Influence of different yield loci on failure prediction with damage models

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Abstract. Advanced high strength steels are widely used in the automotive industry to simultaneously improve crash performance and reduce the car body weight. A drawback of these multiphase steels is their sensitivity to damage effects and thus the reduction of ductility. For that reason the Forming Limit Curve is only partially suitable for this class of steels. An improvement in failure prediction can be obtained by using damage mechanics. The objective of this paper is to comparatively review the phenomenological damage model GISSMO and the Enhanced Lemaitre Damage Model. GISSMO is combined with three different yield loci, namely von Mises, Hill48 and Barlat2000 to investigate the influence of the choice of the plasticity description on damage modelling. The Enhanced Lemaitre Model is used with Hill48. An inverse parameter identification strategy for a DP1000 based on stress-strain curves and optical strain measurements of shear, uniaxial, notch and (equi-)baxial tension tests is applied to calibrate the models. A strong dependency of fracture strains on the choice of yield locus can be observed. The identified models are validated on a cross-die cup showing ductile fracture with slight necking.

1. Introduction

Failure assessment in sheet metal forming simulation is usually based on the Forming Limit Curve (FLC) in principal strain space. By means of this failure criterion localized necking can be predicted in the range between uniaxial and (equi-)baxial tension. The FLC is only valid for proportional loading paths and not appropriate to predict shear fracture, fracture under bending or fracture with an underlying complex loading history such as edge-fracture. These drawbacks are of secondary importance using mild steels but become critical for Advanced High Strength Steels (AHSS). AHSS show rather excellent properties in modern car body manufacture. Due to their heterogeneous microstructural composition with a soft ferrite matrix and hard martensite particles especially dual-phase steels (DP) exhibit high strength and a comparatively high formability which makes them suitable for crash relevant parts, e.g. B-pillars. Nevertheless this heterogeneity of microstructural phase properties leads to a heterogeneous strain distribution and to a damage evolution [1]. DP steels exhibit the classical stress-state dependent overlapping stages of damage evolution, namely void nucleation, growth and coalescence. In the theory of damage mechanics the void growth is thereby controlled by hydrostatic stresses with the characteristic parameter stress triaxiality, whereas the shape is influenced by the deviatoric component of the stress tensor, characterized by the Lode-Parameter, the normalized third invariant of the deviatoric stress tensor or normalized shear stresses. During sheet metal forming the damage evolution might lead to fracture with slight necking, fracture on tight radii or edge-fracture. These failures can hardly be predicted with the FLC. To improve failure prediction special emphasis is placed on phenomenological damage models [2] and advanced fracture criteria [3] in research and industry. These models incorporate the dependency of ductile failure mechanisms by formulations of the fracture strain depending on the stress triaxiality and the Lode-Parameter. Moreover, advanced fracture criteria as well as phenomenological damage models formulated in the framework of Continuum Damage Mechanics (CDM) introduce a damage variable based on Kachanovs idea of a reduction in the load carrying cross...
section as a result of the formation of voids [4]. Thereby CDM based models compute effective stresses and thus link the scalar damage parameter with the stress tensor. In this context the Enhanced Lemaitre Model [2] and GISSMO (Generalized incremental stress-state dependent model) [5] show promising results in forming and crash simulation. Both models can be calibrated inversely on the basis of stress-strain curves of specimens representing several stress-states. Within this work both models are comparatively reviewed for the application in sheet metal forming on basis of experimental investigations of a DP100. Using GISSMO, the influence of the choice of yield locus on failure prediction is investigated.

2. Material modelling

In general, sheet metal forming simulation is based on an appropriate plasticity model containing a yield function $\Phi$ with a respective yield stress $\sigma_y$ and a model dependent equivalent stress $\bar{\sigma}$:

$$\Phi = \sigma - \sigma_y = 0$$  \hspace{1cm} (1)

Assuming isotropic hardening, the yield stress $\sigma_y$ is a function of the accumulated equivalent plastic strain $\varepsilon$.

The yield functions von Mises, Hill48 and Barlat2000 used in this contribution can be found in [6], [7] and [8], respectively.

2.1. Enhanced Lemaitre Model

The classical Lemaitre Model follows Kachanovs idea of a reduction in the load carrying cross section by introducing effective stresses $\bar{\sigma}$ [9]:

$$\bar{\sigma} = \frac{\sigma}{1-D}$$  \hspace{1cm} (3)

The onset of failure is obtained when the damage variable $D$ reaches a material specific critical damage value $D_{cr}$. The classical Lemaitre Model was enhanced in past and recent research work to account for the “void closure effect” under hydrostatic pressure ($h$) and the dependency of the failure strain on the Lode-parameter to better predict shear-dominant fractures ($2\tau_{max}/\bar{\sigma}$) [2]. The respective damage evolution reads

$$D = \left(\frac{2\tau_{max}}{\bar{\sigma}}\right)^\gamma \left\{ \frac{Y - Y_0}{S} \right\} \frac{\dot{\varepsilon}}{(1-D)\varepsilon}, \text{ with } Y = 1 + \frac{\vartheta}{E} \left\{ \sum_i \left(\bar{\sigma}_i^\gamma + h(-\bar{\sigma}_i^\gamma)\right) \right\} \frac{\vartheta}{2E} \left\{ \bar{\sigma}_i^\gamma - h(-\bar{\sigma}_i^\gamma)\right\}.$$  \hspace{1cm} (4)

Figure 1. (a) Fracture lines shown qualitatively in dependency of $\theta$ and $h$; (b) Normalized maximum shear stress as function of $\eta$ [2]
Damage evolution starts when modified elastic energy density $Y$ becomes greater than the initial elastic energy density $Y_0$. Besides the “void closure” parameter $h$ and the critical damage parameter $D_\alpha$, the Enhanced Lemaitre Model is characterized by the scaling factor of elastic energy density $S$, the exponent of elastic energy density $s$, the damage exponent $n$, and the parameter for shear dominant fractures $\theta$. Figure 1 illustrates qualitatively the effect of $h$ and $\theta$ in dependency of the stress triaxiality $\eta$. For $\theta = 0$ and $h = 1$ the Enhanced Lemaitre Model is reduced to the classical Lemaitre model [2]. Choosing $0 \leq h < 1$, e.g. $h = 0.2$, the “void closure” effect is considered and the fracture curve loses its symmetry. The parameter for shear dominant fractures $\theta$ influences the fracture curve particularly in case of plane shear ($\eta = 0$) and plane-strain ($\eta = 1/\sqrt{3}$) [2].

2.2. **GISSMO**

The basis of GISSMO is a damage evolution depending on a failure curve $\bar{\varepsilon}_f(\eta)$. The failure curve itself depends on the stress triaxiality. The damage evolution is driven by evolution of equivalent plastic strain and can be influenced by the damage exponent $n$ [10]:

$$ \bar{D} = \frac{n}{\bar{\varepsilon}_f(\eta)} D^{\frac{1}{n}} \bar{\varepsilon} $$

Failure is initiated when $D = 1$. The damage parameter is coupled to the stress tensor after reaching the so-called instability curve $\bar{\varepsilon}_i(\eta)$, when the indicator $F$ reaches the critical value of 1. The evolution of $F$ proceeds in the same manner like the evolution of the damage parameter [10]:

$$ \tilde{F} = \frac{n}{\bar{\varepsilon}_w(\eta)} F^{\frac{1}{n}} \tilde{\varepsilon} $$

The “magnitude” of coupling depends on the fading exponent $m$ [10]:

$$ \tilde{\varepsilon} = \frac{\bar{\varepsilon}}{1-D} $$

with $\tilde{D} = 0$, if $F < 1$ and $\tilde{D} = \left( \frac{D-D_\alpha}{1-D_\alpha} \right)^n$, if $F = 1$ (7)

Here, $D_\alpha$ is the value of the damage parameter, when $F$ reaches unity. By setting $m = 1$ and $D_\alpha = 0$ equation (3) is recovered. The effect of the fading exponent, the damage exponent and the schematic behavior of GISSMO are shown in figure 2. For proportional loading paths the points reaching the instability and failure curve coincides with $F$ and $D$ reaching unity. In case of non-proportional loading paths failure can be initiated above or below the respective curves. The evolution of $F$ and $D$ incorporates intrinsically the influence of non-proportional loading paths. With high fading exponents, there is barely an effect of the coupling between plasticity and damage.

![Figure 2.](image)

Figure 2. (a) Schematic behaviour of GISSMO with instability (red) and fracture curve (grey); (b) Effect of the damage exponent $n$; (c) Effect of the fading exponent $m$ [10]
3. Experimental procedure
The material models are calibrated using experimental data of a commercially produced DP1000 with a sheet thickness of 0.98 mm. The microstructure of this advanced high-strength steel is composed of about 27 % ferrite, 60 % bainite/tempered martensite, 10 % martensite and 2 % retained austenite with an average ferrite grain size of 1.26 µm. The fine-grained multiphase microstructure of this steel leads to the mechanical properties listed in table 1. Here, longitudinal (LD), diagonal (DD) and transversal (TD) refer to the direction (D) of applied tensile load with respect to the rolling direction. These mechanical properties are determined according to SEP1240 with specimen geometry specified in DIN EN ISO 6892-1:2017-02. The material shows slight anisotropic behaviour in plane characterized by higher strength values and lower formability in transverse direction.

**Table 1.** Mechanical properties of DP1000

| D     | \( R_{p0.2} \) [GPa] | \( R_{m} \) [GPa] | \( R_{p0.2}/R_{m} \) | \( A_{G} \) [%] | \( A_{80} \) [%] | \( n_{2,3} \) [-] | \( r_{2,3} \) [-] |
|-------|----------------------|------------------|---------------------|----------------|----------------|----------------|----------------|
| LD    | 0.708                | 1.060            | 0.67                | 9              | 14             | 0.13           | 0.70           |
| DD    | 0.674                | 1.034            | 0.65                | 9              | 13             | 0.13           | 1.13           |
| TD    | 0.714                | 1.084            | 0.66                | 8              | 12             | 0.12           | 0.86           |

The initial yield stress of 0.667 GPa under equi-biaxial conditions is determined via bulge-test according to DIN EN ISO 16808:2013-02. In behalf of parameter identification of the damage models four ductile fracture experiments covering a triaxiality range between simple shear and biaxial tension are conducted with the digital image correlation system gom ARAMIS (10 Hz, strain gauge length 0.5mm) as illustrated in figure 3: a shear tensile test (ST), an uniaxial tensile test (UAT), a plane-strain tension test with a notched specimen (PST) and an (equi-)biaxial tensile specimen (BAT). The specimens are detailed in [10] and [11]. It has to be mentioned, that the strain path of the UAT specimen changes to the plane-strain stress state in the localization area.

![Figure 3. Ductile fracture specimens and the corresponding stress states](image)

4. Parameter identification
First, the parameters of the plasticity models must be determined. Instead of extrapolating the flow-curves by means of the principle of equivalent plastic strain on basis of the bulge test, the flow-curves are extrapolated reversely with a combined Swift-Hockett-Sherby law on the basis of the ductile fracture experiments with loading direction parallel to RD. This curve is used for all three yield loci. All simulations are performed with fully-integrated, quadrangular shell elements with an edge-length of 0.50 mm in the commercial FE-code LS-Dyna. The initial yield loci for Hill48 is determined directly with the initial yield stress in longitudinal direction and the \( r \)-values in longitudinal, transversal and diagonal directions from the uniaxial tensile test (table 1). For Barlat2000 (yield locus exponent: \( a = 6 \)) additional information concerning the initial yield stress in transversal and diagonal as well as under equi-biaxial tension is necessary. Here the parameters of the yield locus are determined inversely. In figure 4 the resulting yield loci and the predicted \( r \)-values as well as the initial yield stresses with respect to RD are displayed. Expectedly, Barlat2000 shows the best results, whereas both other yield functions show slight deviations from the experimental data points.
Figure 4. (a) Initial yield loci; (b) Predicted r-value with respect to RD; (c) Predicted initial yield stress with respect to RD

The optimization software LS-Opt is chosen for the parameter identification of the Enhanced Lemaitre Model to apply a meta-model based optimization strategy with a curve matching as objective function. To reduce the number of parameters for the optimization process \( Y_0 \) and \( D_{\text{cr}} \) are calculated by equations given by [9]. The “void closure” parameter is kept constant with \( h = 0.2 \) as proposed by Lemaitre [9]. Furthermore \( S \) is kept constant with a value of 0.05 GPa. Hence \( \theta, s \) and \( \beta \) are determined via LS-Opt. The resulting parameter set is shown in figure 5 (a). The supporting points of the fracture and instability curves in GISSMO are determined starting with the optically measured von Mises equivalent plastic strains at the onset of fracture \( \varepsilon_f \), via reverse engineering. Non-linear damage accumulation is invoked by \( n = 2 \). The fading exponent \( m \) is set to 100. Figure 5 (b) displays the resulting curves in the space of von Mises equivalent plastic strain and triaxiality. One can recognize a strong dependency of the resulting fracture strains on the chosen yield function. These fracture strains are higher for Barlat2000 for the UAT and PST specimen, which both show a pronounced necking before fracture.

Figure 5. (a) Enhanced Lemaitre Model: Identified parameter set; (b) GISSMO: Instability (dotted lines) and fracture curves (continuous lines) in dependency of different yield functions
In case of simple shear Barlat2000 leads to the lowest fracture strain. The (equi-)biaxial stress state shows the lowest deviation between the fracture strains for the three yield functions. The fracture strains of GISSMO in combination with Barlat2000 are in good accordance with the experimentally measured ones.

In figure 6 the resulting engineering stress-strain curves and the punch force-displacement curve are shown for the four material models in comparison with the experimental ones. Deviations for the onset of failure for the tensile tests (ST, UAT and PST) can be found using the Enhanced Lemaitre Model with a Hill48 yield function. In comparison with the combination of Hill48 with GISSMO the decrease in stress level is slightly higher due to the stronger effect of coupling the plasticity and damage model. The onset of failure is predicted well with the combination of GISSMO and the three yield functions. The best accordance in stress level can be identified for the combination of Barlat2000 and GISSMO, even though the decrease in stress level is slightly too high due to the development of a stronger localization. Especially for simple shear and plane-strain stress the stress level is overestimated with the combination of von Mises with GISSMO due to the poor description of the yield locus. Using GISSMO the shear tension specimen shows a stepwise failure process due to stepwise element deletion, which leads to oscillations in the stress-strain curve.

Figure 6. Engineering Stress-Strain curves: ST (a), UAT (b), PST (c); Punch Force-Displacement curve: BAT (d)

5. Validation
The material models are validated within this contribution using a component part, namely a cross-die sample, which exhibits loading paths similar to a B-pillar. The cross-die cups manufactured from DP1000 show tensile fracture with minor necking (figure 7 (a)). The onset of fracture takes place in the cup wall at a drawing depth of 24 mm. The location of fracture is predicted well with the Enhanced Lemaitre Model and the combination of Hill48 and Barlat2000 with GISSMO. Using the von Mises model the fracture is predicted too early in the die corner. In addition to the correct location of failure
the drawing depth at the onset of fracture is determined correctly with the combination of Hill48 and Barlat2000 with GISSMO. The Enhanced Lemaitre Model overestimates the drawing depth slightly in analogy to the ductile fracture experiments.

![Figure 7.](image)

(a) Fracture of cross-die cup with slight necking at a drawing depth of 24 mm; (b) Prediction of onset of fracture at a drawing depth of 26 mm with Hill48+Lemaitre; (c) 21 mm with von Mises+GISSMO; (d) 24 mm with Hill48+GISSMO; (e) 24 mm with Barlat2000+GISSMO

6. Conclusion

Within this contribution the Enhanced Lemaitre Model and GISSMO are applied for failure prediction of a dual-phase steel with a tensile strength of 1 GPa. There were deviations for the engineering stress-strain curves especially in the range between uniaxial and plane-strain tension with the strategy used for identification of the Enhanced Lemaitre Damage. This influenced the predictability of failure in the cross-die cup. It is shown that GISSMO is able to predict the failure behaviour in sheet metal forming simulation. Using this damage model, a strong dependency of fracture strains on the chosen yield function can be shown. This implicates on the one hand that an inverse parameter identification scheme seems to be favourable using a macroscopic modelling approach in an industrial context, which is not able to capture every physical detail. On the other hand it can be concluded, that failure predictions with models calibrated using a direct method of parameter identification based on experimentally measured fracture strains are very sensitive to the chosen yield function.

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