A COMPARATIVE STUDY OF FAILURE WITH INCREMENTAL FORMING

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Abstract. Incremental forming (ISF) is an innovative flexible sheet metal forming process which can be used to manufacture complex shapes from various materials. Due to its flexibility, it has attracted more and more attention over recent decades. Localized deformation and shear through the thickness are essential characteristics of ISF. These lead to specific failure modes and formability of ISF that are different from the conventional stamping process. In this contribution, three continuum damage models (Lemaitre, Gurson, extended GTN models) are formulated and fully coupled with the finite element simulation in a commercial software ABAQUS to predict failure in incremental forming. A comparative investigation of these three damage models has been carried out to analyze both the deformation behavior and failure mechanisms.

1. Introduction
Single point incremental forming (SPIF) is the flexible process of converting a flat sheet of metal into a desired geometry without a high cost die. Due to its advantages, it has attracted more and more attentions and has been used to produce the customized complex dimensional shape products. The sheet metal in the incremental forming process not only suffers stretching and thinning deformation mode, the transverse shear through the sheet thickness also has a great influence on the formability that is restricted by geometric instabilities due to necking and strain localization, and thus the understanding of damage development and accuracy prediction of failure is of great importance. Unfortunately, the fracture is not preceded by localized necking in incremental forming which were confirmed by M. Skjoedt and Martins [1, 2]. This implies that forming limit diagrams (FLDs) of conventional sheet metal forming are inapplicable to describe failure in SPIF. In order to model the plastic flow and fracture of these ductile structural metals, numerous failure criteria (including coupled and uncoupled damage approaches) are proposed. To account for the damage-behavior coupling, two approaches are widely used: the physically motivated approach initially developed by Gurson [3] and the phenomenological approach based on continuum damage mechanics (CDM) [4]. The CDM model takes the triaxiality into the thermodynamic damage force $Y$ when it is expressed in the stress space [4]. However, the third stress invariant is not considered. The original Gurson model introduces a strong coupling between plastic strain and damage, and the presence of micro voids in the formulation leads...
to a yield surface that depends on both the hydro-static pressure and porosity. The extended Gurson model introduced the shear effects by considering the influence of both the hydro-static pressure and Lode angle on damage evolution [5]. Although significant research efforts have been devoted to the understanding and description of the phenomenon of ductile fracture and to the formulation of constitutive models, the improper application of the models to various metal forming process may result in misleading ductile fracture predictions.

In this study, the finite element model of incremental forming fully coupled with ductile damage model are performed. The developed constitutive subroutines are implemented in the explicit scheme program. The effects of different damage models on the incremental forming have been studied.

2. Formulation of damage model

There are several damage models used to predict the failure for ductile materials. The governing equations of the constitutive models under analysis are briefly reviewed in this section.

2.1. Lemaitre damage model

The constitutive equations for ductile damage have been proposed by Lemaitre [4]. The Lemaitre damage model is a fully coupled Elasto-plasticity-damage model, which is based on a thermodynamic framework and has been extensively used in the prediction of internal damage and failure in ductile metals.

By assuming homogeneous distribution of microvoids and the hypothesis of strain equivalence, the effective stress tensor can be represented as

\[ \sigma_{\text{eff}} = \frac{\sigma}{1 - D} \]  

where \( \sigma_{\text{eff}} \) is the effective stress tensor, \( \sigma \) is the stress tensor for the undamaged material, in addition, the damage variable, \( D \).

The damage energy release rate, \(-Y\), corresponds to the variation of internal energy density which can be given by

\[ -Y = \frac{\sigma_{\text{eq}}^2}{2E(1-D)^2} \left[ \frac{2}{3} (1 + \nu) + 3 (1 - 2\nu) \left( \frac{p}{\sigma_{\text{eq}}} \right)^2 \right] \]  

For the yield function \( \Phi \), the following von-Mises type form is adopted

\[ \Phi(\sigma, \varepsilon_{\text{eq}}, D) = \frac{\sigma_{\text{eq}}}{1 - D} - \sigma_Y(\varepsilon_{\text{eq}}) \]  

2.2. GTN and modified GTN models

The Gurson-Tvergaard-Needleman (GTN) model, which is one of the most well known extensions of Gurson's model, assumes both isotropic hardening and damage. The damage variable in this model is represented by an effective porosity \( f^* \). The flow potential is generalized into the form:

\[ \Phi(\sigma, \varepsilon_{\text{eq}}, f^*) = J_2(S) - \frac{1}{3} \left\{ 1 + q_3 f^{*2} - 2q_1 f^* \cosh\left( \frac{q_2 f^*}{2\sigma_Y} \right) \right\} \sigma_Y^2 \]  

where the parameters \( q_1 \), \( q_2 \) and \( q_3 \) are the introduced material parameters.

The evolution of the porosity is given by:

\[ \dot{f} = \dot{f}^N + \dot{f}^G + \dot{f}^{\text{shear}} \]
The nucleation mechanism is driven by the plastic strain and can be represented as:

\[
\dot{f}_N = \frac{f_N}{s_N \sqrt{2\pi}} \exp\left[-\frac{1}{2} \left(\frac{\varepsilon_P - \varepsilon_{N}}{s_N}\right)^2\right] \dot{\varepsilon}_P
\]

(6)

The most significant contribution to the evolution of spherical voids is the growth mechanism, which can be expressed by:

\[
\dot{f}^G = (1 - f) \text{tr} (\dot{\varepsilon}_P) = (1 - f) \dot{\varepsilon}_P^p
\]

(7)

Under shear dominated loading conditions, the distortion of voids and inter-void linking play a critical role in the evolution of the material internal degradation. Therefore, in order to improve the GTNs model predictive ability, under both zero and low levels of stress triaxialities, Xue [5] has proposed the introduction of a shear mechanism. The rate of this shear mechanism can be mathematically expressed by:

\[
\dot{f}^{\text{shear}} = k_\omega f_\omega (\sigma) \frac{S : \dot{\varepsilon}_P}{\sigma_{eq}}
\]

(8)

3. Numerical Examples

In this section, square box application of ISF was investigated with the use of numerical treatment based on Explicit integration scheme. During the incremental forming, the tool moves along the prescribed path generated by CNC machine center to impose deformation onto a square sheet. The results obtained by performing numerical simulations with the previously described damage models, will be presented and discussed.

Figure 1: Triaxility distribution at different steps

(a) Corner Path 1  (b) Edge Path 2  (c) BackCorner Path 3  (d) BackEdge Path 4

Figure 2: The distribution of shear plastic strain through thickness
3.1. The effect of stress triaxility
In this section, four paths: corner path(1), edge path(2), back corner path(3), and back edge path(4) and four typical steps including corner feeding, and circulating deformation are selected to study the stress triaxility distribution during the incremental forming process, which can be seen in Figure 1. From there, it is clear seen that the stress triaxility changes a lot during the incremental forming. It is out of the stress triaxility range covered by the conventional sheet metal forming process. This can also been seen in Figure 2, which demonstrates the distribution of shear plastic strain through the thickness. It means that the material during the incremental forming surfer the shear stress through the thickness.

3.2. The comparison of damage prediction
Figure 3 show the damage prediction obtained from the original Gurson model, Modified GTN model with different shear effects, and Lemaitre continuum damage model. It can be seen that with the increasing damage effect, the void fraction increases. The large damage distributed around the cup corner, the failure will occurs in the near corner. Compared with GTN model, the Lemaitre model overestimates the material failure.

4. Conclusions
In this work, ductile damage models have been implemented in the explicit integration scheme by developing VUMAT subroutine. All of these damage models have been used to predict the failure of metallic sheets subjected to incremental forming. The stress triaxility varies at large ranges during incremental forming and The shear effect has a great influence on the failure prediction. Lemaitre continuum damage model overestimated the fracture depth of incremental forming material. This comparison provides an insight possibility to study incremental forming process and evaluate the influence of various processing parameters on the formability.

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