Considering damage history in crashworthiness simulations

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Summary:

On behalf of improvements for crashworthiness simulations, great effort has been done throughout the past years regarding the treatment of crack formation and propagation. Current state of the art here is the use of failure models that accumulate damage on an incremental basis. Most models are based on the observations of Bridgman [1], who found that failure strain in metallic materials depends on the hydrostatic pressure. Examples of models in use are the Gurson model with extensions by Tvergaard and Needleman [2], and the failure model of Johnson and Cook [3]. As a shortcoming, the mechanical properties of sheet metal parts for crashworthiness calculations are usually assumed to be as in material delivery state. This disregards the changes in properties resulting from previous treatment in the process chain of sheet metal part manufacturing, including deep-drawing. Namely, an increase in flow stress due to work hardening can be expected, which can play an important role especially for low-speed impact cases. Since plastic pre-straining also results in a reduction of the remaining strain to failure, plastic pre-damage has to be taken into account. This leads to the need of considering damage in forming simulations.
For crashworthiness calculations, the constitutive models used are usually isotropic and based on the von Mises flow rule. For forming simulations, a more sophisticated and anisotropic description of yield loci is considered important, which makes it necessary to use different constitutive models for both parts of the process chain. A damage model suitable to be used for both disciplines therefore has to be able to correctly predict damage regardless of the details of the constitutive model formulation.

In the following, the damage model GISSMO (Generalized Incremental Stress-State dependent damage MOdel), which is currently under development at Daimler will be presented. The main issues of the model are a combination of the proven features of failure description provided by damage models for crashworthiness calculations, together with an incremental formulation for the description of material instability and localization. Yet, a user-friendly and simplified input of material parameters is intended, which will be achieved by a phenomenological formulation of ductile damage. Special attention is paid to considering the point of instability or localization, as is a central issue in forming simulations. For crashworthiness simulations of ductile materials, the correct description of instability and localization can also greatly influence calculation results.
The constitutive model used in the actual working state is the anisotropic yield locus by Barlat, Lege and Brem 1991 [4], which is used to allow for a consideration of anisotropic yield loci in crashworthiness calculations also.

In general, it can be expected that stress states usually will not be the same in a forming process compared to a following crash loading. The model therefore includes not only the description of failure, but also functionality to provide an incremental and therefore path-dependent treatment of instability. This is needed to avoid a limitation of the traditional forming limit curve (FLC), which considers only the final state of deformation at the end of a forming process, and therefore does not take into account possible changes in strain path. Therefore the conventional FLC can not be used for multi-stage deformation processes, as which the two steps – forming and crash - of the sheet metal process chain can be considered.

In order to allow for the treatment of arbitrary strain paths in the prediction of localization and failure, incremental formulations were chosen for both. The concept is to independently accumulate a measure for forming intensity F, and a measure for damage D, respectively.

$$\Delta D = \frac{n}{\varepsilon_f} D^{\left(1-\frac{1}{n}\right)} \Delta\varepsilon_v \tag{1}$$

This equation represents a generalization of the well-known linear accumulation rule for damage as was proposed by Johnson and Cook [3]. In this equation, the exponent n allows for a nonlinear accumulation of damage until failure. This introduces a possibility to fit the model to data of multi-stage material tests. The actual equivalent plastic strain increment is denominated as $\Delta\varepsilon_v$.
The quantity ε_f represents the triaxiality-dependent failure strain, which is used as a weighting function in this relation. The input of this failure strain is realized as a load curve of failure strain values vs. triaxiality, which allows for an arbitrary definition of triaxiality-dependent failure strains. This is needed to ensure flexibility when used for a wide range of different metallic materials.

As soon as the forming intensity measure F reaches unity, a coupling of accumulated damage to the stress tensor using the effective stress concept proposed by Lemaitre is initiated.
When – as an input for the accumulation of forming intensity F – a curve of triaxiality-dependent material instability is used, this value represents the onset of material instability, and therefore the end of mesh–size convergence of results.
For the practical application of the model to finite element simulations with limited mesh sizes, this marks the beginning of a need for regularization of different mesh sizes. For the GISSMO model, the regularization treatment is combined with the damage model. The basic idea here is to regularize the amount of energy that is dissipated in the process of crack development and propagation. For the finite element model, this means to vary the rate of stress reduction through element fadeout.
This is achieved through a modification of Lemaitre's effective stress concept:

$$\sigma^* = \sigma \left(1 - \left(\frac{D - D_{crit}}{1 - D_{crit}}\right)^m\right) \quad for\ D \geq D_{crit} \tag{2}$$

This introduces an exponent m, which governs the rate of stress fading, and can be defined depending on the actual element size.

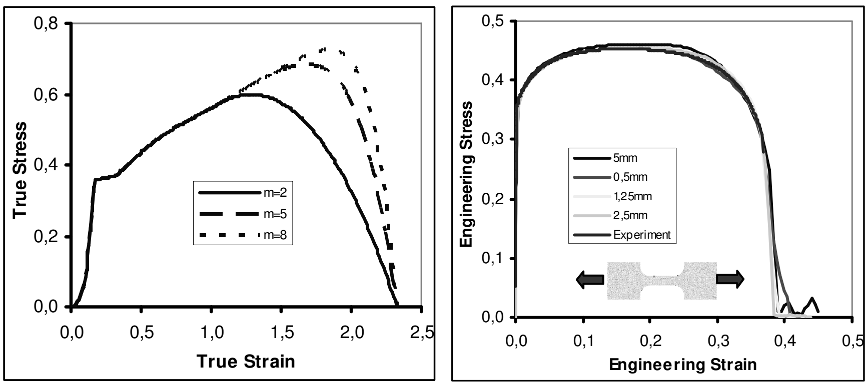

Figure 1: a.) Influence of the fading Exponent m b.) Regularization of tensile test simulations with different element sizes

Keywords:

Process Chain, Ductile Damage, Strain Path Dependent FLC

1 Path-dependent localization

In the following, the methods of treating material instability or localized deformation, as are used in the GISSMO model will be described. The basic idea is to determine the strains at localization from tests under constant stress state (proportional loading). For example, tensile tests with various notch radii, shear tests and biaxial tests can be used. The resulting forming limit curve is used as an input for the material model. This curve is used as weighting function for the path-dependent accumulation of necking intensity up to the expected point of instability.
In general, the localization behaviour of materials in numerical simulations depends on yield locus and flow stress evolution. As the direct determination of flow curves from specimen tests is not possible for the post-critical range of deformation, stress extrapolation based on assumptions is used. Due to this, and as a cause of the inherent mesh-dependency of results in the post-critical range, the used parameters of an extrapolation would determine the material properties in the post-critical range, and lead to mesh-dependent results. Therefore, a damage-based regularization for the post-critical range is used. A more comprehensive description of localization issues can be found in De Borst et al. [9].
A motivation for this treatment of instability is to determine the beginning of material softening, which is used as a damage threshold for the coupling of damage to flow stress in crashworthiness applications. This will be described further in chapter 3.

1.1 Strain and stress measures

The traditional way of treating possible instabilities in sheet metal forming processes is the comparison of resulting strains in the final stage with a fixed curve of principal strain values (Forming Limit Curve - FLC). As is well known, this forming limit curve does not take into account any changes in strain path, as it considers only the final stage of deformation.
A practical approach for a strain-path dependent forming limit determination was made by Müschenborn and Sonne [5]. They proposed a transformation of the FLC from principal strain (ε_1, ε_2) – space to a notation using the equivalent plastic strain ε_v :

$$\varepsilon_v = \frac{2}{\sqrt{3}} \sqrt{\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_1 \varepsilon_2} \tag{3}$$

The idea in treating non-proportional strain paths was to consider the FLC curve as the locus of equivalent strain to necking, depending on the respective strain state.

The usual notation for crashworthiness purposes is a characterization of load state using the invariants of the stress tensor. This is sufficient for isotropic material models, since the invariant notation is independent of the respective material direction considered.
For the plane stress case, which is an usual assumption for sheet metal problems, strain increments can be directly related to stress values. Therefore, the strain-based notation of the FLC can be transformed to a notation in invariants of the stress tensor. In crashworthiness calculations, the notation using the stress triaxiality η is common practice:

$$\eta = \frac{\sigma_m}{\sigma_v} \tag{4}$$

with σ_m (mean stress) being the first invariant of stress tensor

$$\sigma_m = \frac{\sigma_1 + \sigma_2}{3} = -p \tag{5}$$

For plane stress $(\sigma_3=0)$.
σ_v is the equivalent or von Mises stress

$$\sigma_v = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1 \sigma_2} \tag{6}$$

Using these quantities, the FLD can be directly transformed to this notation. It will be used in the following, since the GISSMO model is formulated in these quantities. Both strain- and stress-based notation are equivalent for the isotropic and plane stress case and proportional loading, therefore a determination of the necking locus could also be formulated in strain-based notation.

Using the ratio of principal strain increments

$$\rho = \frac{d\varepsilon_2}{d\varepsilon_1} \qquad (7)$$

which is equal to the ratio of principal strains if proportional loading is assumed, and the ratio of principal stresses

$$\alpha = \frac{\sigma_2}{\sigma_1} = \frac{1 + 2\rho}{2 + \rho} \qquad (8)$$

The triaxiality ratio η can be expressed as a function of the principal strain ratio:

$$\eta = \frac{\alpha + 1}{3\sqrt{\alpha^2 - \alpha + 1}} \qquad (9)$$

This relation is only valid for plane stress, isotropy and proportional loading. Similar transformations to a number of different notations can also be found in Bai and Wierzbicki [6].

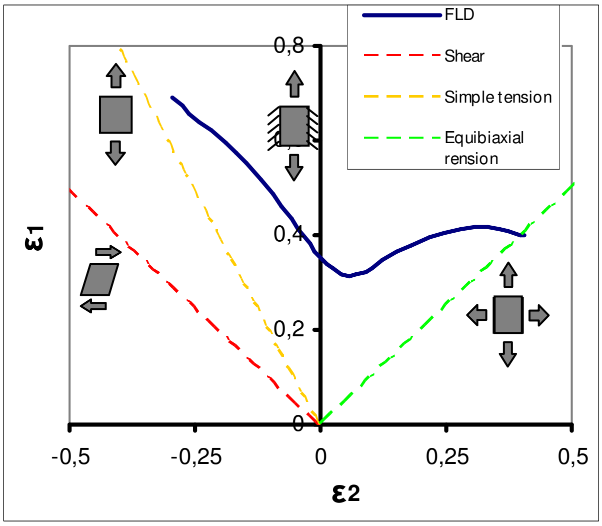

Figure 1: FLC in principal strain coordinates

Transformed to the space of equivalent plastic strain and triaxiality:

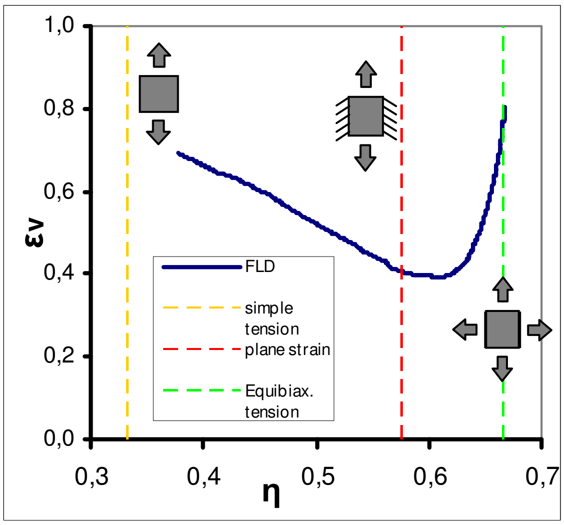

Figure 2: FLC in equivalent strain/triaxiality coordinates

The usual way would be to compare the actual value of accumulated equivalent plastic strain to the limit value for a respective triaxiality. This corresponds to using the principal strain notation, and would inherently result in the same limitations as there is no consideration of strain path changes.

1.2 Linear accumulation of the instability criterion

The implementation in the GISSMO model is therefore using the transformed FLC curve in coordinates of equivalent plastic strain and triaxiality as a weighting function for the accumulation of “Forming Intensity”, which, in this context, rather is a measure of the remaining formability.
To this purpose, the forming limit curve is introduced to the linear incremental formulation that was proposed by Johnson and Cook [3] for the linear accumulation of damage to failure:

$$\Delta F = \frac{\Delta\varepsilon_v}{\varepsilon_{v,loc}} \tag{10}$$

Where $\varepsilon_{v,loc}$ is the equivalent plastic strain to localization, defined as a function of triaxiality η – see figure 2. F is therefore accumulated linearly, while the function of equivalent plastic strain to necking represents a triaxiality-dependent weighting function. When F reaches unity, necking is expected to occur. For proportional loading as a special case, the strain to necking will be the same as predicted by the standard FLC.

1.3 Nonlinear accumulation of the instability criterion

Recent publications indicate a possible nonlinearity in the relation of damage and equivalent plastic strain, even for proportional strain paths. Weck et al. [7] performed measurements on a model material, that showed a rather exponential relation between strain and damage in form of void growth. It seems a reasonable assumption that the development of plastic strain up to necking also obeys a nonlinear relation, yet no method that would allow for a direct measurement of this quantity is known to the authors.
Despite of this, a nonlinear means of accumulation is introduced to the GISSMO model, using the same relation as for the accumulation of ductile damage to failure. An identification of parameters for this relation will hardly be possible from direct tests, rather by means of reverse engineering simulations of multi-stage forming processes. The introduction of an additional parameter n therefore makes it possible to fit the model to existing test data.
The linear accumulation (Equation 8) is replaced by

$$\Delta F = \frac{n}{\varepsilon_{v,loc}} F^{\left(1-\frac{1}{n}\right)} \Delta\varepsilon_v \tag{11}$$

introducing the accumulation Exponent

$$n \geq 1$$

For n=1, (11) reduces to the linear form (10).
For proportional loading, or – in general – constant values of $\varepsilon_{v,loc}$, (11) can be integrated to yield a relation between the “forming intensity” F and the equivalent plastic strain:

$$F = \left(\frac{\varepsilon_v}{\varepsilon_{v,loc}}\right)^n \quad for \quad \varepsilon_{v,loc} = const. \tag{12}$$

For n=1, (12) is a linear relation of current equivalent plastic strain and equivalent plastic strain to failure.

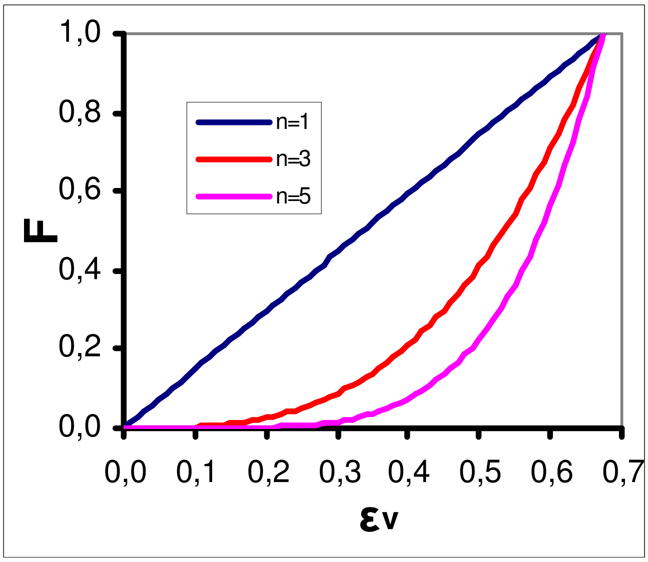

Figure 3: Nonlinear accumulation εv,loc=0,68

Using these relations, the Forming Intensity parameter F is accumulated the same way as the damage parameter D. The difference is limited to the use of a different weighting function, which is defined as a curve of limit strain depending on triaxiality for F, whereas for the failure parameter D the fracture strain as a function of triaxiality is input.

2 Post-critical behaviour

The post-critical range of deformation usually is not of interest for forming simulations, since the occurrence of instability or necking phenomena are considered as failure.

Yet, for crashworthiness purposes it is important to capture the post-critical behaviour of a material, since a maximum in energy absorption can be achieved only through a complete use of material ductility. The modelling of the post-critical behaviour of metals using the Finite Element Method always introduces an undesired mesh-size dependency on results. As soon as the instability develops, deformation reduces to a localized area and is no longer uniform. From this point on, no mesh convergence can be achieved. Through discretisation, an artificial length scale is introduced to the model, which will lead to unphysical results if no countermeasures are taken.

For the correct description of post-critical behaviour, different flow curves for each mesh size considered would have to be used, since the amount of energy that has to be dissipated in post-critical regime strongly depends on the mesh size. Instead of using this rather impractical approach, the mesh-size regularization is realized through the damage formulation. Energy regularization is done through the definition of a mesh-size dependent failure strain, and the coupling of damage to the stress tensor in post-critical deformation. The GISSMO model uses the effective stress concept, which was proposed by Lemaitre [8].

2.1 Damage-dependent flow stress

As was proposed by Lemaitre [8], damage and stress tensor are related according to the effective stress concept:

$$\sigma^* = \sigma(1 - D) \tag{13}$$

In combination with the treatment of material instability as described above, a damage threshold can be defined. As the damage parameter D reaches the damage threshold, damage and flow stress will be coupled. The current implementation allows for to either enter a damage threshold as a fixed input parameter, or to use the damage value corresponding to the instability point detected as described above. Either way, as soon as the post-critical range of deformation is reached, a value of critical damage D_{crit} is determined and used for the calculation of the effective stress tensor:

$$\sigma^{*} = \sigma \left(1 - \left(\frac{D - D_{crit}}{1 - D_{crit}} \right)^{m} \right) \qquad (14)$$

$$for \;\; D \geq D_{crit}$$

With fading exponent m, which will be further described below.

2.2 Energy dissipation and fadeout

In order to model the physical phenomena of failure, which include the formation of voids and micro-cracks, formation of a macroscopic crack, and crack propagation up to complete failure, it is necessary to take into account the amount of energy that is dissipated throughout the process. Also, for numerical reasons, it is not helping model stability to simply delete elements which are still holding considerable amounts of stress.

The strategy followed in the GISSMO model is the definition of an element-size dependent fading exponent m, see equation (14). Using this coefficient, one can directly influence the amount of energy that is dissipated during element fade-out. In figure 4, this shows as the area below the true stress-true strain curve.

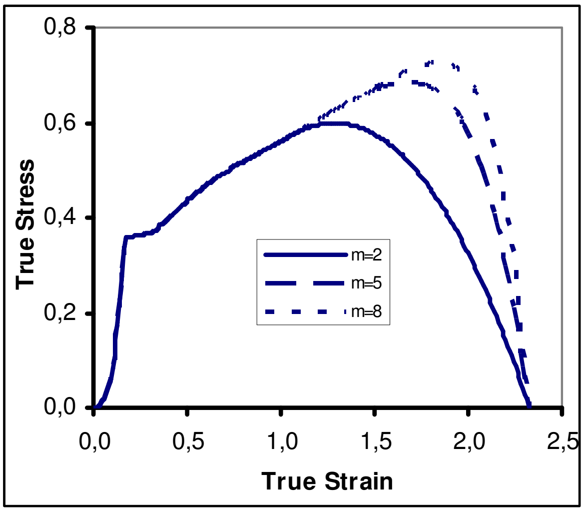

Figure 4: Influence of the fading Exponent m

This allows for a regularization not only of fracture strains, but also of the energy consumed during the post-critical deformation.

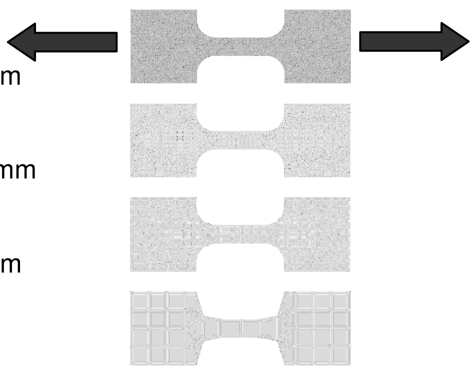

Figure 5: Different discretisations of tensile test specimen

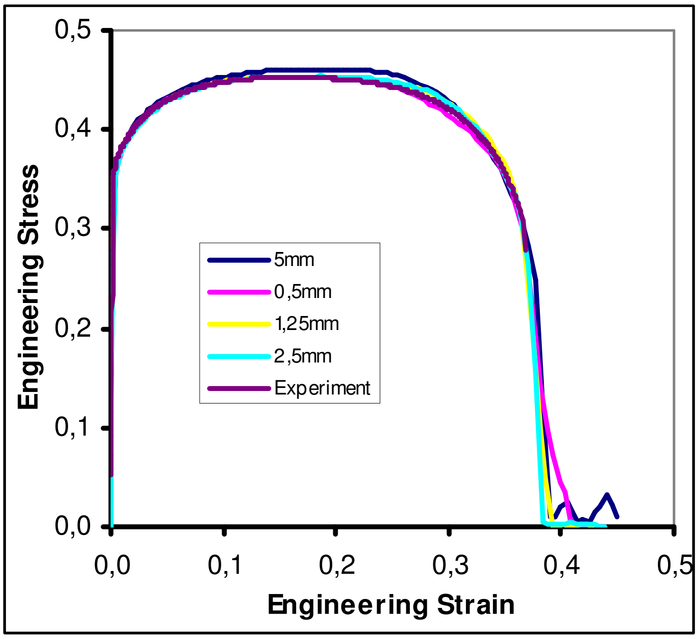

Figure 6: Simulations of tensile tests using different mesh sizes compared to experimental curve

Using this, one can achieve a reasonably good regularization of the resulting engineering stress-engineering strain curves in tensile tests with different mesh sizes, see figures 5 and 6.

3 Demonstrator part

As a demonstrator part, the well known Cross-Die is used. It provides a wide range of stress states, which allows for a proof of failure prediction in a region showing a certain stress state.
The following picture shows a simulation using example material parameters of a dual phase steel:

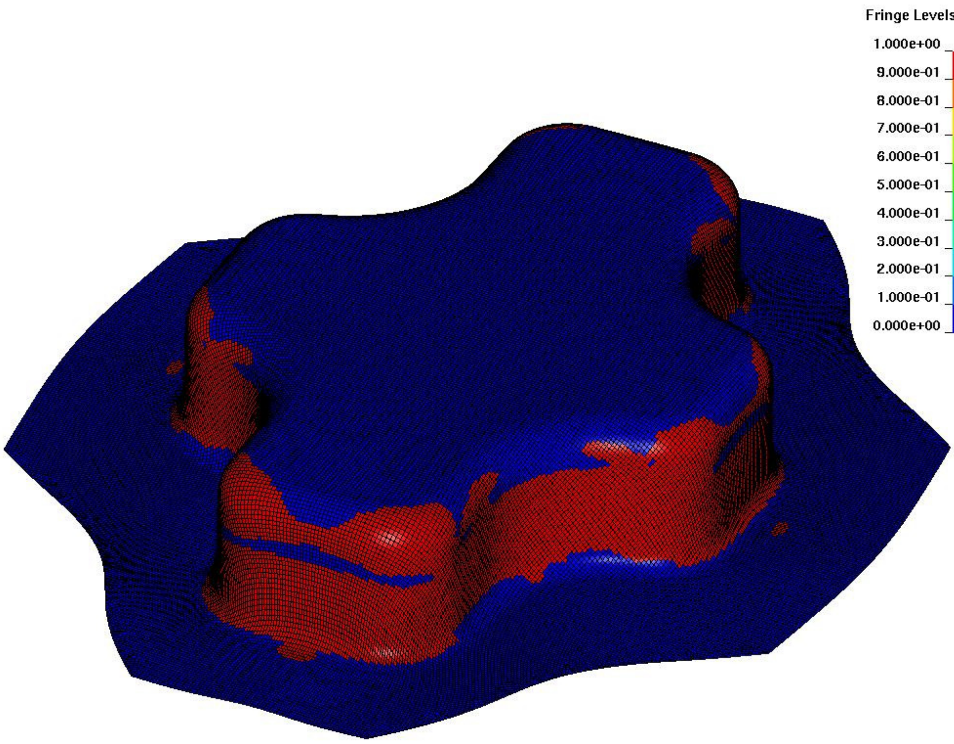

Figure 7: Contour plot showing regions with beginning localisation (F=1), drawing depth 43mm

In these regions, the coupling of damage and stress tensor according to equation (14) is used, and localization develops. This leads to rupture shortly after:

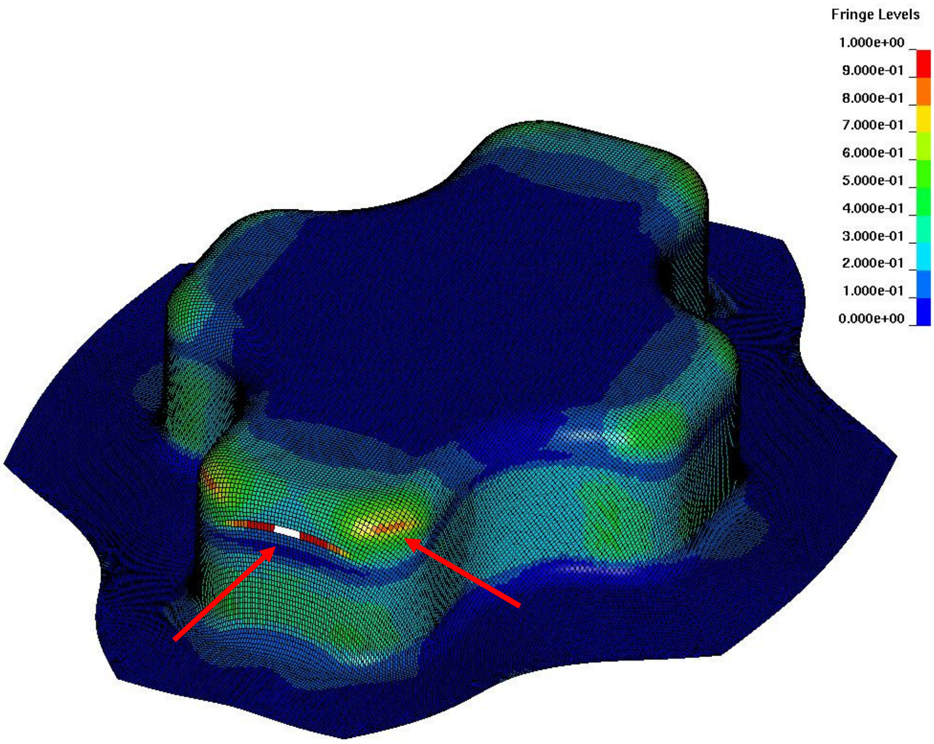

Figure 8: Contour plot of damage D at the moment of crack initiation (Arrows). Drawing depth 50mm

The regions at the edge of the specimen at which the value of the damage parameter D are close to unity can be seen. The first failed elements are deleted at the front side of the specimen.

4 Conclusions

The described working state of the GISSMO damage model as described above shows some promising potential when used for the simulation of tensile, shear and biaxial test specimen. Though phenomenological, it introduces a number of features that might be suited to describe the physics of ductile damage and failure in a variety of stress states and for different materials. Yet, limitations in predictive performance result not only from deficiencies in material modelling, but also from coarse discretization especially in crashworthiness simulations. Further research has to be done to take modelling problems resulting from limited mesh sizes into account. Further work on the model is needed in order to extend the functionality, including a visco-plastic formulation that allows for a consideration of strain-rate effects on material behaviour. Further simulations and comparison with results from deep-drawn parts will have to be conducted to proof the practical relevance of the methods described above.
Depending on the materials, a greater number of different specimen tests will be needed to identify the parameters for the damage model. Methods of numerical optimization will have to be considered in order to allow for an effective preparation of material cards.

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6 Literature

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