# Parameter identification of two phenomenological damage models for sheet metal forming

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## 1 Motivation

In modern car body manufacture, the widespread high-strength steels are less ductile. They are more sensitive to damage effects than conventional deep-drawing steels due to their multiphase microstructure and various inclusions. For example, voids nucleate in dual-phase steels at the phase-boundaries between martensite and ferrite at low plastic strains. The voids grow and coalesce during further loading and thus the material fails without severe necking. The Forming Limit Curve (FLC) as the classic failure criterion in forming simulation is only partially suitable for this class of steels. Besides ductile failure without severe necking shear fracture cannot be predicted using the FLC. An improvement can be obtained by using damage mechanics. The objective of this contribution is the comparative assessment of the Enhanced Lemaitre Damage Model and GISSMO (Generalized Incremental Stress State dependent Model) for the application in sheet metal forming simulation.

## 2 Damage modeling – Enhanced Lemaitre Damage Model and GISSMO

Damage indicator models as well as models formulated in the framework of Continuum Damage Mechanics (CDM) introduce a damage variable $D$ based on Kachanovs idea of a reduction in the load carrying cross section as a result of the formation of voids. Assuming an initial damage value of $D = 0$, damage indicator models like the Modified Hosford-Coulomb criterion predict the onset of failure reaching a critical damage value ($D_{crit} = 1$ for most models). CDM based models like the Enhanced Lemaitre Model and GISSMO compute effective stresses and thus link the scalar damage parameter with the stress tensor. The damage mechanisms are described in a phenomenological manner depending on the triaxiality (void growth) and the Lode-parameter (void shape and inter-void linking). Experimental investigations for various multiphase steels show porosities of about one percent of the undamaged material [1]. This amount of porosity is within such a low range that the computation of effective stresses is not mandatory. However, to compensate the shortcoming of shell elements in the post necking area, the coupling between damage and plasticity model may be reasonable.
The classical Lemaitre Model ([2]) was enhanced in past and recent research works 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 ($2\tau_{max}/\bar{\sigma}$) [3], [4].

$$\dot{D} = \left(\frac{2\tau_{max}}{\bar{\sigma}}\right)^{\theta} \langle\frac{Y-Y_0}{S}\rangle^{s} \left(\frac{\dot{\varepsilon}_{pl}}{(1-D)^{\beta}}\right) \text{ with } Y = \frac{1+\vartheta}{E}\left(\sum_{i=1}^{3}(\langle\sigma_i\rangle^2 + h\langle-\sigma_i\rangle^2)\right) - \frac{\vartheta}{2E}\left(\langle\sigma_m\rangle^2 - h\langle-\sigma_m\rangle^2\right) \quad (3)$$

The onset of failure is obtained when $D$ reaches a material specific critical damage value $D_{crit}$. Results of [4] and [5] reveal that this damage model with seven parameters shows sufficient flexibility to fit complex fracture curves.
The basis of GISSMO is an incremental damage accumulation which depends on a failure curve. The failure curve itself depends on the stress triaxiality. The damage parameter $D$ intrinsically incorporates the influence of non-proportional loading paths. The damage accumulation is driven by the evolution of equivalent plastic strain and can be influenced by a damage exponent $n$. The damage parameter is coupled to the stress tensor after reaching the so-called instability curve. The "magnitude" of coupling depends on the fading exponent $m$. For further information regarding GISSMO see reference [6].

## 3 Parameter identification

In the course of these investigations, both damage models are calibrated inversely for a dual-phase and complex-phase steel with a tensile strength of 1 GPa. The experimental basis for the parameter identification consists of the classical mechanical properties as well as the force-displacement curves of a shear tension, a uniaxial tension, a plane-strain tension and an equi-biaxial tension test to cover a triaxiality range between 0 and 0.67. The uniaxial and plane-strain tension specimens, in particular, exhibit non-proportional loading paths. The plastic material behavior is modelled with Hill48's yield criterion and with a tabulated flow-curve for isotropic hardening. The flow-curve is determined with a

multiplicative Hocket-Sherby - Swift approach, which is approximated via reverse-engineering to all four experiments.
The optimization software LS-Opt is used for the parameter identification of the Enhanced Lemaitre Damage Model. To reduce the number of parameters for the optimization process $Y_0$ and $D_{crit}$ are calculated with formulas proposed by Lemaitre [2], $h$ is assumed to be 0.2 and $S$ is kept constant with a value of 0.5 GPa. Hence $\theta$, $s$ and $\beta$ are determined via LS-Opt.
The material card for GISSMO is generated via reverse engineering. To fit the experimental force-displacement curves the failure strains of the failure curve are adjusted for respective triaxialities, the position of the instability curve is determined and suitable values for $n$ and $m$ are choosen.
For both steels, the numerically determined curves computed with GISSMO lay in good accordance with the experimental ones. For DP1000, the onset of failure is determined slightly too early with the Lemaitre Model. The highest deviation between the experimental and numerical curves can be found for the Nakajima specimen representing the equi-biaxial tension stress-state. For CP1000, on the other hand, the onset of failure is overestimated for the shear tension and equi-biaxial tension test.

## 4 Validation

Two principle parts are used to validate the calibrated models. A cross-die cup is used for failure with underlying triaxialities between uniaxial and equi-biaxial tension. The failure for lower triaxialities is represented with a curved cup. Figure 1 shows an example of simulations with GISSMO and the respective fractured cups for DP1000.

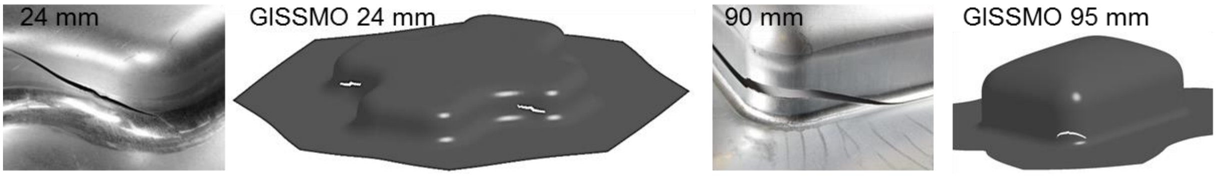


*Fig.1: GISSMO: Comparison of experiment and simulation for DP1000 (left: cross-die cup; right: curved cup)*

For the cross-die cup the drawing depth predicted by the GISSMO model lies within the experimental scattering and the onset of failure is predicted in the frame of the cup. The Enhanced Lemaitre Damage Model predicts a drawing depth of 19 mm. The onset of failure takes place at the die corner due to the premature onset of failure in the equi-biaxial tension stress state. With an experimental drawing depth of about 90 mm for the curved cup and a numerically computed drawing depth of 95 mm GISSMO slightly overestimates the onset of failure for lower triaxialities. With the Lemaitre model no failure is observed till a drawing depth of 100 mm. This can be explained by the strong influence of considering the “void closure effect” on damage accumulation for negative triaxialities.

## 5 Summary

In this contribution it is shown that GISSMO can be calibrated via reverse engineering and that the model is able to predict the failure behavior of high-strength steels in sheet metal forming simulation. With the strategy used for identification of the Enhanced Lemaitre Damage Model, there were slight deviations for the force-displacement curves in the shear and equi-biaxial stress state. This influences the predictability of failure in simulation of the forming process of the cross-die and curved cup.

## 6 Literature

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