Simple geometries

Cooking pots
Simple geometries

Manufactured by *Deep Drawing*
More complex geometries

Planes and car prototypes
More complex geometries

Implants

Incremental-formed titanium plate
More complex geometries

Implants

Manufactured by ????
A sheet metal is deformed by a small tool.

The tool could be guided by a CNC (milling machine, robot).
Single point incremental forming
SPIF

Video
Single point incremental forming
SPIF

Advantages

- **Dieless**, with high sheet formability.
- Easy shape generation.
- For rapid prototypes, small batch productions, etc.
## Single point incremental forming

**SPIF**

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>- <strong>Dieless</strong>, with high sheet formability.</td>
<td>- Poor geometrical accuracy.</td>
</tr>
<tr>
<td>- Easy shape generation.</td>
<td>- Process slowness.</td>
</tr>
<tr>
<td>- For rapid prototypes, small batch productions, etc.</td>
<td>- Characterization of service life.</td>
</tr>
<tr>
<td></td>
<td>- <strong>The increased formability</strong>.</td>
</tr>
</tbody>
</table>
The high formability of SPIF

sine law:

\[ t_f = t_0 \sin \alpha \Rightarrow t_f \approx 0.35 \]

\[ \epsilon \gg 1.0 \]
The high formability of SPIF

Detail:

\[ t_0 = 1.0 \text{ mm} \]

\[ t_f \approx 0.25 \text{ mm} \]
The high formability of SPIF
Why formability is so high?

Forming Limit Curves

Reddy et al. [2015]
Methodology

Hypothesis

- The crack is preceded by damage.
- Damage is governed by microvoid nucleation, growth and coalescence.
- Damage is observed in SPIF [Lievers et al., 2004].
Methodology

Hypothesis

- The crack is preceded by damage.
- Damage is governed by microvoid nucleation, growth and coalescence.
- Damage is observed in SPIF [Lievers et al., 2004].

Tasks

1. Implementation of a damage model (Gurson) in the LAGAMINE FE code.
2. Identification of the material parameters of the damage model.
3. Evaluate the model to understand the process mechanics leading to fracture.
Main question

Is the Gurson model with a shear extension able to predict failure in SPIF process?
## Main question

**Is the Gurson model with a shear extension able to predict failure in SPIF process?**

## Objectives

- Efficient numerical model.
- Limitations of the **damage model** (if any).
- Reproduce the **SPIF process** mechanics.
Presentation contents
Constitutive modeling

- Elasticity

\[ \varepsilon = \frac{1}{2G_s} \sigma - \nu \frac{1}{E} \frac{1}{3} \text{tr} (\sigma) I \]
Constitutive modeling

- Elasticity
  \[ \epsilon = \frac{1}{2G_s} \sigma - \nu \frac{1}{E} \text{tr}(\sigma) I \]

- Plasticity
  - Hill [1948] yield locus
    \[ F_p = \sqrt{\frac{1}{2} (\sigma - \mathbf{X}) : \mathbb{H} : (\sigma - \mathbf{X}) - \sigma_Y (\bar{\epsilon}^P) = 0} \]
  - Isotropic hardening: Swift law
    \[ \sigma_Y (\bar{\epsilon}^P) = K \left( \bar{\epsilon}^P + \epsilon_0 \right)^n \]
  - Kinematic hardening: Armstrong and Fredrick [1966]
    \[ \dot{\mathbf{X}} = C_X \left( \mathbf{X}_{\text{sat}} \dot{\epsilon}^P - \mathbf{X} \bar{\epsilon}^P \right) \]
Constitutive modeling

- **Elasticity**

  \[
  \epsilon = \frac{1}{2G_s} \sigma - \frac{\nu}{E} \frac{1}{3} \text{tr}(\sigma)I
  \]

- **Plasticity**
  - Hill [1948] yield locus
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    F_p = \sqrt{\frac{1}{2} (\sigma - \mathbf{X}) : \mathbf{H} : (\sigma - \mathbf{X}) - \sigma_Y (\bar{\epsilon}^P)} = 0
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  - Isotropic hardening: Swift law
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    \]
  - Kinematic hardening: Armstrong and Fredrick [1966]
    \[
    \dot{\mathbf{X}} = C_X (X_{\text{sat}} \dot{\epsilon}^P - \mathbf{X} \bar{\epsilon}^P)
    \]

- **Damage ...**
The damage model

Basic hypothesis

- Material deterioration that leads to material failure.
- Associated with the evolution of micro voids.

Cross section (2000x)

Anne Mertens, ULg
The damage model

Void evolution

Base material
The damage model

Void evolution

Nucleation  Growth  Coalescence

Base material

Lassance et al. [2007]
The Gurson [1977] model

**Approach**

- Micromechanics based yield criterion.
- Damage variable: void volume fraction (porosity).

\[
F_p(\sigma, f, \sigma_Y) = \frac{\sigma_{eq}^2}{\sigma_Y^2} - 1 + 2f \cosh \left( \frac{3 \sigma_m}{2 \sigma_Y} \right) - f^2 = 0
\]
The Gurson [1977] model

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Von Mises
The Gurson [1977] model

**Approach**

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\]

Matrix mass conservation:

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

1 material parameter:

\[
f_0
\]
The Gurson-Tvergaard-Needleman (GTN) extension:

- Nucleation [Chu and Needleman, 1980].
- Void growth (classical volumetric assumption).
- Coalescence [Tvergaard and Needleman, 1984].

\[ \dot{f} = \dot{f}_{\text{nucleation}} + \dot{f}_{\text{growth}} \]
\[ F_p(\sigma, f^*, \bar{\sigma}) = \frac{\sigma^{eq}}{\bar{\sigma}^2} - 1 + 2q_1 f^* \cosh \left( -\frac{3}{2} q_2 \frac{\sigma_m}{\bar{\sigma}} \right) - q_3 (f^*)^2 = 0 \]
GTN extension
Tvergaard [1982]

\[ F_p(\sigma, f^*, \epsilon_M^P) = \frac{\sigma_{eq}^2}{\sigma_Y^2} - 1 + 2q_1 f^* \cosh \left( -\frac{3q_2 \sigma_m}{2\sigma_Y} \right) - q_3 (f^*)^2 = 0 \]

Matrix hardening:

\[ \sigma_Y = \sigma_Y(\epsilon_M^P) \]

2 material parameters:

\[ q_1, q_2 \ (q_3 = q_1^2) \]
\[ \dot{f} = \dot{f}_{\text{nucleation}} + \dot{f}_{\text{growth}} \]

\[ \dot{f}_{\text{nucleation}} = A \dot{\varepsilon}_M + B (\dot{\sigma}_{eq} + c \dot{\sigma}_M) \]

- \( \dot{\varepsilon}_M \): Strain
- \( \dot{\sigma}_{eq} \): Stress
\[ \dot{f} = \dot{f}_{\text{nucleation}} + \dot{f}_{\text{growth}} \]

\[ \dot{f}_{\text{nucleation}} = \frac{A}{\sqrt{2\pi}} f_N \exp \left[ -\frac{1}{2} \left( \frac{\epsilon_P^p - \epsilon_N}{S_N} \right)^2 \right] \]

\[ B(\sigma) = 0 \]
\[ \dot{f} = \dot{f}_{\text{nucleation}} + \dot{f}_{\text{growth}} \]

\[ \dot{f}_{\text{nucleation}} = A \dot{\epsilon}_M^P + B (\dot{\sigma}_{eq} + c \dot{\sigma}_M) \]

\[ A(\epsilon_M^P) = \frac{1}{\sqrt{2\pi}} \frac{f_N}{S_N} \exp \left[ -\frac{1}{2} \left( \frac{\epsilon_M^P - \epsilon_N}{S_N} \right)^2 \right] \]

\[ B(\sigma) = 0 \]

3 material parameters:

\[ f_N, \epsilon_N, S_N \]
Coalescence
Tvergaard and Needleman [1984]

\[
f^* = \begin{cases} 
  f & \text{if } f < f_{cr} \\
  f_{cr} + K_f (f - f_{cr}) & \text{if } f > f_{cr}
\end{cases}
\]

\[K_f = \frac{f_u - f_{cr}}{f_F - f_{cr}}\]
Coalescence
Tvergaard and Needleman [1984]

\[
f^* = \begin{cases} 
  f & \text{if } f < f_{cr} \\
  f_{cr} + K_f (f - f_{cr}) & \text{if } f > f_{cr}
\end{cases}
\]

Effective porosity \( f^* \)

\[
K_f = \frac{f_u - f_{cr}}{f_F - f_{cr}}
\]

2 material parameters:

\[
f_{cr}, f_F \left( f_u = \frac{1}{q_1} \right)
\]
Shear extensions

- Coupling of stress and damage history.
- Triaxiality: measure of the stress state.

\[ T(I_1, J_2) = \sigma_m \sigma_{eq} \quad T \to 0 = \epsilon_f \to \infty \]

[Shear extensions graph with fracture strain and T axis]

[Pineau and Pardoen, 2007]
Shear extensions

- Coupling of stress and damage history.
- Triaxiality: measure of the stress state.

\[ T(I_1, J_2) = \frac{\sigma_m}{\sigma_{eq}} \]

\[ T \to 0 \implies \epsilon_f \to \infty \]

[Pineau and Pardoen, 2007]
Shear extensions
Failure modes

Cavity controlled \((T = 1.10)\)

Shear controlled \((T = 0.47)\)

[Barsoum and Faleskog, 2007]
Shear extensions
Failure modes

Cavity controlled ($T = 1.10$)  Shear controlled ($T = 0.47$)

[Barsoum and Faleskog, 2007]

- GTN model → No damage is predicted when $T = 0$.
- At low triaxiality, void shape evolution becomes important.
Shear extensions

Nahshon and Hutchinson [2008]

\[ \dot{f} = \dot{f}_g + \dot{f}_n + \dot{f}_{\text{shear}} \]

\[ \dot{f}_{\text{shear}} = k_\omega f_\omega(\sigma) \frac{\sigma_{\text{dev}} : \dot{\epsilon}^P}{\sigma_{\text{eq}}} \]
Shear extensions

Nahshon and Hutchinson [2008]

\[ f = f_g + f_n + f_{\text{shear}} \]

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

1 material parameter: \( k_\omega \).

Note: \( \omega(\sigma) \) is a scalar functions of the stress.
Numerical implementation

- Based on Ben Bettaieb et al. [2011b,a]
- Complete GTN model:
  - Kinematic hardening (classical non-linear).
  - Nucleation and coalescence (GTN model).
  - Shear [Nahshon and Hutchinson, 2008].
Numerical implementation

- Based on Ben Bettaieb et al. [2011b,a]
- Complete GTN model:
  - Kinematic hardening (classical non-linear).
  - Nucleation and coalescence (GTN model).
  - Shear [Nahshon and Hutchinson, 2008].
  - Matrix anisotropy (Hill type) [Benzerga and Besson, 2001]:

\[
\tilde{q} = \sqrt{\frac{1}{2} \left( \sigma - X \right) : \mathbb{H} : \left( \sigma - X \right)}
\]
Integration scheme

Equations set

\[ F_p(\sigma, X, H) = 0 \]
\[ d\epsilon^P = d\lambda \frac{\partial F_p}{\partial \sigma} \]
\[ dH = h(d\epsilon^P, \sigma, H) \]
Integration scheme

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\[ F_p(\sigma, X, H) = 0 \]
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Backward Euler
Aravas [1987]

\[ \epsilon_{n+1} = \epsilon_n + \Delta t \dot{\epsilon}_{n+1} \]
\[ \Delta t = t_{n+1} - t_n \]
Integration scheme

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Ben Bettaieb et al. [2011b]

\[ \Gamma(Y) = 0 \]
\[ Y_i = \{ \Delta \epsilon_p, \Delta \epsilon_q, n_1, n_2, n_3, n_4, n_5, \epsilon^p_M, f \} \]
Integration scheme

**Equations set**

\[ F_p(\sigma, X, H) = 0 \]
\[ d\epsilon^P = d\lambda \frac{\partial F_p}{\partial \sigma} \]
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**Backward Euler**

Aravas [1987]

\[ \epsilon_{n+1} = \epsilon_n + \Delta t \dot{\epsilon}_{n+1} \]
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**N-R iteration**

**Ben Bettaieb et al. [2011b]**

\[ \Gamma(Y) = 0 \]
\[ Y_i = \{ \Delta \epsilon_p, \Delta \epsilon_q, n_1, n_2, n_3, n_4, n_5, \epsilon^P_M, f \} \]
### Numerical validation

**Hydrostatic test** Nahshon and Xue [2009]

<table>
<thead>
<tr>
<th>Gurson parameters</th>
<th>$q_1$</th>
<th>$q_2$</th>
<th>$q_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_N$</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$f_0$</td>
<td>0.04</td>
<td>0.30</td>
<td>0.10</td>
</tr>
<tr>
<td>$f_f$</td>
<td>0.005</td>
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Numerical validation
Hydrostatic test Nahshon and Xue [2009]

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<td>0.25</td>
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</tbody>
</table>

Volumetric strain \([-\]

Hydrostatic stress ratio \([-\]

Void volume fraction \([-\]

Volumetric strain \([-\]

GUR3Dext
Nahshon 2009

GUR3Dext
Nahshon 2009
Numerical validation
Shear test Nahshon and Xue [2009]

![Diagram of a cube with arrows indicating shear test direction]

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Numerical validation
Shear test Nahshon and Xue [2009]

Gurson parameters

<table>
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<tr>
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<th>value</th>
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<td>0.10</td>
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<tr>
<td>$f_f$</td>
<td>0.25</td>
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</table>

Equivalent strain $[-]$

Equivalent stress ratio $[-]$

Void volume fraction $[-]$

GUR3Dext
Nahshon2009

0 2.0

0 2.0

0 2.5
- DC01 ferritic steel (EN 10330).
- 1.0 mm thickness.

**Microstructure:**

![Microstructure Image]

<table>
<thead>
<tr>
<th>Mn</th>
<th>C</th>
<th>Al</th>
<th>Ni, Cu, Cr, P</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.21</td>
<td>0.049</td>
<td>0.029</td>
<td>&lt;0.025</td>
</tr>
</tbody>
</table>

Anne Mertens, ULg
Experimental setup

Uniaxial Zwick machine

Load capacity: ±100 kN

Bi-axial machine
Digital Image Correlation (DIC)

- Contactless method for displacements and strains.
- Pattern tracking.

CMOS cameras, resolution 1280x800
Experimental test campaign

Specimens

Tensile

Shear

Plane strain
Plasticity tests

Tensile and shear test

Stress [MPa]

500

0

0

Strain [-]

0.5

Tensile

45

RD,TD

Shear

36
Plasticity tests

Tensile and shear test

Stress [MPa]

-300
0
300

Strain [-]

0
0.5

Stress [MPa]

500

Precharge degree

10%
20%
30%

Strain [-]

0

0.4

RD,TD

45

Tensile

Shear

Bauschinger test

36
Plasticity tests

**Tensile and shear test**

Stress [MPa]

Strain [-]

**Bauschinger test**

Stress [MPa]

Strain [-]
Identification of material parameters

- Hardening ($K, n, \epsilon_0, C_x, X_{sat}$) → Inverse optimization (OPTIM).

\[
\text{error norm} = \sqrt{\sum_{i=1}^{N} (y_i^{FE} - y_i^{exp})^2}
\]
Identification of material parameters

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Identification of material parameters

Tensile test

Stress [MPa]

Exp
num

10%
30%

Exp
num

Strain [−]

Bauschinger test

Strain [−]

-300
0
300

Stress [MPa]

Exp
num

10%
30%

Exp
num
Identification of material parameters

Tensile test

Stress [MPa]

Strain [-]

Bauschinger test

Stress [MPa]

Strain [-]
<table>
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<tr>
<th>Difference with plasticity</th>
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<tr>
<td>- Microscopic scale,</td>
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<td>- Force vs. displacement instead of stress vs. strain.</td>
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<td>- Coupling between variables.</td>
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GTN characterization
Methodology

Difference with plasticity

- Microscopic scale, heterogeneous deformation.
- Force vs. displacement instead of stress vs. strain.
- Coupling between variables.
## GTN parameters characterization

### Automatic optimization (OPTIM) issues

- CPU time, iterations, etc.
- Sensitivity of nucleation, coalescence parameters.
- Introduction of weights in the error norm.
GTN parameters characterization

Automatic optimization (OPTIM) issues

- CPU time, iterations, etc.
- Sensitivity of nucleation, coalescence parameters.
- Introduction of weights in the error norm.

Approach:

Displacement

Force

Plasticity

Nucleation

Coalescence

LAGAMINE

OPTIM

\( d_1 \) \hspace{1cm} \( d_2 \)

Displacement
Macroscopic test campaign

\[ R = 5 \]
\[ T \approx 0.6-0.7 \]
\[ \omega \approx 0.25-0.4 \]

\[ R = 10 \]
\[ T \approx 0.5-0.7 \]
\[ \omega \approx 0.2-0.4 \]

\[ \text{hole} \]
\[ T \approx 0.35-0.6 \]
\[ \omega \approx 0.0 \]

\[ \text{shear} \]
\[ T \approx 0.0 \]
\[ \omega \approx 1.0 \]
# Force predictions

<table>
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<tr>
<th>Set name</th>
<th>$f_0$</th>
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<th>$S_N$</th>
<th>$f_c$</th>
<th>$f_F$</th>
<th>$k_\omega$</th>
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<tr>
<td>set1</td>
<td>0.0008</td>
<td>0.0025</td>
<td>0.175</td>
<td>0.42</td>
<td>0.0055</td>
<td>0.135</td>
<td>0.25</td>
</tr>
<tr>
<td>set2</td>
<td>0.0008</td>
<td>0.0025</td>
<td>0.175</td>
<td>0.42</td>
<td>0.0045</td>
<td>0.145</td>
<td>0.25</td>
</tr>
<tr>
<td>set3</td>
<td>0.0008</td>
<td>0.0025</td>
<td>0.175</td>
<td>0.42</td>
<td>0.0025</td>
<td>0.170</td>
<td>0.075</td>
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## Force predictions

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### Graph

- Force vs. Displacement
- **R=5**
- **R=10**
- **hole**

![Graph showing force vs. displacement for different sets and radii](image-url)
## Force predictions

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<td>0.0025</td>
<td>0.175</td>
<td>0.42</td>
<td>0.0045</td>
<td>0.145</td>
<td>0.25</td>
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<tr>
<td>set3</td>
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<td>0.170</td>
<td>0.075</td>
<td></td>
<td>0.0025</td>
<td>0.170</td>
<td>0.075</td>
</tr>
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</table>

### Diagrams

- **Left diagram:**
  - Force [N] vs. Displacement [mm]
  - R = 5 and R = 10 curves
  - Hole markers

- **Right diagram:**
  - Force [N] vs. Displacement [mm]
  - Shear markers
Strain prediction

Strain localization is not captured
Strain prediction

Shear strain [-]

Displacement [mm]

shear
DIC vs. FE predictions
Axial strain

notch $R = 5$

notch $R = 10$
DIC vs. FE predictions

Axial strain

DIC

Numerical

hole

shear

0.60
0.00
0.10
−0.25
## Discussion

### Results
- Loss on load carrying capacity is captured.
- Strain localization is not captured.
- Limitations of the GTN model.

### Source of errors
- Parameters $q_1$ and $q_2$ were not calibrated.
- Hardening stagnation.
- Mesh sensitivity.
Simulate SPIF is not easy

- Small contact zone with a very long path.
- High strains.
- Incremental deformation, simulation time.
- Sensitivity of force prediction to FE choice, constitutive law.
- Boundary conditions, grip modeling.
- Springback, bending.
- Elastic strains.
Forming Limit Curve (FLC): classic approach.

Through the thickness shear, Bending-under-tension, cyclic effects, etc.
Definition

Mechanism of degradation leading to fracture (Damage $\neq$ formability)
**Definition**

*Mechanism of degradation leading to fracture* (Damage $\neq$ formability)

Malhotra et al. [2012].

- Shear itself cannot explain higher formability:
- Early localization: Noodle theory.
Finite element type

Shell

Solid-shell

Brick

RESS solid-shell element [Alves de Sousa, 2006].

Numerical technique: Enhanced assumed strain (EAS)

\[ \epsilon = \epsilon_{\text{com}} + \epsilon_{\text{EAS}} \]
Finite element type

- RESS solid-shell element [Alves de Sousa, 2006].
- Numerical technique: Enhanced assumed strain (EAS)

\[ \epsilon = \epsilon^{\text{com}} + \epsilon^{\text{EAS}} \]
- Most basic SPIF test.
- Experimental data by Hans Vanhove (KULeuven).
Shape: top and bottom surface

- $X \ [\text{mm}]$
- $Z \ [\text{mm}]$

Exp
GTN+shear

Cross section

- $x$
- $y$
Numerical-Experimental validation

Shape: top and bottom surface

- X [mm]
- Z [mm]

- Force
- Ref. Time [s]

- Exp
- GTN+shear
Two-slope pyramid

Description

- For shape accuracy assessment.
- Experimental DIC shape by Amar Behera (KULeuven).
Numerical predictions

Experimentally there is no crack!

Shape: bottom surface

\[ Z \text{ [mm]} \]

\[ X \text{ [mm]} \]

\[ \begin{array}{c}
\text{exp} \\
\text{num}
\end{array} \]

cross section
Numerical predictions
Experimentally there is no crack!

- Shape: bottom surface

- Forces: no experiments available

With coalescence, the model predicts fracture... prematurely
Benchmark for failure angles.

- DC01, 1.0 mm $\Rightarrow \alpha = 67^\circ$

DC01 steel, 1.0 mm $\Rightarrow$ failure angle: $67^\circ$
Numerical predictions

The crack is predicted at $\alpha = 48^\circ$
Numerical predictions

The crack is predicted at $\alpha = 48^\circ$

Aerens et al. [2009] formula:

$$F_{z_s} = 0.0716 R_m t^{1.57} d_t^{0.41} \Delta h^{0.09}$$

... $(\alpha - d\alpha) \cos(\alpha - d\alpha)$

$\alpha = 47^\circ \quad 1219.70 \text{ N}$

$\alpha = 48^\circ \quad 1222.49 \text{ N}$

$\alpha = 67^\circ \quad 1158.01 \text{ N}$
Analysis of fracture prediction

1 Predicted force overestimation.
2 Bad modeling of the deformation.
3 Limitations of the GTN model.
Analysis of fracture prediction

1. Predicted force overestimation.
2. Bad modeling of the deformation.
3. Limitations of the GTN model.

Porosity for the $47^\circ$ cone

Porosity for the $48^\circ$ cone

$\epsilon_f \approx 0.8$
Conclusions

Contributions

- Fully implicit implementation of the GTN+shear model.
- Extensive experimental data and material identification.
- Good shape prediction in SPIF (FE element type).

Issues

- The chosen damage model is capable to predict failure in the SPIF process but not accurately.
- GTN model uncouples the hardening and damage.
- Force prediction in SPIF.
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Perspectives

- Modification of the hardening in the GTN model [Leblond et al., 1995].
- Implement different type of damage model [Lemaitre, 1985; Xue, 2007].
- Effect of hardening stagnation on damage.
Perspectives

- Modification of the hardening in the GTN model [Leblond et al., 1995].
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- Effect of hardening stagnation on damage.

SPIF

- Remeshing + Damage in LAGAMINE.
- Different EAS modes solid-shell.
Experimental and Numerical Characterization of Damage and Application to Incremental Forming

PhD thesis presentation

Carlos Felipe Guzmán

Department ArGEnCo
University of Liège, Belgium

February 1st, 2016
Incomplete pole figures:

(110)  (200)  (211)

Philip Eyckens, KULeuven
Shear extensions

\[ f^* \rightarrow D \]

\[ \dot{D} = K_f \left( q_1 \dot{f} + \dot{D}_{\text{shear}} \right) \]

\[ \dot{D}_{\text{shear}} = k_g f^{1/3} g_\theta(\sigma) \varepsilon_{eq} \dot{\varepsilon}_{eq} \]

Xue [2008]

Note: \( g_\theta(\sigma) \) and \( \omega(\sigma) \) are scalar functions of the stress.
Shear extensions

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<td>[ f^* \rightarrow D ]</td>
<td>[ \dot{f} = \dot{f}_g + \dot{f}<em>n + \dot{f}</em>{\text{shear}} ]</td>
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1 material parameter: \( k_g \) or \( k_\omega \).

Note: \( g_{\theta}(\sigma) \) and \( \omega(\sigma) \) are scalar functions of the stress.
Integration scheme
Consistent tangent matrix, algorithm approach

\[ \sigma = \sigma(\epsilon) \]

\[ d\sigma = D : d\epsilon \quad ; \quad D := \frac{\partial \sigma}{\partial \epsilon} \]
Integration scheme
Consistent tangent matrix, algorithm approach

\[ \sigma = \sigma(\epsilon) \]

\[ d\sigma = D : d\epsilon \ ; \quad D := \frac{\partial \sigma}{\partial \epsilon} \]

\[ \sigma_{n+1} = C : (\epsilon_{n+1} - \epsilon_{n+1}^P) \]

\[ d\sigma = C : d\epsilon - C : d\Delta \epsilon^P \]

Linearization

Relate \( d\epsilon \) with \( d\Delta \epsilon^P \)
Integration scheme
Consistent tangent matrix, algorithm approach

\[ \sigma = \sigma(\epsilon) \]

\[ d\sigma = D : d\epsilon \ ; \quad D := \frac{\partial \sigma}{\partial \epsilon} \]

\[ K : \partial \Delta \epsilon^P = L : \partial \sigma \]

\[ D = C - C(K + LC)^{-1}LC \]

\[ \frac{\partial F_p}{\partial \sigma}, \frac{\partial F_p}{\partial \Delta \epsilon^P}, \frac{\partial F_p}{\partial H_\beta}, \frac{\partial^2 F_p}{\partial \sigma^2}, \frac{\partial \sigma \partial \Delta \epsilon^P}{\partial \sigma}, \ldots \]

Kim and Gao [2005] approach

Extension to Kinematic hardening
Numerical validation
Hydrostatic test, Aravas [1987]

Elasto-plastic parameters

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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<tr>
<td>$E$</td>
<td>210 GPa</td>
<td></td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.3</td>
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<tr>
<td>$K$</td>
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Gurson parameters

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Hydrostatic stress ratio $[-]$

Void volume fraction $[-]$

Volumetric strain $[-]$
Tensile test
Aravas [1987]

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Numerical validation
Shear test Xue [2008]

Gurson parameters

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Matrix plastic strain $[-]$ 500
Equivalent stress [MPa]

$\kappa g = 0$
$\kappa g = 0.25$
$\kappa g = 3$ GUR3Dext
Xue2008

Damage $[-]$ 70
Numerical validation
Shear test Xue [2008]

Gurson parameters

\[
\begin{array}{c|c|c|c}
q_1 & 1.5 & f_N & 0.04 \\
q_2 & 1.0 & \epsilon_N & 0.20 \\
q_3 & 2.25 & S_N & 0.10 \\n\end{array}
\]

Matrix plastic strain [-]

Equivalent stress [MPa]

0 4.0

Damage [-]

0 1.2

Matrix plastic strain [-]
State variables analysis
State variables analysis

\[ \text{Porosity } [-] \]

- elem=118
- elem=404
- elem=690

Indent 1

Indent 2

Ref. Time [s]

0 0.2 0.8 1.0 1.8

f_0
SPIF line test
State variables analysis

Triaxiality $[-]$
SPIF line test
State variables analysis

Triaxiality $[-]$

Hyd. strain $[-]$

Ref. Time [s]

0 0.2 0.8 1.0 1.8

Ref. Time [s]

0 0.2 0.8 1.0 1.8

elem=118
elem=404
elem=690

$6 \cdot 10^{-4}$

$1.2 \cdot 10^{-3}$

$72$
SPIF Two-slope pyramid
Mesh and boundary conditions

\[(u_x)_O = -(u_x)_P\]
\[(u_y)_O = -(u_y)_P\]
\[(u_z)_O = (u_z)_P\]
SPIF Two-slope pyramid
Numerical predictions

Porosity $f$
SPIF Two-slope pyramid
Numerical predictions

Porosity $f$

Eq. macro. strain $\epsilon_q$
Cone test
Mesh and boundary conditions


