NUMERICAL PREDICTIONS OF DUCTILE FRACTURE LIMITS IN DEEP DRAWING PROCESSES

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ABSTRACT
In this work, two numerical ductile fracture criteria based on finite element (FE) simulations are proposed for the prediction of ductile fracture limits (DFLs) for sheet metals. An elastic–plastic model coupled with the Lemaitre continuum damage theory has been implemented into the ABAQUS/Explicit software to simulate simple sheet stretching tests as well as the Nakazima deep drawing tests with various sheet specimen geometries. The first numerical criterion is based on the analysis of the thickness strain concentration and damage evolution in the central part of the specimens in order to determine the occurrence of ductile fracture. The second numerical criterion relies on a damage threshold at which is associated the occurrence of ductile fracture. The DFLs thus predicted by numerical simulations of simple sheet stretching with various specimen geometries and Nakazima deep drawing tests are compared with the experimental results.

Keywords: sheet metal forming, finite element simulation, damage, ductile fracture limits.

INTRODUCTION
The formability of sheet metals is usually characterized by forming limit diagrams (FLDs) obtained by the Nakazima or Marciniak deep drawing tests. The FLD is a limiting curve that depicts the in-plane major and minor strains of the sheet at the onset of localized necking, which precedes the final fracture. However, it is still difficult to accurately determine the occurrence of strain localization through experimental procedures.

In this work, numerical ductile fracture criteria, based on finite element (FE) simulations, are proposed for the prediction of ductile fracture limit (DFL) for a steel material. The material is described by an elastic–plastic model coupled with the Lemaitre isotropic damage approach (Lemaitre, 1985).

The resulting constitutive equations have been implemented into the ABAQUS/Explicit code, within the framework of large strain and a three-dimensional formulation. Several specimen geometries have been simulated in order to reproduce all of the strain paths that are typically encountered in sheet metal forming processes.

Two different FE models are considered to predict the DFLs of the studied material. First, the DFLs are predicted using simple sheet stretching tests, based on different specimen geometries, in which no contact with tools is considered. Then, the FE model based on the Nakazima deep drawing test (Nakazima, 1968) is used to predict the DFLs of the steel material. To obtain the DFL curve of the studied material, two numerical criteria are presented in this work to detect the occurrence of the fracture of the sheet specimens. The initiation of fracture is first detected when a sudden change in the evolution of the thickness...
strain at the central area of each specimen is observed. The second numerical criterion is based on a critical damage threshold, at which is associated the occurrence of ductile fracture. All points of the DFL curve, which are obtained using the FE simulations combined with the numerical ductile fracture criteria, are compared with the experimental results taken from (Aboutalebi, 2012).

CONSTITUTIVE EQUATIONS OF THE DUCTILE DAMAGE MODEL

In this section, the elastic–plastic behavior law coupled with a ductile damage model is briefly presented. The latter is based on the continuum damage mechanics and, more specifically, on the Lemaitre isotropic damage model (Lemaitre, 1985). Using the concept of effective stress \( \bar{\sigma} \), and the strain equivalence principle, the continuum damage is introduced via the scalar variable \( d \) by the following expression:

\[
\sigma = (1-d) \bar{\sigma} = (1-d) C \varepsilon^e ,
\]

where \( \sigma \) is the Cauchy stress tensor, \( C \) is the fourth-order elasticity tensor, and \( \varepsilon^e \) is the elastic strain tensor. The plastic yield function \( f \) is written in the following form:

\[
f = \bar{\sigma}(\bar{\sigma},X) - Y \leq 0 ,
\]

where \( \bar{\sigma}(\bar{\sigma},X) = \sqrt{(\bar{\sigma}' - X):(M:(\bar{\sigma}' - X))} \) is the equivalent stress, and \( \bar{\sigma}' \) is the deviatoric part of the effective stress. The fourth-order tensor \( M \) contains the six anisotropy coefficients of the Hill quadratic yield criterion (1948). The isotropic hardening of the material is described by the size of the yield surface \( Y \), while kinematic hardening is represented by the back-stress \( X \).

The plastic flow rule is given by the normality law, which defines the plastic strain rate \( D^p \) as

\[
D^p = \lambda \frac{\partial f}{\partial \sigma} = \lambda M: (\bar{\sigma}' - X),
\]

where \( \lambda \) is the plastic multiplier, and \( \partial f / \partial \sigma \) is the flow direction, normal to the yield surface in the stress space. With a special choice of co-rotational frame, which is associated with the Jaumann objective derivative, the Cauchy stress rate is written in the following form:

\[
\dot{\sigma} = (1-d) C : (D - D^p) - \frac{\dot{d}}{1-d} \bar{\sigma} .
\]

The evolution law for the damage variable is expressed by the following equation:

\[
\dot{d} = \begin{cases} 
\frac{1}{(1-d)^\beta} \left( \frac{Y_e - Y_{ei}}{S} \right)^\gamma \dot{\lambda}, & \text{if } Y_e \geq Y_{ei}, \\
0 & \text{otherwise}
\end{cases}
\]

where \( Y_e \) is the strain energy density release rate (see, e.g., Lemaitre, 1992; Lemaitre, 2000).

The above constitutive equations are implemented into the finite element code ABAQUS/Explicit using a co-rotational frame. The fourth-order Runge–Kutta explicit time integration scheme is used to update the stress state and all internal variables.
MATERIAL PARAMETERS

The material used in the simulations is the St14 steel. The associated elastic–plastic material parameters are summarized in Table 1, according to the Ludwig isotropic hardening law defined by the following expression (see Aboutalebi, 2012):

$$\sigma_y = \sigma_0 + k (\varepsilon^{pl})^n,$$

where $\sigma_y$ is the current size of the yield surface, and $\varepsilon^{pl}$ is the equivalent plastic strain. In Eq. (6), $\sigma_0$ is the initial yield stress, while $k$ and $n$ are material constants.

<table>
<thead>
<tr>
<th>E [MPa]</th>
<th>V</th>
<th>$\sigma_0$ [MPa]</th>
<th>$k$ [MPa]</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>St14 steel</td>
<td>180000</td>
<td>0.3</td>
<td>159</td>
<td>630</td>
</tr>
</tbody>
</table>

The Lemaitre damage parameters of the studied material were identified by (Aboutalebi, 2012) using Vickers micro-hardness test on ruptured specimens and are given in Table 2.

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$s$</th>
<th>$s_i$</th>
<th>$Y_{ei}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>St14 steel</td>
<td>1</td>
<td>2.532</td>
<td>1</td>
</tr>
</tbody>
</table>

DESCRIPTION OF THE FE MODEL

In this work, the ductile fracture limit predictions of the St14 steel material are determined using the above elastic–plastic behavior model coupled with ductile damage. The numerical simulations are performed with the ABAQUS/explicit code.

Eight specimens with different geometries, as illustrated in Fig. 1, are used for the simulations. These specimens are commonly used in experiments (see, e.g., Ozturk, 2004) to characterize the formability of sheet metals. Each specimen reproduces a particular strain path, which is typically encountered in sheet metal forming processes, and these strain paths range from uniaxial tension to equibiaxial expansion.

Two ductile fracture approaches are used for predicting the DFLs of the studied material. First, simple sheet stretching simulations, based on the different specimens (see Fig. 1), are performed. Then, the simulation of the deep drawing process, according to the Nakazima test (see, e.g., Nakazima, 2008), is conducted with the considered specimen geometries.
Fig. 1 Geometry and characteristic dimensions of the notched and rectangular specimens used for the simulations.

The schematic view of the Nakazima deep drawing test is illustrated in Fig. 2. The geometric parameters used for the simulations are (ISO 12004-2, 2008):

- Punch diameter $D_p = 100$ mm;
- Initial sheet thickness $t = 0.8$ mm;
- Die radius $r_d = 9$ mm;
- Die opening diameter $D_d = 120$ mm.

Fig. 2 - Schematic view of the Nakazima deep drawing test.
Due to the symmetry of the problem, only one quarter of the geometry is discretized for each specimen. Figure 3 shows an illustration of the finite element model used for the simulation of the uniaxial tensile specimen having a width of 25 mm in the central area (corresponding to the first specimen in Fig. 1).

![Finite element model](image)

Fig. 3 - FE model used in the simulations: (a) uniaxial tensile specimen and (b) Nakazima deep drawing test applied to the sheet metal specimen.

In the critical central region of each specimen, a fine mesh with an average size of 0.4 mm is used in the sheet plane, whereas the thickness is discretized using three layers of elements. All specimens are modeled with the eight-node three-dimensional continuum finite element with incompatible modes (C3D8I), which is available in Abaqus. This element has 2×2×2 integration points, which allows modeling the sheet thickness with a total of six integration points.

The forming tools are modeled as discrete rigid bodies. The friction coefficient between the tools and the specimen is assumed to be equal to 0.05 (Aboutalebi, 2012).

**NUMERICAL RESULTS AND DISCUSSION**

The numerical predictions of the ductile fracture limits associated with the simple sheet stretching and Nakazima simulations on various specimen geometries are presented in this section. Two numerical criteria are adopted to predict the critical in-plane strains at the onset of fracture. The first criterion is based on the analysis of the evolution of the thickness strain in the central area of each specimen.

The onset of fracture is detected when a sudden change in the evolution of the thickness strain in the central area is observed. The minor and major in-plane principal strains, corresponding to the occurrence of fracture, are then reported into the DFL diagram. To illustrate this procedure, Fig. 4 shows the evolution of the thickness strain and damage variable in the central area of the specimen having a width of 25 mm, using both a simple sheet stretching
test and Nakazima’s deep drawing test. This numerical criterion is then applied to all specimens in order to obtain a complete DFL for the studied material.

The second numerical criterion is based on a critical damage threshold at which is associated the occurrence of fracture. Unlike the numerical criterion described above, a critical damage value is used here for all simulations using the various specimen geometries. This critical damage value has been identified by Aboutalebi (2011) from Vickers micro-hardness test.

Using simple sheet stretching tests and Nakazima deep drawing tests, the simulations are performed until the damage variable reaches the critical damage value of 0.434 in the central area of the specimens. At this instant, the minor and major in-plane principal strains are plotted into the DFL diagram.

Figure 5 compares the predicted DFLs of the studied material based on the simulations of both simple sheet stretching and Nakazima tests, combined with the two numerical fracture criteria. The DFLs obtained using the thickness strain analyses as numerical criterion for the occurrence of fracture are shown in Fig. 5a, while the DFLs using the critical damage threshold criterion are presented in Fig. 5b.

All DFL predictions are compared to the experimental results provided in Aboutalebi (2012). It can be noticed, in general, that the numerical predictions of the DFLs obtained by the Nakazima deep drawing tests are closer to the experimental results than those predicted by simple sheet stretching tests. More specifically, the DFLs predicted by Nakazima deep drawing tests are in reasonably good agreement with the experimental results for strain paths close to the uniaxial tensile test for both numerical criteria.

For strain paths around the plane strain loading path (minor strain close to zero), the predicted DFLs obtained by the critical damage criterion are in good agreement with experiments. For strain paths located in the range of positive biaxial stretching (i.e., neighborhood of the equibiaxial strain path), no experimental results are available in Aboutalebi (2012).
CONCLUSION

In this paper, an elastic-plastic model has been coupled with the Lemaitre ductile damage approach in order to predict ductile fracture in sheet metal forming. The whole set of coupled constitutive equations has been implemented into the finite element code ABAQUS/Explicit in the framework of large strains and a fully three-dimensional formulation. Two numerical fracture criteria have been considered for predicting the occurrence of ductile fracture in sheet metals. The first numerical criterion is based on the analysis of the thickness strain evolution during the FE simulations, while the second criterion is based on a critical damage threshold at which is associated the occurrence of ductile fracture. For the FE simulations, simple sheet stretching tests as well as Nakazima deep drawing tests on various specimen geometries, covering all possible strain paths, were used in conjunction with the numerical fracture criteria. The numerical results in terms of DFL curves were compared to the experimental results taken from Aboutalebi (2012). Good agreement between the predicted DFLs and the experiments has been obtained around the plane strain loading path in the case of the Nakazima tests combined with the critical damage threshold criterion. Due to the low cost and computational efficiency of the numerical alternative for the DFL prediction, as compared to the lengthy and expensive experimental procedures, one can conclude that the combination of finite element simulations and numerical ductile fracture criteria is a promising numerical tool in the prediction of ductile fracture in the context of sheet metal forming processes.

REFERENCES


