On Closing the Constitutive Gap Between Forming and Crash Simulation

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Abstract

With increasing requirements on crashworthiness, and light-weight car body structures being a central issue in future automotive development, the use of high strength steel qualities has become wide-spread in modern cars. Since these materials often show significantly lower ductility than conventional steels, it is of great importance to precisely predict failure under crash loading conditions. Hence constitutive models in crashworthiness applications – as for instance the Gurson/Johnson-Cook model which is applied widely at Daimler AG – need to be initialized with correctly determined internal variables mapped from a corresponding sheet metal forming simulation.

Here two principle ways could be used theoretically: On the one hand different understanding of damage and failure in crashworthiness and sheet metal forming applications may be unified by a generalized incremental stress state dependent damage model (GISSMO). This approach can be considered as an attempt to replace the currently used FLD for the failure description in forming simulations. Furthermore, an advantage would be the inherent ability to account for load-path dependent failure behavior.

On the other hand the already applied Gurson model in crash simulations may be fed by an estimation of the internal damage value from the forming simulation. The idea here would be to perform the forming simulation with a state-of-the-art anisotropic material model like e.g. the Barlat model, with a simultaneously executed estimation of Gurson's damage evolution law.

The present paper will enlighten these two possible approaches. Furthermore it will be shown that damage prediction in metal forming processes and subsequently the use of the results as initial damage values in crash simulations is possible and necessary to predict structural failure in crashworthiness simulations.

Keywords: forming to crash process chain, failure and damage prediction

1. Introduction

Crashworthiness simulations of car body structures are an important part of the CAE development chain for car design. 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 weight reduction to an immense effort.
One way to achieve light-weight structures with good crash safety properties 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 gaining more and more importance 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 manufacturing process chain

Since the use of metal forming simulations is common practice in the automotive industry, it seems on hand to transfer calculated results such as plastic strains, resultant work-hardening and damage from forming to crash simulations. Methods have been developed to map data between the different meshes used in forming and crash simulations.

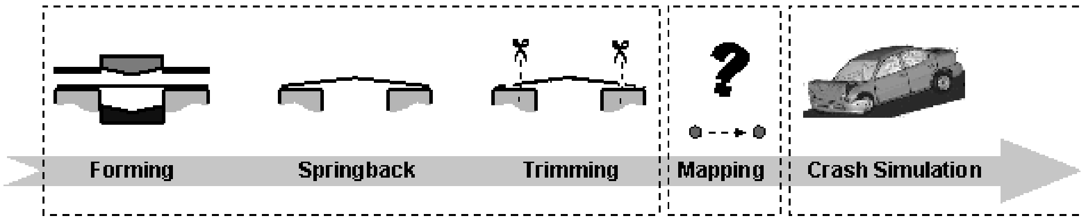

Figure 1: *The process chain of forming to crash simulation*

Since fracture behaviour of high strength steels strongly depends on the loading conditions, plastic pre-strain as a scalar quantity alone is not sufficient to predict the remaining ductility of these materials. Due to the need of taking into account possible changes in load path, an additional damage parameter as an internal variable of a constitutive model is used. By employing a cumulative damage formulation, changes in strain path (non-proportional loading) with variations of the respective failure strain are considered.

2.1 Material models along the process chain

On the "forming" side of the process chain, the most important issue is to accurately describe the material yield locus. Taking into account possible initial anisotropy of sheets, complex formulations of yield locus and work hardening are used. As an example of many different formulations in use, the model of Barlat&Lian (1989) [1] may be named.

For the purpose of crashworthiness simulation, sheet metal anisotropy usually is not considered. Main issues are the prediction of structural folding patterns and energy absorption properties. Due to these differences, the use of the same constitutive model for both simulations would offer capabilities that are not needed to both sides. Additionally, a great amount of experience has been collected so far by using the established material models on both sides. Furthermore, there are many proven material property cards already existing for the respective models.

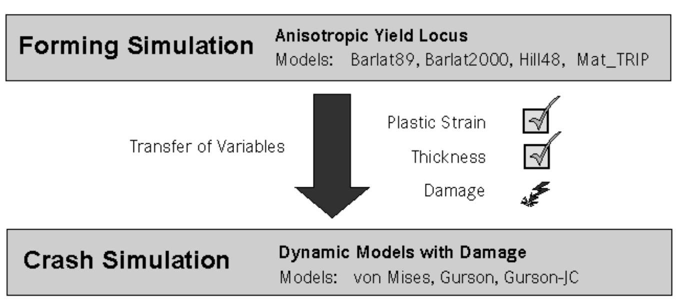

Figure 2: *Material models*

The concept that is actually followed by Daimler AG Sindelfingen is to add a damage model to an existing forming material model, so the resulting damage data can be transferred to a crash simulation later on. To do this, several combinations of constitutive models for forming and crash simulation are possible. As damage values are usually not to be easily converted from one damage model to another, a sensible combination should involve the same damage model on both sides of the process chain.

Two possible combinations of models are considered herein:

- 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 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 in combination with forming material models

The Gurson-model with extension by Tvergaard and Needleman [8] is based on a micromechanical model describing 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.

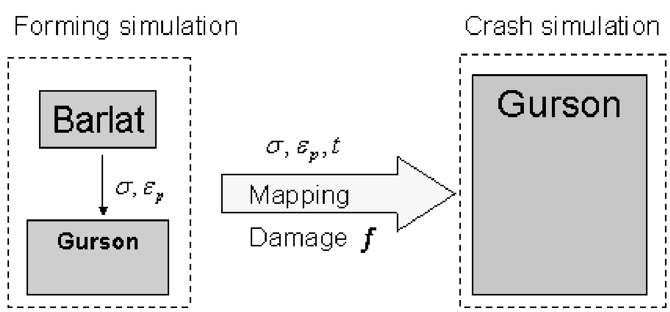

Figure 3: *Combination of Gurson and Barlat models*

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 the 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 $\dot{\varepsilon}_p^{pl}$ 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 is shown by a plastic Poisson's ratio ν_p 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.

3.1 The model of Barlat&Lian 1989

The model of Barlat and Lian [1] on the other hand is based on the assumption of isochoric plastic behaviour, thus by definition yielding a volumetric strain rate $\dot{\varepsilon}_p^{pl}$ equal to zero.

For the plane stress case (implemented in LS-DYNA® as Mat_036), the yield function is defined as

$$\Phi = a\left|K_1 + K_2\right|^M + a\left|K_1 - K_2\right|^M + c\left|2K_2\right|^M = 2\sigma_Y^M \tag{4}$$

with

$$K_1 = \frac{\sigma_x + h\sigma_y}{2}$$

$$K_2 = \sqrt{\left(\frac{\sigma_x - h\sigma_y}{2}\right)^2 + p^2\tau_{xy}^2}$$

Here, σ_Y is the actual yield stress; a, c, h and p are anisotropy parameters usually calculated from planar r-values.

3.2 Adapting the Gurson model

The difference in volumetric plastic straining by itself is the reason for the fact that the Gurson model cannot be coupled to an isochoric material model by simply transferring the calculated stress and strain tensors. To calculate the corresponding pore volume fraction from an isochoric constitutive model, the volumetric strain rate of the Gurson model has to be estimated from the existing strain rate tensor. For this purpose, the compatibility equation and the flow rule of the Gurson model are used:
The associated flow rule

$$\Delta\varepsilon_{ij}^{p} = \Delta\lambda \frac{\partial\Phi}{\partial\sigma_{ij}} \tag{5}$$

is separated into a volumetric and deviatoric part

$$\left.\begin{aligned} \Delta\varepsilon_{kk}^{p} &= \Delta\varepsilon_{p} = \Delta\lambda \frac{\partial\Phi}{\partial p} \\ \Delta\varepsilon_{eq}^{p} &= \Delta\varepsilon_{q} = \Delta\lambda \frac{\partial\Phi}{\partial q} \end{aligned}\right\} \Delta\varepsilon_{p} \frac{\partial\Phi}{\partial q} + \Delta\varepsilon_{q} \frac{\partial\Phi}{\partial p} = 0$$

$$\rightarrow \quad \Delta\varepsilon_{p} = -\Delta\varepsilon_{q} \frac{\frac{\partial\Phi}{\partial p}}{\frac{\partial\Phi}{\partial q}} \tag{6}$$

Employing the respective derivatives of the flow rule $\Phi(\sigma_{ij})$, and approximating using a Taylor series expansion, leads to the following relation for the volumetric strain increment as a function of the deviatoric strain increment:

$$\Delta\varepsilon_{p} = -\Delta\varepsilon_{q} \frac{-3q_2 q_1 \sigma_M f^{*}}{2q} \sinh\left(\frac{-3q_2 p}{2\sigma_M}\right) \tag{7}$$

By using this relation, the adjacent volumetric strain increment of the Gurson model can be estimated from an isochoric model like Barlat.
The differences in mechanical behaviour between the two models are yet not cured. Since the Gurson model would lead to a material change in volume, which the Barlat model does not, different strains will be calculated. This leads to incorrect values of damage when compared to a pure Gurson model, getting worse the higher the void volume fraction, and therefore the change in volume is. This is a principal problem of the two material models, which can be considered fundamentally incompatible. A simulation using the Gurson model, simply leads to different results in terms of strains compared to e.g. the Barlat model.

To solve this problem, a correction term to the Gurson damage evolution is considered. Based on the known relation of two principal plastic strains, for incompressible models like Barlat in uniaxial tension $(-\varepsilon_1 = 2\varepsilon_2)$, and the relation for arbitrary Poisson's ratio $(-\nu\varepsilon_1 = \varepsilon_2)$, a correction term was derived:

$$\Delta f = c\left[(1-f)\Delta\varepsilon_q \frac{3q_2 q_1 \sigma_M f^*}{2q}\sinh\left(\frac{-3q_2\eta p}{2\sigma_M}\right) + A\Delta\varepsilon_q\right] \tag{8}$$

with

$$c = \frac{4}{4 + 3\,q_2^2\; q_1\; f^*\eta} \tag{9}$$

The relation derived as equation (8) associates isochoric strain increments of the Barlat model to an increment of void volume fraction of the Gurson model. For the uniaxial tension case, the correction term is exact for the known appearance of the strain rate tensors of both models. For different load cases such as equibiaxial tension, this relation has to be set up separately, as no closed formulation of the correction term for arbitrary values of triaxiality η can be found. As a workaround, a correction factor S was introduced based on phenomenological findings. The correction term now reads as follows:

$$c = \frac{4}{4 + q_2^2 q_1 f^* S} \tag{10}$$

Using simple numerical tests of characteristic load cases, a table of correction factors S can be defined, to get a satisfactory fit of damage evolution for arbitrary values of triaxiality η. Further informations about this issue can be found in Schmeing *et al.* [7].

3.3 Extension of the Gurson model to shear-dominated failure

Special importance for an experimental proof of concept comes to the use of specimen which actually show reproducible crack formation undergoing a forming process. One such specimen, which is used in the forming methods development department at Daimler, is the Cross-die (see figure 7). Intended for formability tests, it shows a wide range of triaxialities from equibiaxial tension $(\eta = 2/3)$ and pure shear $(\eta = 0)$ to negative values, corresponding to compressive stress states. In these tests, certain grades of high strength steels show failure in areas undergoing shear-dominated deformation. The Gurson model is not suited to describe this behaviour (see also Feucht *et al.* [5]).
Possible 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.

4. The generalized incremental stress-state dependent damage model (GISSMO)

Most of the problems addressed above, resulting from coupling the Gurson model to an isochoric forming material model, can be avoided by the use of a less complicated damage model. Widely in use is the damage model of Johnson and Cook [4].

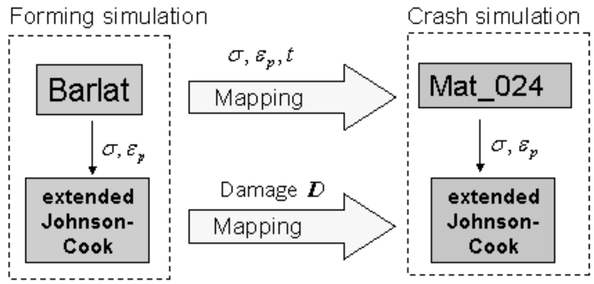

Figure 4: *Combination of Johnson-Cook criterion and Barlat model*

In its original formulation, this model shows a linear accumulation of damage D depending on the ratio of failure strain to the actual equivalent plastic strain increment.

$$D = \int \frac{d\varepsilon_e^p}{\varepsilon_f} < 1 \tag{11}$$

with

$$\varepsilon_f = \left(d_1 + d_2 \exp\left(-d_3\eta\right)\right)\left[1 + d_4 \ln\left(\frac{\dot{\varepsilon}_e^p}{\dot{\varepsilon}_0}\right)\right] \tag{12}$$

The failure strain is hereby defined as a monotonically falling function of triaxiality η.
Contrary to this, recent publications by Bao and Wierzbicki [2], Barsoum and Faleskog [3] and others are pointing to a dependence of failure strains not only on triaxiality, but also on the Lode angle, which is representing a third invariant of stress tensor. Thus making it possible to distinguish between stress states of axisymmetric nature and plane strain conditions.

4.1 Needed extensions of the Johnson-Cook criterion

For the plane stress case, the stress tensor expressed in principal stresses per definition yields one principal stress equal to zero. Due to this, the stress tensor can be uniquely described by two invariants, which implies that a description of failure strain depending on triaxiality alone is sufficient as long as plane stress conditions prevail. In automotive structures, mostly consisting of thin sheets, plane stress as an assumption is also manifested in simulations by the use of shell element discretisation. Due to this, stress states from calculations are plane per definition, except for out-of-plane shear stresses that result from some shell formulations.

4.1.1 Failure strain in plane stress conditions

Nevertheless, a failure surface for arbitrary states of stress, defined in the coordinates of triaxiality and a Lode-dependent parameter can lead to a more complex relationship between triaxiality and failure strain for the plane stress case also. Generally, a minimum in failure strain can be expected for deformation under plane strain conditions. Keeping to this, the shape of the curve of failure strain vs. triaxiality is suspected to look different from the monotonically decreasing Johnson-Cook curve. Local minima in failure strains can be expected for triaxiality values of $\eta = 0$ (shear), and $\eta = 1/\sqrt{3} \cong 0{,}58$, since these stress states fulfil plane stress as well as plane strain conditions.

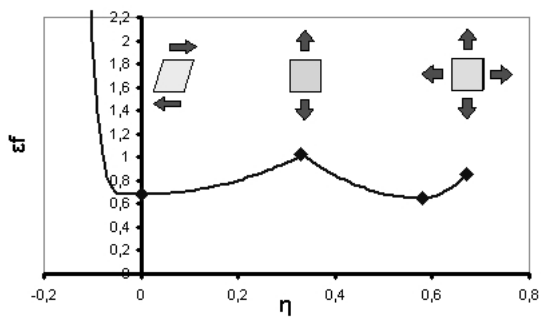

Figure 5: *Failure strain vs. triaxiality (plane stress)*

The practical implementation of this concept at Daimler is to define a curve of failure strains as a function of triaxiality η, defined on certain characteristic points that can be determined by sheet metal coupon tests. Data input is made flexible by defining a load curve of failure strain vs. triaxiality.

4.1.2 Damage accumulation

Another aspect, which is completely different in the Gurson and Johnson-Cook model, is the way of damage accumulation. Being linear in the Johnson-Cook model, it is quite similar to the well known Miner rule used for fatigue calculations. The micromechanical Gurson model on the other hand, shows a strongly nonlinear relation between the damage parameter f and increasing plastic strain ε_p, even for load cases of constant triaxiality. Resulting from the theory of void growth behaviour, simulation results mostly show good accordance to practical observations in tensile load cases. Observations on model materials, e.g. by Weck et al. [9], also show a rather exponential growth of damage or void volume with increasing plastic strain.
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 D:

$$\dot{D} = f(D,\eta) \tag{13}$$

As a simple solution satisfying this requirement, a power law function can be used:

$$D = \left(\frac{\varepsilon_p}{\varepsilon_f}\right)^n \qquad for\ \varepsilon_f = const.\ only! \tag{14}$$

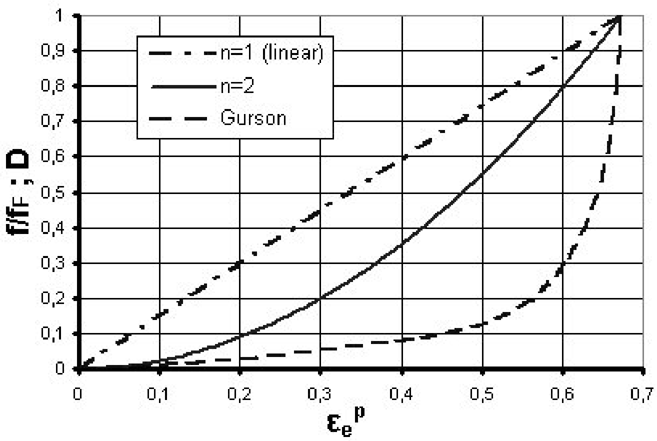

Figure 6: *Normalized damage accumulation*

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

$$\dot{D} = \frac{n}{\varepsilon_f} D^{\left(1-\frac{1}{n}\right)} \dot{\varepsilon}_p \tag{15}$$

By choosing an exponent $n = 1$, (14) is simplified to the linear Johnson-Cook criterion.
This formulation was also proposed by Xue [11], motivated by considerations on low cycle fatigue.
By implementing the extensions described above, the damage model has lost its similarity to the Johnson-Cook model, and will be called GISSMO (generalized incremental stress-state dependent damage model) from here on.

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 5 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 7). 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 7). 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.

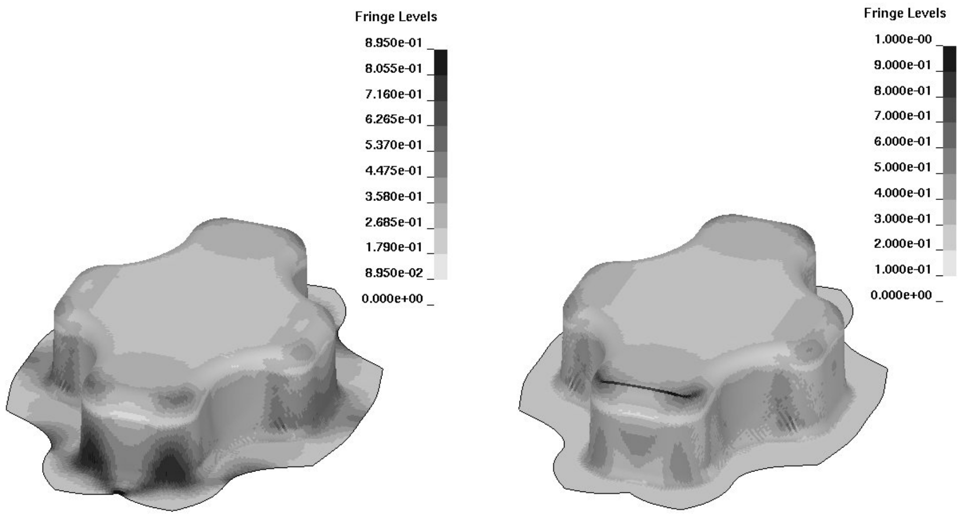

Figure 7: *Cross-die; Contours of equivalent plastic strain (left) and damage D (right)*

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.

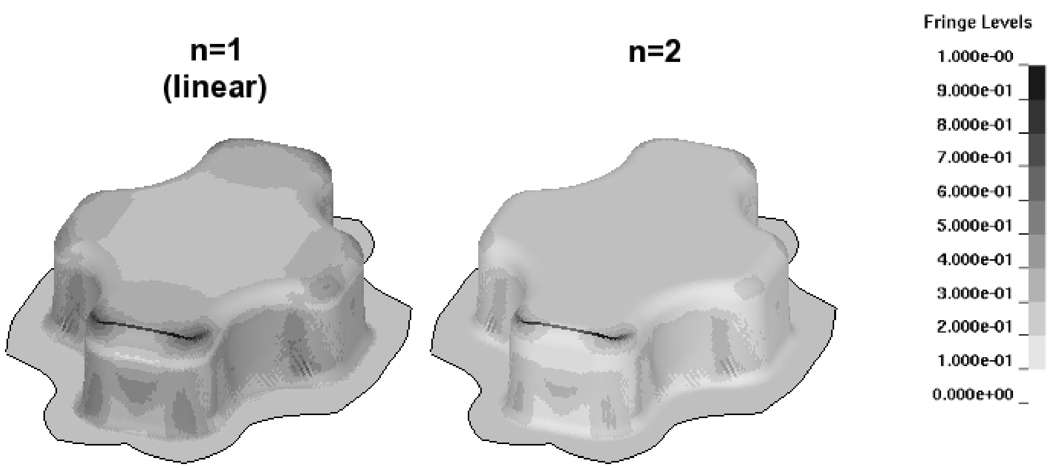

Figure 8: *Cross-die; contours of damage D*

Figure 8 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 possibilities for determination and transfer of local pre-damage data from forming to crash simulations, are promising potential to make crack prediction in crash simulations more accurate in the future. Both options proposed, for the combination of a material model for forming simulations (like Barlat89), with a crash damage model, can be improved by implementing the described extensions to the damage models. As some unintended, but very welcome "side-effect", the damage models also show a promising results in predicting ductile failure in forming simulations. The use of these damage models could therefore also lead to an improved failure prediction in forming simulations.

7. Acknowledgement

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