Experiments and numerical simulation of stress-state-dependent damage in sheet metal forming

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Abstract. Experiments and corresponding numerical simulations with new biaxially loaded specimens taken from thin metal sheets are discussed. Inelastic deformations as well as damage and fracture behavior of the specimens are investigated under different biaxial loading conditions covering a wide range of stress states to analyze the stress-state-dependent damage and failure mechanisms in ductile metals. During the experiments strain fields in critical regions of the specimens are analyzed by digital image correlation. Corresponding numerical simulations deliver information on stress states in tested specimens. The results are used to propose stress-state-dependent damage and failure criteria corresponding to various damage mechanisms depending on stress triaxiality and the Lode parameter. They are validated by series of biaxial experiments with newly developed specimens and corresponding numerical simulations. This demonstrates the efficiency of the new specimens’ geometries covering a wide range of stress states in the shear-tension and shear-compression regime allowing validation of stress-state-dependent functions for the damage criteria and damage evolution laws.

1. Introduction
Products of modern metal forming processes have to fulfill economic, environmental and material strength requirements due to increasing demands of the customers like requirements on lightweight design leading to improved energy consumption or cost efficiency and to enforce the safety. Thus, the use of high quality metals like high strength steels, advanced high strength steels and aluminum alloys has been increased and numerical simulations for optimization of forming processes currently receive remarkable attention. This requires highly predictive and practically applicable constitutive theories as well as corresponding efficient and accurate numerical methods to study damage and failure processes leading to macro-cracks and to final fracture in materials and structures. Many industrial processes like rolling and forging are often characterized by remarkable negative hydrostatic stress states and, therefore, damage and fracture mechanisms at negative stress triaxialities are here of special interest.

Characteristics of damage and failure processes depend on stress state acting in a material point. Thus, development of accurate and realistic phenomenological continuum models must be based on detailed experimental and numerical investigations on both the macro- and the micro-level to examine and to understand the complex stress-state-dependent damage and fracture mechanisms. Corresponding constitutive models have to be evaluated and quantification of
damage at different stress states must be performed to predict and to judge quality of metal forming processes.

Experiments on stress-state-dependent damage and failure in ductile metals have been proposed in the literature using carefully designed specimens. For example, uniaxial tension tests with un-notched and differently notched specimens and corresponding numerical simulations have been proposed to investigate dependence of damage and failure on different positive stress triaxialities [1-4]. New geometries of uniaxially loaded specimens have been developed to analyze the behavior under nearly zero stress triaxialities where shear mechanisms occur in their critical parts [1, 2, 4, 6]. In addition, butterfly specimens with complex geometries have been developed to study the behavior under wider regions of stress triaxialities. They can be loaded in different directions using special experimental equipment [3, 6]. Alternatively, two-dimensional experiments and different geometries of cruciform specimens have been examined [7]. Similarly, biaxial experiments with new shear-tension-specimens in combination with numerical calculations have been presented by [8-10] to investigate stress-state-dependent damage and failure behavior in thin sheets.

From theoretical point of view anisotropic continuum damage models are more qualified for numerical simulation of stress-state-dependent damage and failure behavior. However, their practical applicability may be limited by large number of constitutive parameters and problems in their identification. Thus, in the present paper an efficient phenomenological continuum damage mechanics model will be briefly discussed. Biaxial experiments with differently loaded newly developed cruciform specimens will be discussed. Formation of strain fields in critical regions of the specimens are analyzed by digital image correlation (DIC) technique. Numerical simulation of the biaxial experiments have been performed and stress fields in the critical regions of the specimens where damage and fracture will occur are predicted. These numerical results are used to explain stress-state-dependent damage and failure processes especially in the region of nearly zero and negative stress triaxialities.

2. Continuum damage model

The phenomenological damage model proposed by [11] is used to predict inelastic deformation and anisotropic damage behavior in ductile metals. In the continuum approach the damage process is governed by the evolution of damage strains on the macro-scale caused by different stress-state-dependent damage and failure processes on the micro-level. The continuum model is based on the introduction of damaged and associated fictive undamaged configurations and the kinematic approach takes into account introduction of elastic, plastic and damage strain rate tensors. In these configurations, free energy functions are formulated characterizing the elastic behavior of the undamaged matrix material as well as the damage-elastic behavior of the defect-containing aggregate. With respect to the undamaged configurations plastic behavior is modeled by a yield criterion and a non-associated flow rule. In a similar way, damage behavior is described by a damage criterion and a non-associated damage rule both depending on the stress triaxiality and the Lode parameter and formulated with respect to the damaged configurations.

In particular, determination of onset and continuation of damage is based on the concept of damage surface formulated in stress space [11,12]. Thus, the damage condition

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

(1)

is expressed in terms of the stress invariants \( I_1 \) and \( J_2 \) of the Kirchhoff stress tensor and the damage threshold \( \sigma \) represents the material toughness to micro-defect propagation. In Eq. (1) the variables \( \alpha \) and \( \beta \) represent damage mode parameters corresponding to the different damage mechanisms acting on the micro-level: shear modes for negative stress triaxialities, void-growth-dominated modes for large positive triaxialities and mixed modes (simultaneous growth
of voids and evolution of micro-shear-cracks) for lower positive stress triaxialities. In addition, the influence of the Lode parameter is taken into account because it has been shown that its effect on the evolution of the microstructure is remarkable especially in low stress triaxiality regions. Therefore, the damage mode parameters $\alpha$ and $\beta$ in Eq. (1) depend on the stress intensity $\sigma_{eq} = \sqrt{3J_2}$ (von Mises equivalent stress), the stress triaxiality

$$\eta = \frac{\sigma_m}{\sigma_{eq}} = \frac{I_1}{3\sqrt{3J_2}}$$

defined as the ratio of the mean stress $\sigma_m$ and the von Mises equivalent stress $\sigma_{eq}$ as well as on the Lode parameter

$$\omega = \frac{2T_2 - T_1 - T_3}{T_1 - T_3} \quad \text{with } T_1 \geq T_2 \geq T_3$$

expressed in terms of the principal stress components $T_1$, $T_2$ and $T_3$.

For the tested aluminum alloy the dependence of $\alpha$ and $\beta$ on stress state has been examined in detail performing numerical simulations on the micro-scale by [13]. For practical applications simplified functions have been proposed by [9] still allowing accurate modeling of failure behavior observed in different experiments. It is worthy to note that the parameters $\alpha$ and $\beta$ correspond to different damage and fracture mechanisms acting on the micro-level. Therefore, they can be seen to be typical parameters for a wide class of metals and not only for the aluminum alloy under investigation. Thus, only the damage threshold $\sigma$ in the damage criterion (1) is a material parameter whereas $\alpha$ and $\beta$ are not.

In particular, the parameter $\alpha$ is taken to be

$$\alpha(\eta) = \begin{cases} 
-0.15 & \text{for } \eta \leq 0 \\
0.33 & \text{for } \eta > 0 
\end{cases}$$

and the parameter $\beta$ is given by the non-negative function

$$\beta(\eta, \omega) = -1.28 \eta + 0.85 - 0.017 \omega^3 - 0.065 \omega^2 - 0.078 \omega \geq 0 .$$

Furthermore, the damage strain rate tensor can be determined by the damage rule

$$\dot{H}^{da} = \dot{\mu} \left( \tilde{\alpha} \frac{1}{\sqrt{3}} I + \tilde{\beta} N \right)$$

where $\dot{\mu}$ is a non-negative scalar-valued factor. In Eq. (6) the normalized stress related deviatoric tensor $N = \frac{1}{2\sqrt{J_2}} \text{dev} \mathbf{T}$ has been used and $\dot{\mu}$ represents in the proposed continuum damage approach the equivalent damage strain rate measure characterizing the amount of increase in irreversible damage. The parameters $\tilde{\alpha}$ and $\tilde{\beta}$ are kinematic variables describing the portion of volumetric and isochoric damage-based deformations. These parameters also correspond to different damage and fracture mechanisms on the micro-scale. Again, they are based on numerical analyses with void-containing unit cells under various three-dimensional loading conditions [13] as well as on comparison of test results and numerical simulations of different experiments with uniaxially and biaxially loaded specimens [9].

In particular, the parameter $\tilde{\alpha}$ characterizing the amount of volumetric damage strain rates caused by volume change of micro-defects is given by

$$\tilde{\alpha}(\eta) = \begin{cases} 
0 & \text{for } \eta \leq 0 \\
0.5714 \eta & \text{for } 0 < \eta \leq 1.75 \\
1 & \text{for } \eta > 1.75 
\end{cases}$$
The parameter $\bar{\beta}$ corresponding to the amount of anisotropic isochoric damage strain rates caused by evolution of micro-shear-cracks is taken to be

$$\bar{\beta}(\eta, \omega) = \bar{\beta}_0(\eta) + (-0.0252 + 0.0378 \eta) \bar{\beta}_\omega(\omega)$$

with

$$\bar{\beta}_0(\eta) = \begin{cases} 0.87 & \text{for } \eta \leq \frac{1}{3} \\ 0.979 - 0.326 \eta & \text{for } \frac{1}{3} < \eta \leq 3 \\ 0 & \text{for } \eta > 3 \end{cases} \quad \text{and} \quad \bar{\beta}_\omega(\omega) = \begin{cases} 1 - \omega^2 & \text{for } \eta \leq \frac{2}{3} \\ 0 & \text{for } \eta > \frac{2}{3} \end{cases}.$$  

It can be summarized that the macroscopic damage rule (6) takes into account volumetric parts (first term in Eq. (6)) corresponding to isotropic growth of voids on the micro-scale as well as deviatoric parts (second term in Eq. (6)) corresponding to anisotropic evolution of micro-shear-cracks, respectively. Therefore, both basic damage mechanisms discussed above (growth of isotropic voids and evolution of micro-shear-cracks) acting on the micro-level are involved in the macroscopic damage rule (6) of the phenomenological continuum model. In addition, it should be noted that although the stress-state-dependent functions (4, 5) and (7-9) show discontinuities with respect to their arguments no corresponding numerical instabilities have been observed during numerical simulations of various experiments performed by the authors [8, 9].

3. Experiments and numerical simulations

A new test program has been developed to propose biaxial experiments analyzing the influence of stress state on inelastic deformation behavior, damage and fracture in ductile metals undergoing combined tensile, shear and compressive loading conditions [8]. The experiments with specimens taken from aluminum alloy sheets are performed using a biaxial testing machine containing four electro-mechanically, individually driven cylinders. Different specimen’s geometries have been proposed in [10] and in the present paper the behavior of the H-specimen shown in Fig. 1 will be discussed in detail with focus on the effect of the length of the notched parts. In addition, corresponding finite element simulations have been carried out using the finite element program ANSYS enhanced by a user-defined material subroutine based on the proposed continuum model to analyze the stress states in the critical notched regions. The underlying finite element mesh is shown in Fig. 2.

![Figure 1. H-specimen](image1)

![Figure 2. Mesh of notched region](image2)

During the biaxial experiments forces $F_{2,1}$ and $F_{2,2}$ will lead to shear mechanisms in the notched parts of the H-specimen whereas $F_{1,1}$ and $F_{1,2}$ lead to superimposed tension or compression loading, see Fig. 3. In the analyses displacements $\Delta u_{ref}$ between the red points
shown in Fig. 4 predicted by the numerical simulation (Fig. 4a) and measured during the experiments (Fig. 4b) are compared.

Experimentally obtained load-displacement curves for specimens with different lengths of the notched part for shear-compression loading $F_1/F_2 = -0.5/1$ are shown in Fig. 5. After elastic loading a large inelastic part up to final fracture can be seen. Different load maxima are reached depending on the length of the notched parts. In addition, experimental and numerically predicted load-displacement curves for the notch length of 6mm are plotted in Fig. 6 showing very good agreement.

During the biaxial experiments strain fields are analyzed by DIC and the first principal strain $\epsilon_1$ is shown in Fig. 7. Remarkable localization of strains can be seen with maxima of about 25% and the strain behavior for different lengths of the notched parts is very similar. In addition, numerically predicted principal strains $\epsilon_1$ are also shown in Fig. 7 and these strain fields agree very well with the experimental ones. Furthermore, based on numerical simulations the stress states in the tested specimens can be predicted. In the notched regions the stress triaxiality $\eta$ and the Lode parameter $\omega$ are also shown in Fig. 7. In particular, the distribution of the stress triaxiality in the notch area is nearly homogeneous with value of about $\eta = -0.1$. On the other hand, for the notch length 0.3mm the Lode parameter in the center is $\omega = 0.0$ but with increasing notch length a slight decrease up to $\omega = 0.2$ is numerically predicted. Thus, for
Figure 7. Experimentally measured first principal strain $\varepsilon_1$ and numerically predicted first principal strain $\varepsilon_1$ for different geometries under shear-compression loading (-0.5/1); stress triaxiality $\eta$; Lode parameter $\omega$
Figure 8. Stress triaxiality $\eta$ of 6mm H-specimen under different loading conditions

Figure 9. Details of fractured specimens
the H-specimen with different notch length the stress distribution is nearly homogeneous in the center of the notch and only small differences in the amounts of stress variables are predicted depending on the notch length.

Moreover, stress triaxialities in the notch area depending on the loading conditions are shown in Fig. 8. For example, for tension loading \( F_1/F_2 = 1/0 \) large stress triaxialities up to \( \eta = 0.96 \) are numerically predicted in the center of the notch area. These large values are caused by notches in both thickness and in the loading plane. For shear loading \( F_1/F_2 = 0/1 \) the distribution of the stress triaxiality in the notch area is more homogeneous with \( \eta = 0.0 \). Superposition of shear with tension loading \( F_1/F_2 = 0.5/1 \) leads to small positive stress triaxialities \( \eta = 0.2 \) whereas for combination of shear and compression \( F_1/F_2 = -0.5/1 \) \( \eta = -0.4 \) is numerically predicted. Thus, biaxial experiments with the H-specimen cover a wide range of stress triaxialities leading to different damage and failure modes.

For H-specimens with different notch lengths fracture modes depending on loading conditions are shown in Fig. 9. For tension and shear-tension loading vertical cracks can be seen and this fracture mode does not depend on the length of the notched part. On the other hand, for shear and shear-compression loading the fracture line moves to a diagonal one with larger angle for smaller notches.

4. Conclusions

An anisotropic continuum damage model taking into account stress-state-dependent failure mechanisms on the micro-level has been briefly discussed. Validation is based on biaxial experiments with newly developed specimens mainly undergoing shear-compression loading appearing in metal forming processes. Digital image correlation technique has been used to analyze current strain fields in critical regions of the specimens. Furthermore, corresponding numerical simulations have been performed. Load-displacement curves and stress and strain states have been examined and compared with available experimental data allowing validation of the proposed stress-state-dependent equations. Therefore, the proposed phenomenological continuum damage model can be used in numerical analyses to optimize sheet metal forming processes. In addition, biaxial experiments with the H-specimen are recommended to analyze stress-state-dependent damage and failure mechanisms in thin sheets.

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