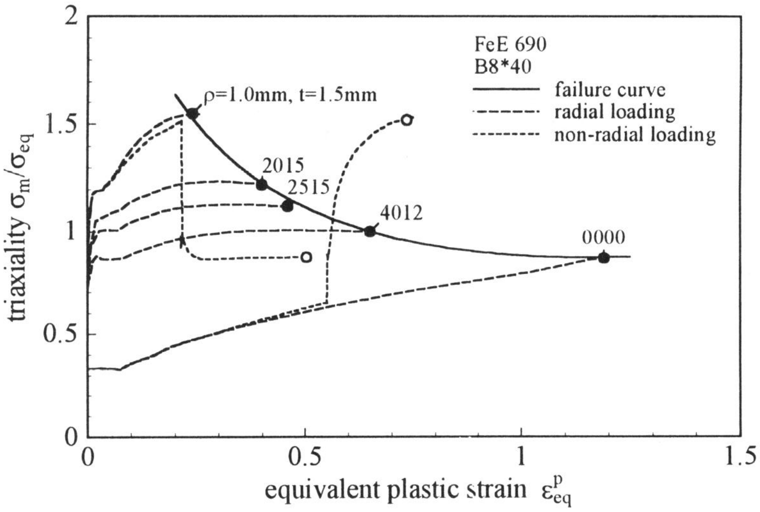

Figure 3. Load histories and initiation values of different specimens

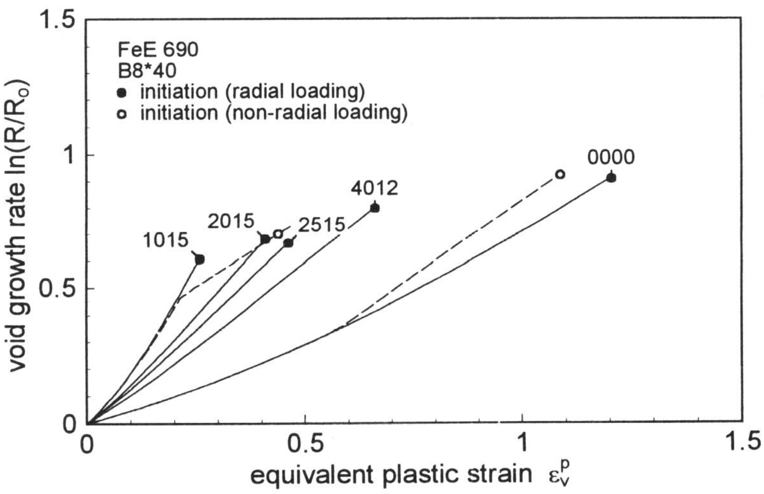

Figure 4. Void growth rates of different specimens