Consistent Damage Modelling in the Process Chain of Forming to Crashworthiness Simulations

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Summary:

Increasing crashworthiness requirements, together with the need of substantial weight reduction, are pushing the use of high strength steel grades in automotive car body structures. For being able to provide a reliable prediction of crash performance, methods to predict crack formation in structural parts have to be improved. To ensure this, a pre-damage of sheet metal parts, manufactured by means of deep-drawing processes, has to be taken into account. A new damage model for use both in forming and crashworthiness simulations is presented. Differences to existing damage models are pointed out, and calculations on a demonstrator part are shown.

Keywords:

Process Chain, Ductile Damage, Crash Simulation

1 Introduction

In recent years, the requirements on passive safety of cars have grown to high standards, leading to a permanent demand on an increase in simulation accuracy. Additionally, demands on fuel efficiency and CO_2 – reduction are confronting the car body designers with the need of substantial weight reduction.
One way to achieve light-weight structures with good crash safety performance is to replace conventional deep-draw steels by more sophisticated materials. Besides of using classic light-weight materials such as aluminum, magnesium or fibre reinforced plastics, new high strength steel grades are becoming more and more important for the construction of car body structures. Often showing rather complex work-hardening and fracture behaviour, new methods are to be developed to precisely predict failure as crack development under crash loading. Quantitatively considering local pre-damage from foregoing forming processes, seems to be a necessary extension of existing failure prediction methods for crashworthiness calculations.

2 The process chain of sheet metal part manufacturing

The part of the process chain that is considered in the following starts with the forming process. Since the use of metal forming simulations has become usual practise in the automotive industry, it seems on hand to make further use of the calculated results by transferring them to a following crashworthiness simulation. By transferring the calculated local sheet thickness after forming, one can improve the geometrical description of a FE model.
Another quantity that can be transferred rather easily from one simulation to the other, is the distribution of local plastic pre-strain as a scalar quantity. This can provide valuable information on the actual state of strain hardening in a part. Yet, a strong dependence of failure strains on the actual loading conditions can be observed for high strength steel materials. Due to this, local plastic pre-strain values alone are not sufficient to describe local pre-damage of a part, since no information about the loading history of the respective part is included. Furthermore, in most cases strain states under forming and crash loading will be of completely different nature, making a simple criterion like the maximum plastic strain to failure suitable only for very special load cases.
A possibility to avoid this problem, is the use of incremental damage models for both sides of the process chain. This makes it necessary to use a damage model for forming simulations also, which is differing from the usual practise so far. The conventional way to determine the formability of a part would be the use of forming limit diagrams (FLD), considering only the final deformation state of a part. Thus, this method does not deliver any information about the load path the part was subjected to while being deep-drawn. Consequently, the predictive capabilities of the FLD are limited, especially for the use with complex forming operations and advanced high strength materials.

2.1 Material models

The two different simulation disciplines (forming and crash) are posing different demands on the material model used: On the “forming” side of the process chain, a precise description of the yield locus is most important, as the simulated plastic flow is strongly influenced by effects of anisotropy and work-hardening. In order to take into account a possible initial anisotropy of sheets, several different material models with different complexity are in use for this purpose. As an example of a widely used forming material model, the model of Barlat and Lian 1989 [1] will be named in the following. Being rather a “classic” of forming material models, several more sophisticated models were developed in later times.

For crashworthiness simulations, the focus is laid rather on the description of dynamic material behaviour, often combined with failure prediction. A typical material model for crashworthiness simulations is the isotropic von Mises constitutive model, which is implemented in LS-DYNA as MAT_024. Good experience was also made using the Gurson model (MAT_120), which describes damage with related softening and failure. Anisotropy usually is not considered for this purpose.

The concept followed at Daimler, to ensure a consistent modelling of damage throughout the process chain, is to keep the established material models on both sides of the process chain. The idea is to combine the existing constitutive models on both sides with a damage model, allowing for a direct transfer of damage data from one simulation to the other.

The two combinations considered so far are:

- The Gurson model, used in combination with an anisotropic material model (e.g. Barlat89) only for damage accumulation in the forming simulation, and as stand-alone constitutive model with damage for the crash simulation
- A generalized incremental, stress-state dependent damage model (GISSMO), combined with an anisotropic material model for forming simulation, and with a von Mises material model for crash simulation

Both combinations lead to the fact that a damage model has to run in the background of a forming simulation, without any interaction of the damage model on the forming constitutive model.

3 The Gurson model

The Gurson-model, with extensions by Tvergaard and Needleman [8], is based on a micromechanical description of growth and nucleation of spheroid voids in rigid-perfectly plastic material. It offers a complete description of ductile material behaviour, including softening and failure. When combined with a forming simulation, the calculated void volume fraction f can be mapped as a pre-damage parameter to the crash simulation later on.

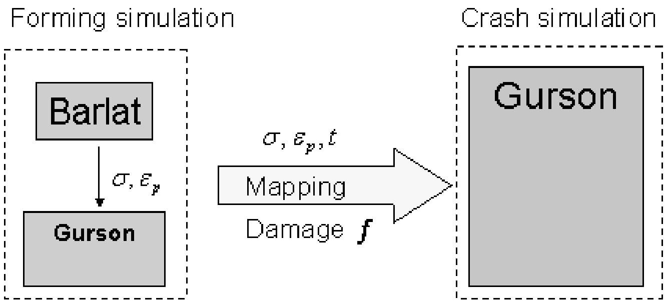

Figure 1: Combination of Gurson and Barlat models

3.1 Properties

The model offers a yield function dependent on hydrostatic pressure and the effective void volume fraction f:

$$\Phi = \frac{q^2}{\sigma_M^2} + 2q_1 f^* \cosh\left(\frac{-3q_2 p}{2\sigma_M}\right) - 1 - (q_1 f^*)^2 = 0 \tag{1}$$

With
σ_M: actual flow stress in matrix material
p: hydrostatic pressure
q: equivalent (von Mises) stress
f^*: effective void volume fraction

Damage evolution is defined in a cumulative way:

$$\Delta f = \underbrace{(1-f)\Delta\varepsilon_p^{pl}}_{void\ growth} + \underbrace{A\Delta\varepsilon_M^{pl}}_{void\ nucleation} \tag{2}$$

with

$$A = \frac{f_N}{s_N\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\varepsilon_M^{pl}-\varepsilon_N}{s_N\sqrt{2\pi}}\right)^2}$$

As can be seen from equation (2), damage evolution consists of void growth due to volumetric plastic straining, and nucleation of voids due to deviatoric plastic straining. Usually, void growth is considered the dominating mechanism of material deterioration under tensile loading. This implies the volumetric part of the plastic strain rate being different from zero, as long as the void volume fraction f – and therefore the damage – is growing. This will happen under arbitrary loading conditions of tensile nature, i.e. positive mean stress. Although based on the von Mises plastic potential, the Gurson model violates by its definition the assumption of isochoric plastic flow, which is common in classical plasticity theory. In terms of practical use, this shows by a plastic Poisson's ratio being different from 0.5.

$$\nu_p = -\frac{\varepsilon_{p,yy}}{\varepsilon_{p,xx}} \tag{3}$$

The rise in volume is caused by a growing void volume fraction f.

3.2 Problems in using the Gurson model

As described above, the Gurson model, as a micromechanically motivated model, is showing a rather complex behaviour, which makes using the model as a pure postprocessing parallel to a forming material model difficult.

3.2.1 Adapting the Gurson model to isochoric forming material models

A special property of the Gurson model are variable values of the plastic poisson's ratio, as was described above. While the matrix material is considered incompressible, the macroscopic poisson's ratio is decreasing with growing damage due to the generated volume of voids.

By direct comparison to an incompressible material model like Barlat89 (MAT_036), one can see the difference in plastic poisson's ratio increasing with growing damage.

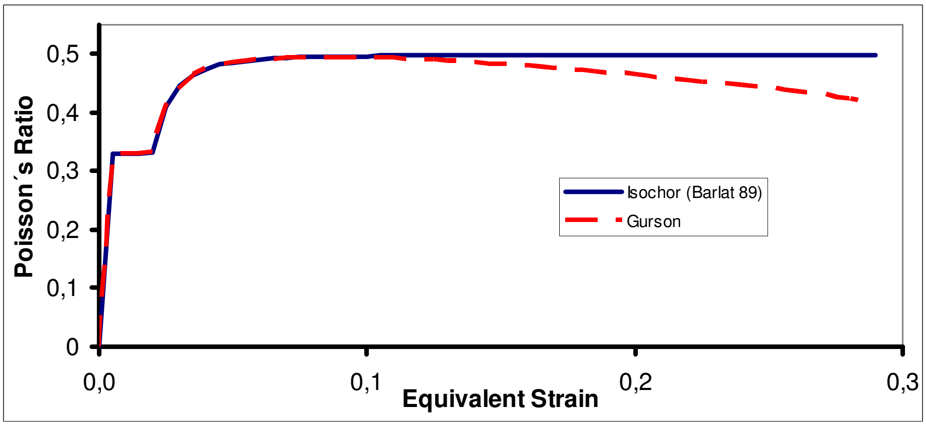

Figure 2: Poisson's ratio, Gurson and Barlat 89

This shows as an actual difference in calculated strain results for the two material models. To adapt the Gurson model to a volume-conserving forming constitutive model, it is necessary to calculate the related volumetric strain of the Gurson model from the purely deviatoric plastic strain rate tensor of the forming material model.

This can be achieved by deriving a relation from the flow function of the Gurson model. Yet, the problem of actually different strain results for the two constitutive models can not be solved in a general way, making a correction term for plastic straining necessary. This makes a practical use of the Gurson model for damage prediction in forming simulations even more difficult. Further information about this issue can be found in Schmeing et al. [7]

3.2.2 Fitting of material input parameters

In order to use the Gurson material for a prediction of damage, the input parameters of the model have to be fitted to existing test data. Due to numerous input parameters, which are actually coupled by the complex functions of flow rule eq. (1) and damage evolution eq. (2), creating an input data card is difficult and time-consuming. The most straight-forward way of creating an appropriate set of input parameters, is to fit the values by means of reverse-engineering simulations of the respective material tests, which has to be done separately for all element sizes considered.

3.2.3 Extension to shear-dominated failure

The Gurson model as described above, is not able to describe failure under conditions of mean stress near zero or negative. This is due to the fact that growth of voids, as the dominating mechanism of damage, vanishes as the mean stress reaches zero. Yet, in some applications of deep-drawing, there are remarkable magnitudes of shear and compressive-shear deformation, which causes a pre-damage that is not considered by the Gurson model.

To solve this problem, extensions of the Gurson model to shear dominated failure have been recently proposed by Nahshon and Hutchinson [6], and Xue [10]. A successful application of the Gurson model coupled to forming simulations, will therefore make it necessary to add such an extension to the Gurson model, to allow for the description of failure in a wide range of applications. For testing purpose, the Gurson model in LS-DYNA has been extended by a formulation based on the proposal of Nahshon and Hutchinson. Results of simulations using this model are showing the desired damage evolution under zero mean stress, yet the fitting of input parameters has been made even more difficult due to additional parameters.

In general, a problem in fitting input parameters using the Gurson model is the inherently prescribed shape of the function of failure strain vs. triaxiality, which often makes it impossible to fit all measured failure strains over triaxiality.

4 A phenomenological Damage model – GISSMO

Most of the problems addressed above, resulting from the use of the micromechanically motivated and hence rather complicated Gurson model, can be avoided by using a phenomenological damage model whose features are tailored to the application.
The chosen model is based on the mean-stress dependent failure criterion of Johnson and Cook [4], with extensions to allow for a more general description of complex failure behaviour, and flexible fitting of input parameters. Up to now, the implementation used is restricted to plane stress conditions, since the application on sheet metal failure prediction usually results in shell element discretisation. A formulation for general states of stress is in preparation, which is in many aspects similar to the formulations recently proposed by Xue and Wierzbicki [2], and Xue [11].

In the following, a short description of the most important extensions to the Johnson-Cook criterion is given. The strategy behind the generalization was to transfer the predictive performance of the proven Gurson model to a much simpler, phenomenological damage model without retaining its disadvantages. By implementing the extensions described below, the damage model lost its similarity to the Johnson-Cook model, and is called GISSMO (Generalized Incremental Stress-State dependent damage MOdel).

4.1 Arbitrary definition of failure strains

In the standard failure criterion of Johnson and Cook, failure strain is defined depending on triaxiality, strain rate and temperature. As adiabatic heating usually does not play an important role in crash situations, temperature dependency will be neglected in the following.
The basic stress-state dependent definition of failure strain is therefore according to the results of Bridgman [5], stating the influence of hydrostatic pressure on ductile damage by means of the formation of microvoids and microcracks.
The failure strain according to Johnson and Cook reads

$$\varepsilon_f = \left(d_1 + d_2 \exp(-d_3\eta)\right)\left[1 + d_4 \ln\left(\frac{\dot{\varepsilon}_e^p}{\dot{\varepsilon}_0}\right)\right] \tag{4}$$

with constants $d_1..d_4$, and Triaxiality η, defined as the ratio of mean stress to equivalent stress

$$\eta = \frac{\sigma_m}{q} \tag{5}$$

This results in an exponential dependency of failure strain on triaxiality, prescribing a monotonically falling function of η. In terms of load cases, this means that failure strain under shear loading (η=0) is defined higher than under uniaxial tension (η=1/3), for example. For a variety of materials, this seems not to be the case, see also Barsoum and Faleskog [3]. To allow for a more flexible fitting on a wide variety of materials, input was changed to a load curve of failure strain vs. triaxiality, which seems to be a sufficient description for the plane stress case. For practical use, several points of failure strains for defined triaxiality can be determined using coupon tests. By interpolating between these data points, a curve of failure strain vs. triaxiality can be generated.

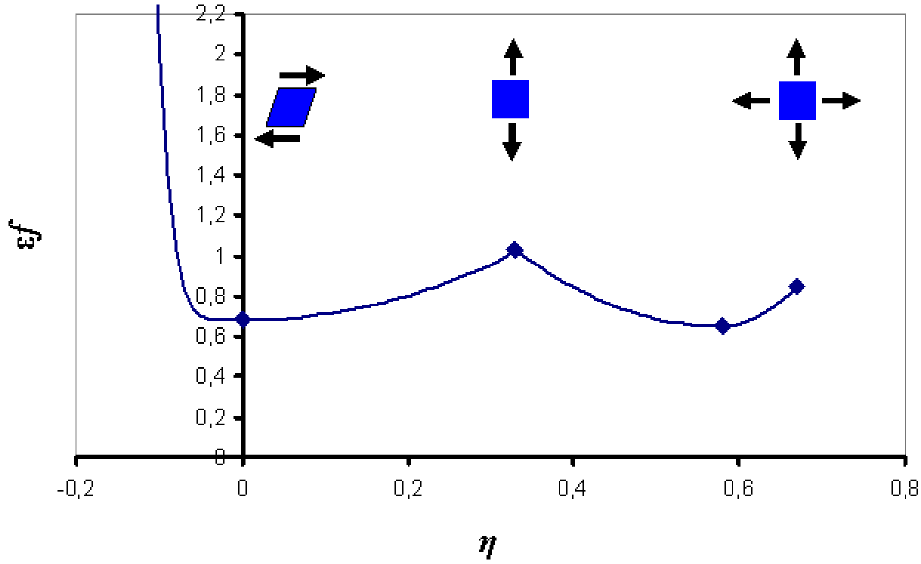

Figure 3: Example of an interpolated failure curve

4.2 Modified Damage Accumulation

One obvious difference between the Gurson damage evolution and the failure criterion of Johnson and Cook, is the way damage is accumulated until failure. This describes an important aspect of the relation between stress and plastic strain rate tensors, and damage, which is considered to be a scalar internal variable. Following a rather complex damage evolution for the Gurson model (eq. (2)), damage is accumulated linearly for the criterion of Johnson and Cook.
Weck et al. [9] were doing CT-measurements of the evolution of pore volume fraction in porous model media under tension. This gives an impression of what might be the real behaviour of this internal variable. It shows a non-linear increase of damage over plastic straining, which corresponds to the damage evolution of the Gurson model.
Looking at the desired use of a damage model to estimate the pre-damage induced to sheet metal parts during forming operations, it seems very important to realistically describe the accumulation of damage, since in forming operations the material usually will not be elongated to strains close to failure. Considering the accumulation of damage following a load path of varying triaxiality, it seems obvious that an incremental formulation depending on the actual value of damage has to be found. This leads to an ordinary differential equation of Damage rate:

$$\dot{D} = f(D,\eta) \tag{6}$$

The desired path-independency of damage rate makes it necessary to avoid a dependency on the actual value of equivalent plastic strain. As a further condition, the existence of a function

$$D = f(\varepsilon,\eta) \qquad for\ \varepsilon_f = const.(proportional\ loading) \tag{7}$$

is required to allow for an easy identification of damage parameters.

As a solution satisfying these requirements, a power law function can be used:

$$D = \left(\frac{\varepsilon_p}{\varepsilon_f} \right)^n \qquad for\ \varepsilon_f = const. \tag{8}$$

By differentiating, one gets to an incremental formulation of non-linear damage evolution:

$$\dot{D} = \frac{n}{\varepsilon_f} D^{\left(1-\frac{1}{n}\right)} \dot{\varepsilon}_p \tag{9}$$

The load-path independency of this damage rate is stated through the absence of equivalent plastic strain in eq. (9). By choosing an exponent n=1, eq. (9) is simplified to the linear Johnson-Cook criterion.

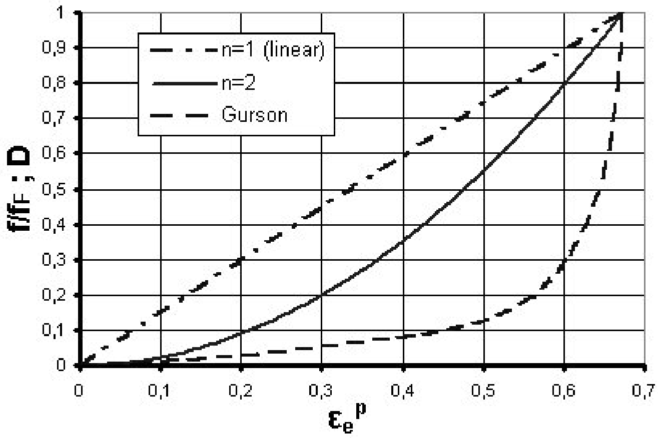

Figure 4: Normalized damage accumulation

This formulation was also proposed by Xue [11], motivated by considerations on low cycle fatigue derived from the empirical Coffin-Manson rule.

4.3 Regularization issues and strategies

4.3.1 Damage coupling by using the effective stress concept

Another important issue for a realistic description of damage, is the coupling of the actual damage parameter to the constitutive model. Especially in simulations of sheet metal coupon tensile tests, it is obvious that strain localisation is the dominating mechanism that triggers failure. The occurrence of strain localisation is directly related to the evolution of flow stress. For the Gurson model, the coupling of damage variable and flow stress is resulting from the demand for equivalence of internal and external plastic work rates. For a growing pore volume fraction, this results in a reduction of macroscopic flow stress, or macroscopic material softening.

For a phenomenologically motivated model like GISSMO, where no direct physical meaning of the damage variable exists, the effective stress concept proposed by Lemaitre [12] can be used. It leads to a reduction of flow stress depending on the actual damage:

$$\sigma^* = \frac{\sigma_f}{1-D} \tag{10}$$

In comparison to the Gurson model, this leads to similar results in terms of softening up to the range of moderate damage values. This is because the macroscopic strain rate and the strain rate in the matrix are nearly equal for moderate values of damage for the Gurson model:

$$\dot{\varepsilon}_{ij} \approx \dot{\varepsilon}_{ij}^M \tag{11}$$

for moderate damage.

4.3.2 Regularization by means of modified damage parameters

Softening material behaviour leads to mesh-dependent simulation results. To ensure accurate results for a wide range of mesh sizes, regularization strategies need to be considered. The element sizes used are introducing some means of artificial length scale to the model. For most materials, an internal length scale in the range of slip band sizes seems to be a reasonable definition, which can be expected to be in the vicinity of tenths of millimetres or less. In crashworthiness simulations, typical element sizes are ranging at least one order of magnitude higher, which introduces an artificial length scale leading to unphysical results as soon as strain localisation occurs.
The way this is dealt with for the Gurson model, is a definition of damage parameters depending on element sizes. This leads to different failure curves depending on the actual element length, which can differ dramatically.

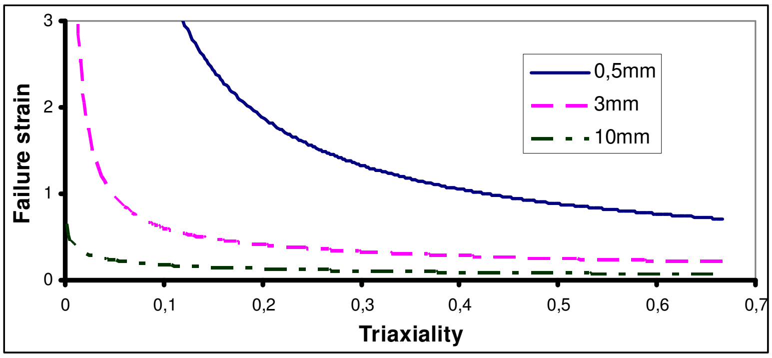

Figure 5: Failure curves for three element lengths of Aluminum material

In the case of damage coupled to the constitutive model, different flow curves would have to be used to account for the differences in localisation behaviour resulting from the different length scales prescribed by the discretisation. There is still the need for some research on this field, to ensure truly mesh-independent results from simulations using strain-softening material models.

5 Simulation of a demonstrator part

As an example for the practical use of a forming simulation coupled with a damage model, the forming simulation of a Cross-die was used. The simulation was done with LS-DYNA, using Mat_036 (Barlat89) coupled with the GISSMO damage model running in background, as described above. The parameters used are for DP600 dual phase steel. As input to the damage model, a curve of failure strains vs. triaxiality similar to the one displayed in figure 3 was used.

5.1 Differences in distribution of strain and damage

One observation that is quite obvious from the results, is that the distribution of equivalent plastic strain, and the calculated damage distribution can differ fundamentally.
For this part, a maximum in equivalent plastic strain can be found at the lower half of the front side (left picture in figure 6). In these spots, the strain state is of compressive nature, combined with shear. High failure strains can be expected for this strain state for ductile materials like DP600. Consequently, the calculated damage values are not reaching the critical level of 1 in these areas (right picture in figure 6). Crack initiation is predicted at the front edge of the part, where the equivalent plastic strain does not reach as high values as it does below. The predicted spot of crack initiation fits to experimental results quite well, as well as the predicted drawing depth.

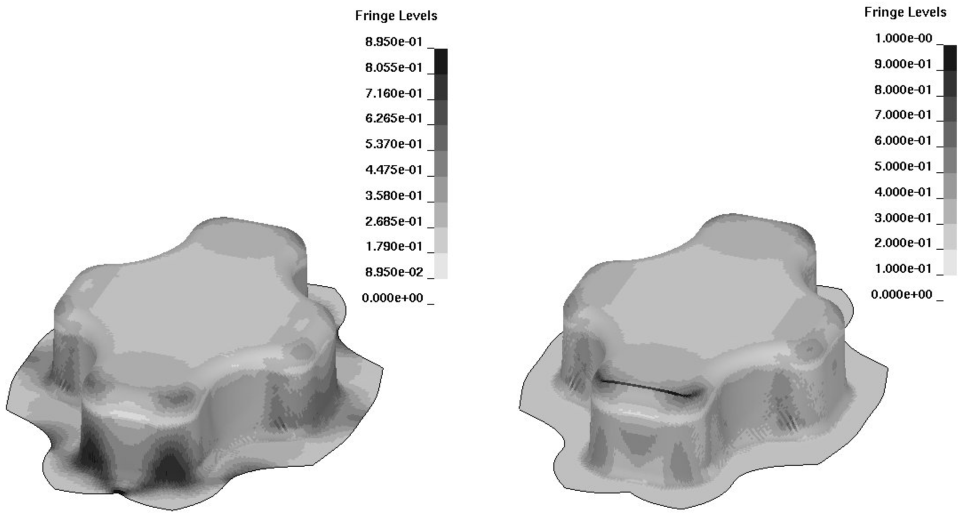

Figure 6: Cross-die; Contours of equivalent plastic strain (left) and damage D (right)

This shows, that an estimation of pre-damage from forming operations by simply considering the equivalent plastic strain values at the end of the process, may not be sufficient for materials that show a rather complex correlation between strain state and the respective failure strain.

5.2 Effects of non-linear damage accumulation on damage distribution

To show the differences resulting from a modified damage evolution, identical models of the Cross-die were used.

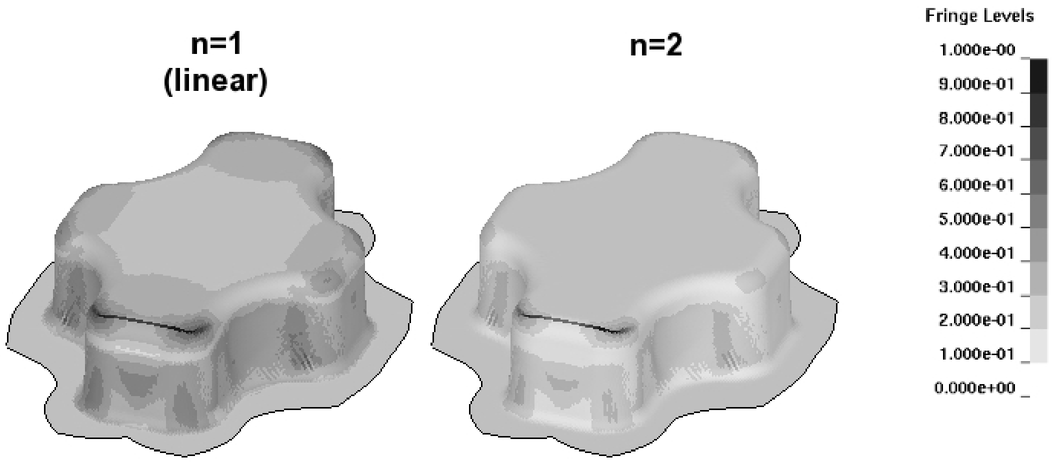

Figure 7: Cross-die; contours of damage D

Figure 7 shows the differences in damage distribution resulting from different exponents n in the evolution law, at the moment of crack initiation (same drawing depth). Damage values of 1 indicate failure, which is predicted at the same spots on the edge of the part for both exponents.
The differences resulting from different exponents in the damage evolution law result in lower damage values in regions that are not close to failure. Assuming the correctness of the investigations mentioned above, local pre-damage would therefore be overestimated by using a linear damage evolution law.

6 Conclusions

The described damage model GISSMO seems to offer promising potential to allow for an accurate, yet easy to use description of damage for the process chain of forming to crash simulations. With the extensions described, a combination to an arbitrary type of material model for forming simulations is possible. The damage results calculated from a forming simulation can therefore help to increase the predictive accuracy of a following crashworthiness simulation. As some "side-effect", an advanced incremental damage model could also lead to an improved prediction of formability problems and failure in sheet metal forming processes. To achieve this, some extra effort must be made concerning a coupling of damage to the constitutive model for forming simulations also.

7 Acknowledgement

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