Numerical simulations of biaxial experiments on damage and fracture in sheet metal forming

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Abstract. The damage and failure process of ductile metals is characterized by different mechanisms acting on the micro-scale as well as on the macro-level. These deterioration processes essentially depend on the material type and on the loading conditions. To describe these phenomena in an appropriate way a phenomenological continuum damage and fracture model has been proposed.

To detect the effects of stress-state-dependent damage mechanisms, numerical simulations of tests with new biaxial specimen geometries for sheet metals have been performed. The experimental results including digital image correlation (DIC) show good agreement with the corresponding numerical analysis. The presented approach based on both experiments and numerical simulation provides several new aspects in the simulation of sheet metal forming processes.

1. Introduction
Elastic material properties, yield stress and coefficients characterizing plastic hardening are determined from one-dimensional tension tests with flat rectangular specimens. In addition tests with differently pre-notched specimens and corresponding numerical simulations have been used to study the stress dependence behavior, see [1] where only triaxialities from 0.33 and 0.6 can be reached. Lower positive stress triaxialities could be reached by one-dimensionally shear specimens [1] and butterfly type specimens have been studied [2] within a special testing device. But it has to be noticed, that it is difficult to study a wide range of stress triaxialities with one-dimensionally loaded specimens. Therefore, biaxially loaded specimens are frequently used to study the yield surface of ductile metals, i.e. at strain states where no major damage can be reported. All these biaxial specimens are characterized by an extensive homogenous central region (see [3]) which does not allow the controlled study of damage behavior. Hence, new geometries of biaxially loaded specimens are proposed to examine stress state dependent damage and failure behavior.

2. Continuum damage and fracture model
The continuum damage model presented by [4] is used to predict the elastic-plastic deformations including damage. It takes into account information of the mechanisms of individual micro-defects and their interactions detected by numerical calculations on the micro-level [5]. The phenomenological approach is based on the additive decomposition of the strain rate tensor into elastic, plastic and damage parts.
In the present paper the focus is on the damage behavior: The generalized elastic-damage constitutive law is a function of elastic and damage strain tensors [4]. This allows simulation of deterioration of elastic material properties caused by formation and growth of micro-defects. In addition, onset and continuation of damage is governed by the stress-state-dependent damage criterion

\[ f^{da} = \alpha I_1 + \beta \sqrt{J_2} - \sigma = 0. \]  

(1)

where \( I_1 \) and \( J_2 \) are the first and second deviatoric stress invariants, \( \sigma \) is the damage threshold and \( \alpha \) and \( \beta \) represent the stress-state-dependent damage mode parameters. These variables are related to different damage mechanisms and depend on the stress triaxiality \( \eta = I_1/(3\sqrt{3}J_2) \) as well as on the Lode parameter \( \omega = (2T_2 - T_1 - T_3)/(T_1 - T_3) \) with \( T_1, T_2 \) and \( T_3 \) being the principal Kirchhoff stress components.

The increase in macroscopic strains caused by formation and growth of micro-defects leading to anisotropic damage behavior is modeled by the damage rule

\[ \dot{H}^{da} = \dot{\mu} \left( \bar{\alpha} \frac{1}{\sqrt{3}} \mathbf{1} + \bar{\beta} \mathbf{N} + \bar{\delta} \mathbf{M} \right). \]  

(2)

Here \( \bar{\alpha} \), \( \bar{\beta} \) and \( \bar{\delta} \) are stress-state-dependent kinematic variables and \( \dot{\mu} \) represents the rate of the equivalent damage strain. In addition, \( \mathbf{N} \) and \( \mathbf{M} \) are normalized deviatoric stress tensors, see [5, 6] for details.

3. Numerical and experimental results

For biaxial testing it is preferable that the geometry of specimens can be used for testing in a large variety of stress states. With this emphasis the geometries shown in Fig. 3 are proposed and studied in detail. The geometry shown in Fig. 3(a) (X1-specimen) has two crosswise arranged notches whereas at the geometry shown in Fig. 3(b) (XO2-specimen) a central hole was added leading to four separated notched regions. Finally for the geometry displayed in Fig. 3(c) (H-specimen) the notches have been arranged parallel to one of the loading axis. All specimens have been fabricated of an aluminum alloy of series 2017, from sheets of 4.0 mm thickness (see [6] for details) whereas all outer specimen dimensions are 240 mm by 240 mm. All material reduction in thickness direction, i.e. notches etc., are of 1.0 mm on each side, leaving 2.0 mm.

Figure 1. New biaxial specimen geometries: (a) X-, (b) XO2- and (c) H-specimen
The corresponding elastic-plastic finite element (FE) simulations have been carried out with Ansys Classic. All experiments have been performed on the biaxial test machine containing four electro-mechanically, individually driven cylinders [6]. The full 3D displacement field of the specimen surface was measured with a digital 3D image correlation (DIC) system [7].

Numerical simulations with the X1-specimen indicated major strain concentrations in the notches with maxima for load cases $F_1/F_2 = 1/-1$ and $F_1/F_2 = 1/0$ at the center of the specimen and for the load case $F_1/F_2 = 1/1$ at the ends of the notches. Based on this observation it is evident to introduce a central opening and thus four separated connectors between the specimen legs are generated. Numerical simulations with the XO2-specimen have shown that this geometry can be used in a large range of stress triaxialities from approximately $-0.1 \leq \eta \leq 0.9$.

The most promising results could be achieved with the H-Specimen. A numerical study program covering load cases from compression dominated $F_1/F_2 = -3/1$ over pure shear $F_1/F_2 = 0/1$ to tension dominated $F_1/F_2 = 3/1$ has been realized. Fig. 3 shows the triaxiality $\eta$ and the Lode parameter $\omega$ under the different loading condition, indicating a very homogeneous distribution with triaxialities in the range $-0.6 \leq \eta \leq 0.8$.

![Figure 2. H-specimen: triaxiality $\eta$ and Lode parameter $\omega$ under different loading conditions](image)

Furthermore, Fig. 3(a) compares $\Delta u_{Ref}$ of all four notches within one experiment. The displacement $\Delta u_{Ref}$ is experimentally taken by the difference in displacements of two reference points on opposite legs of the specimen outside the notched region while numerical results correspond to node displacements of corresponding finite elements. The behavior is almost symmetric while two crosswise arranged notches fractured. It is important to notice that this symmetric behavior is additionally forced by the clamped supports in the biaxial machine. In Fig. 3(b) two experimental and one numerical load-displacement-curves under loading conditions $F_1/F_2 = 0/1$ are compared. Here the experimental curves of the H-specimen show only the usual experimental spreading. Furthermore it can be noted, that the experimental and numerical curves agree quite well.

In Fig. 3 the shear strains analyzed by the DIC system are compared with the corresponding numerically predicted ones at different states throughout the experiment under loading conditions $F_1/F_2 = 0/1$. At both deformation states good agreement can be observed.
Figure 3. H-specimen: (a) comparison between notches within one experiment; (b) numerical and experimental results: load-displacement curves

Figure 4. H-specimen: numerical predicted and experimentally observed shear strains $\gamma_{xy}$

4. Conclusions
New specimen geometries to study the stress state dependence of the damage and fracture behavior of ductile sheet metals are presented and numerically as well as experimentally studied. The geometry of the XO2- and H-specimens are characterized by four independent notched regions where damage and failure behavior can be analyzed. Thus, experiments with these new specimen geometries are recommended for experimental programs to analyze safety and lifetime of metal structures. In the future the experimentally achieved results have to be leaded back to the determination of the material parameters of the continuum damage model.

References
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