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Experimental and numerical investigations on limit strains in ductile fracture

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Abstract

Several incidents in the past showed the risk of a human and/or environmental caused accident which exceeds the design limit of a component. Therefore the quantification of safety margins becomes necessary. According to technical standards, the safety assessment is usually based on stress criteria. The deformation capability of the material is hardly taken into account with these criteria. Limit strain based safety assessment concepts can overcome this disadvantage. The main influence factors on limit strains are the stress triaxiality, the component size, the loading path and the strain rate. To quantify these factors, different experiments are performed with specimens made of the steel 20MnMoNi5-5, which is representative for German nuclear power-plants.

In the range of high stress triaxiality values, different specimens are tested. All the specimens are simulated using Rousselier model to derive the crack initiation location and time. The experimental and numerical results can be used to derive a limit strain curve. The influence of loading paths on failure strains is shown at pre-loaded notched tensile specimens.

Finally, an outlook on the planned experimental and numerical investigations in the range of small stress triaxiality values is given.

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Keywords: limit strains; Rousselier model, pre-load, stress triaxiality, lode angle

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1. Introduction

The design and assessment of components is usually based on stress based criteria (KTA 3201.2 (2013), KTA 3211.2 (2013), ASME BPVC III (2013)). Even though, some of the safety standards tolerate small plastic deformations (DIN EN 13445-3 (2015), ASME BPVC VIII (2013), FKM (2012), CSA-Z662-2007 (2007), DNV-OS-F101 (2012)), the full deformation capability of the material is thereby hardly taken into account. However, especially materials used in power plants have a pronounced deformation capability. For environmental caused incidents it is important to quantify safety margins regarding the deformation capability.

In the past, different limit strain concepts have been developed, restricting the plastic strain by a limit strain curve (Simatos et al. (2011), Herter et al. (2012), Kucharczyp and Münstermann (2013)). The tolerable strain limit for a component is thereby strongly dependent on the stress triaxiality. To describe the ductile failure behavior of a material in finite-element simulations, damage mechanics models can be used (Rousselier (1987), Gurson (1975)). Most of these models describe the material behavior in the range of high stress triaxiality values. To extend the applicability of the models to small stress triaxiality values, coupled approaches have been developed (Nahshon and Hutchinson (2008), Guo et al. (2013), Zhao et al. (2014), Basaran et al. (2010)). The influence of shear on the voids is described by the lode angle parameter (Lode (1926)).

In this paper, the Rousselier model is used for simulations in the range of high stress triaxiality and for simulations of pre-loaded specimens. Furthermore, an outlook on the planned extension of the Rousselier model for small triaxiality values is given.

2. Damage mechanics approach

The process of ductile failure under tensional loading can be described by three different stages (see Fig. 1 (a)). Starting with the void initiation, caused by non-metallic inclusions or precipitations, the process is followed by the growth of the voids. When reaching a critical size, the voids start to coalesce leading to the failure of the material.

Concluded from experimental investigations, void initiation for the investigated material can be approximated by the equivalent stress value exceeding the material yield strength (Seidenfuß (2012)). As a result, the void volume is set to an initial void volume fraction $f_0$.

For the numerical simulation of void growth, the damage mechanics model of Rousselier is used in this paper, (Rousselier (1987)). The model describes the growth of voids. For finite-element calculations, the corresponding flow function is:

$$
\Phi = \frac{\sigma_y}{l \! - \! f} + \sigma_k \cdot D \cdot f \cdot \exp\left[ \frac{\sigma_m}{(l \! - \! f)\sigma_k} \right] - \sigma_y = 0
$$

As in equation (1) the damage evolution depends on local stress and strain state (von Mises equivalent stress $\sigma_y$, hydrostatic stress $\sigma_m$), it is the local formulation of the Rousselier model. The damage is described by the current void volume fracture $f$. $\sigma_y$ is the yield or flow stress, $D$ and $\sigma_k$ are material constants. Because of the local formulation the Rousselier model becomes mesh dependent and the mesh size must be linked to the microstructure described by the critical length $l_c$.

The yield surface of the Rousselier model is visualized in Fig. 1 (b), in contrast to the yield behavior of the von Mises approach. Unlike the von Mises approach, the Rousselier flow function predicts plastic deformation also for hydrostatic stress states.

The coalescence of voids occurs, when the void volume fraction reaches a critical value $f_c$ (Seidenfuß (2012)), leading to a very strong decrease of the element stiffness.
3. Experimental and numerical investigations

All experiments are executed with specimens made from a pipe of ferritic steel 20MnMoNi5-5. The specimens are equally distributed around the pipe circumference to avoid any influences based on inhomogeneity of the material. To evaluate the homogeneity of the material and to determine the true stress-strain curve for the material, 15 tension tests at different positions around the circumference were executed. The results are shown in Fig. 2. The true stress strain curve is derived by an automated numerical approximation (Seidenfuß et al. (2003)) from specimen GKA1 (see Fig. 2). All simulations showed in this paper are executed with finite-element software ADINA.

The parameters needed for the Rousselier model were obtained by numerical calibration using the results from three tension tests with notched round tensile bars. To obtain different stress triaxiality values, the specimens have three different notch radii. In this paper the stress triaxiality is defined as the quotient of hydrostatic stress $\sigma_m$ and von Mises stress $\sigma_v$.

In Table 1 the parameters used for the numerical simulations are listed. Fig. 3 shows the experimental and numerical results for the notched specimens. In Fig. 3 (a) the load is plotted over the displacement measured with a 20 mm strain gage, in (b) the load-necking curve is shown for the notch base. They both show good accordance.
To verify the Rousselier parameters in the range of high stress triaxiality values, C(T)25 specimens with and without side grooves were tested and simulated. The results are shown in Fig. 4.

Fig. 4 (a) shows the comparison of the load-displacement curves for numerical and experimental results. Specimens with and without side grooves can be described by the Rousselier model with high accuracy. Fig. 4 (b) shows the simulated crack front together with the experimental one for the C(T)25 specimens at the end of the experiment.

One goal of the present research work is the investigation of loading path influence on the limit strain. Therefore, tension tests with changing stress triaxiality were executed. In a first step smooth round specimens with a stress triaxiality value of 1/3 were pre-loaded up to a total strain of 4 % respectively 8 %. Fig. 5 (a) shows the stress-strain
curves of the specimens during the pre-loading. After the pre-loading, a notch was added resulting in an increase of stress triaxiality. Two different notch radii, 2 mm and 10 mm, were tested. In Fig. 5 (b) the load-displacement curves are presented. To show the influence of the pre-loading, the load-displacement curves of the notched specimens without pre-loading were added. As expected, a pre-loading leads to higher loads and less deformation compared to the specimens with no pre-loading. In addition, Fig. 5 (b) shows the influence of the pre-load level which results in less deformation for specimens with 8 % pre-load compared to specimens with 4 % pre-load.

Fig. 6 shows the numerical investigations on the pre-loaded specimens. In Fig. 6 (a) the geometry used for the simulations is shown. In Fig. 6 (b) the experimental results are compared to the simulations. Exemplary the results for a 4 % pre-load and a notch radius of 2 mm are shown.

The next steps are further experimental and numerical investigations of loading path influences on limit strains. A set of experiments with tension-torsion specimens is planned. Half of the specimens will be pre-loaded with a tensional load; afterwards torsional load will be applied until failure. The second half will be twisted first and afterwards loaded with uniaxial stress until fracture. The changing load results in a changing stress triaxiality between 0 (torsion) and 1/3 (tension). Furthermore notched hollow cylinders will be pre-loaded with pressure and afterwards tested under tensional load.
In addition experiments with compact tension-shear specimens (CTS-specimen, Richard (1985)) will be conducted. A CTS-specimen consists of a regular C(T)15-specimen enhanced by a specific clamping. The clamping allows a mixed crack mode between mode 1 and mode 2. The specimen together with the clamping is shown in Fig. 7 (a). Fig. 7 (b) shows the test set-up for a loading-angle of $\alpha = 30^\circ$. For a changing loading path, in a two-step test, the loading angle will be changed during the experiment. The influence of a changing loading angle on the crack path will be observed.

![Fig. 7. (a) Geometry of the CTS-specimen together with the clamping (Gehrlicher et al. (2014)); (b) specimen tested under a loading angle of $\alpha = 30^\circ$ (Gehrlicher et al. (2014))](image)

To investigate the effects of multiple loading on limit strains, a set of cyclic tests on smooth and notched round specimens is planned. The tests are executed strain controlled with a strain ratio of $R_c = -1$ and an expected number of cycles until failure of approximately 10. First experiments with increasing amplitudes for every cycle on notched specimens are already completed. More tests with constant amplitude on different stress triaxiality values will be conducted.

Also, for cyclic behavior in the range of high stress triaxiality values, cyclic three point bending tests will be executed.

Regarding the size effect on limit strains, tension tests on notched specimens with different absolute sizes but the same stress triaxiality will be performed.

On the numerical side, the Rousselier model will be extended to describe the material behavior for shear dominated failure (tension tests and CTS-specimen with loading angles $\alpha > 0^\circ$) and kinematic hardening. Two different approaches, a coupled and an uncoupled approach, will be developed.

In the coupled approach, a second parameter $f_d$ characterizing the material damage due to shear will be introduced. The parameter characterizing the void volume fraction under hydrostatic tensional load $f$ remains as parameter $f_m$. To simulate the influence of shear damage the flow function will be enhanced by a third term which depends on the damage parameters $f_d$ and $f_m$, the von Mises equivalent stress $\sigma_v$ and the lode angle parameter $\xi$.

$$\Phi = \frac{\sigma_v}{1-f_m} + f_d \cdot (f_m + A \cdot f_d) \cdot \exp\left[\frac{\sigma_m}{(1-f_m)\sigma_k}\right] + g(f_m, f_d, \sigma_v, \xi) - \sigma_y = 0$$  \hspace{1cm} (2)

Failure occurs, when one of the damage parameter reaches a critical value $f_m \geq f_{mc}$ or $f_d \geq f_{dc}$.

In the uncoupled approach, material behavior for high stress triaxiality values will be described by standard Rousselier model (see equation (1)). For low stress triaxialities, a damage parameter $D$ will be introduced.

$$D = \max_D D^* (\phi, \psi)$$  \hspace{1cm} (3)
D* is a function of the plastic strain rate tensor $\dot{\epsilon}^{pl}_{ij}$ and the stress tensor $\sigma_{ij}$ defined by the polar angle $\phi$ and the azimuthal angle $\psi$. Again, failure occurs when one of the damage parameter reaches a critical value $f \geq f_c$ or $D \geq 1$.

4. Limit strains

The experimental and numerical results of section 3 are used to determine a limit strain concept for the safety assessment of components. As mentioned in the introduction, the limit strain is strongly dependent on the stress triaxiality. Fig. 8 (a) shows the loading paths and limit strains for a tension test, the notched round tensile bars and the C(T)-25 specimens. The accumulated equivalent plastic strain and the stress triaxiality descend from an elastic-plastic simulation, evaluated at the crack initiation location at the crack initiation time obtained by a damage mechanics simulation using the Rousselier model.

A limit strain curve with an exponential behavior can be fitted to the data. This trend cannot be extended to the regime of small and negative stress triaxiality values. Whereas literature shows a decrease in limit strain for small triaxiality values (Bao and Wierzbicki (2004), Wierzbicki et al. (2005), Lou et al. (2012)), some of the regulations limit the strains with a constant value for stress triaxiality values smaller than $1/3$ (FKM (2012)). Based on the planned experimental and numerical work, the limit strain curve will be extended to small stress triaxiality values.

![image](fig8a.png)  
**Fig. 8.** (a) Limit strains at different stress triaxiality values; (b) limit strains for different pre-loads at notched specimens

Fig. 8 (b) shows the influence of a plastic pre-load on the limit strain. For small stress triaxiality values (notch radius 10 mm) there is almost no influence due to the pre-load. At higher values of stress triaxiality (notch radius 2 mm), with an increasing pre-load a reduction in the limit strain can be observed. Also crack initiation occurs at slightly higher stress triaxiality values.

The influence of loading paths as well as the influence of component size will be added to the limit strain concept.

5. Conclusion

The numerical results show, that Rousselier model is well capable of describing ductile fracture for stress triaxialities between $1/3$ and 3. It is also capable to describe the material behavior for a changing loading path under tensile load. From the experimental and numerical results, a limit strain curve for the regime of high stress triaxiality values can be derived. The tests with pre-loaded specimens showed, that the influence of previous plastic deformations depends on the stress triaxiality. To simulate the planned tests with shear dominated failure (tension-torsion specimens, CTS-specimens) and specimens with multiple loading, the Rousselier model needs to be enhanced by additional terms to describe shear failure and kinematic hardening. Two approaches, a coupled and an uncoupled one were proposed.
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