Study of the frictional contact conditions in the hole expansion test

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**Introduction**

**Advanced High Strength Steels (AHSS)**

- Increasing use in the **automotive industry** over the past 20 years
- Good combination of **high strength** and **large elongation** (DP, TRIP, TWIP, etc)
- Improve strength and reduce weight of automotive bodies for **safety** and **fuel efficiency**

![Volvo XC40](image-url)
Introduction

Forming Limit Diagram (FLD)

- Predict a **success or failure** of real sheet forming processes
- High **accuracy** only for **low grade steel sheets**
Introduction

Edge cracking

- **Edge cracking** occurring during the stretch-flanging process of AHSS cannot be accurately predicted by the FLD

- The **AHSS edge cracking** resistance is commonly evaluated by the Hole expansion test
Introduction

Hole expansion test

- The sheet specimen contains a central hole and the tools are axisymmetric.
- The hole expansion ratio (hole edge crack) defines the edge cracking resistance.

Cylindrical punch  $\leftrightarrow$ Fractured specimen  $\rightarrow$ Conical punch
Hole expansion test

Influence of the process conditions on the hole expansion ratio

- The cut edge conditions in the hole (punched, water-jet, EDM)
- The friction conditions in contact area (interface punch–specimen)

Objective: numerical analysis of the frictional contact conditions in the hole expansion test
Hole expansion test

Test conditions from the Benchmark 1: Hole expansion of a high strength steel sheet

- Dual Phase steel (DP980) sheet with 1.2 mm of thickness
- Central hole with 30 mm of diameter
- Periphery of the blank is clamped using a draw-bead (force about 800 kN)

Geometry of the forming tools and specimen used in the hole expansion test
Hole expansion test

Finite element model

- **DD3IMP** in-house finite element code (implicit time integration)
- **1/4 of the model** (symmetry conditions)
- Forming tools are assumed **rigid**
- Plastic behavior of the specimen modelled by the **Swift law** (isotropic work hardening) and the **Hill’48 yield criterion**

\[
\sigma = 1520.5 (0.00021 + e^p)^{0.1201}
\]

\[
\begin{align*}
F &= 0.426; \\
G &= 0.591; \\
H &= 0.408; \\
N &= 1.577
\end{align*}
\]
**Hole expansion test**

**Finite element model**
- Forming tools discretized by Nagata patches
- Blank discretized by **linear** hexahedral (8-nodes) finite elements

- 64,800 finite elements
- 2736 patches
- 2526 patches
- 3 layers of finite elements in the thickness direction
- 100 finite elements in the circumferential direction

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Hole expansion test

Finite element model

- The **Coulomb friction law** is adopted
- Lubricated punch–blank interface
  - 4 **constant** values of friction coefficient
  - **Pressure-dependent** friction coefficient
- Experimental data from *Gil et al (2016)*
  - Strip drawing test
- **No lubricant** on the interfaces between the blank and the upper/lower dies ($\mu=0.15$)

![Friction coefficient vs Contact pressure graph](image.png)

- **Exp. data (DP780)**
- **Friction model**: $\mu = 0.098 + 0.154 \exp(-1.085 p^{0.32})$
  - $\mu = 0.15$
  - $\mu = 0.10$
  - $\mu = 0.05$
  - $\mu = 0.00$

Finite element model

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Hole expansion test

Finite element model

- Inclusion of a **layer of Teflon** (0.3 mm thick) between the blank and the punch head
  - **No sliding** between the blank and the Teflon
  - **No friction** between the Teflon and the punch

- Teflon is assumed **elastoplastic**
  - $E=600$ MPa and $\nu=0.4$
  - $\sigma=46.8(0.014+\varepsilon^p)^{0.43}$
Overview of the hole expansion test simulation

Equivalent stress distribution
Results and discussion

Punch force evolution

- The predicted punch force **increases** with the friction coefficient
- The pressure-dependent friction coefficient provides results identical to $\mu=0.15$
  - Very high contact pressure at the punch head
- **Negligible influence** of Teflon layer on the predicted force evolution

![Graph showing punch force evolution vs punch displacement and contact pressure]

- $\mu=0.00$ (Teflon)
- $\mu=0.00$
- $\mu=0.05$
- $\mu=0.10$
- $\mu=0.15$
- $\mu=f(p)$

Contact pressure [MPa]

- 350
- 311
- 272
- 233
- 194
- 156
- 117
- 78
- 39
- 0

Punch force [kN]

- 180
- 160
- 140
- 120
- 100
- 80
- 60
- 40
- 20
- 0

Punch displacement [mm]

- 0
- 3
- 6
- 9
- 12
- 15
- 18
- 21

5 mm of punch displacement

15 mm of punch displacement
Results and discussion

**Hole diameter**

- The predicted hole diameter decreases with the friction coefficient
  - Low sliding between blank and punch head due to the high friction forces
- The holes are not circular and the shape is affected by the plastic anisotropy
  - Hole diameter slightly larger around the diagonal direction

![Graph showing exponential growth of the hole diameter](image1.png)

![Graph showing hole diameter vs punch displacement](image2.png)

15 mm of punch displacement
Results and discussion

Thickness evolution

- Thickness reduction **similar for both points** on the hole edge
- More pronounced under **frictionless contact** conditions
- Slight increase due to the **localized necking** near the diagonal direction

![Graphs showing thickness evolution](image)
Results and discussion

Thickness distribution

- Thickness distribution evaluated in the 3 different directions (RD, DD and TD)
  - Significantly lower along the DD and similar distributions along RD and TD
- The inclusion of friction leads to a global decrease of the thickness strain in the flat region of the blank

![Graph with thickness distribution](image1)

<table>
<thead>
<tr>
<th>Initial radial coordinate [mm]</th>
<th>Thickness [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RD (μ=0.00)</td>
<td>1.08</td>
</tr>
<tr>
<td>DD (μ=0.00)</td>
<td></td>
</tr>
<tr>
<td>TD (μ=0.00)</td>
<td></td>
</tr>
<tr>
<td>RD (μ=0.15)</td>
<td></td>
</tr>
<tr>
<td>DD (μ=0.15)</td>
<td></td>
</tr>
<tr>
<td>TD (μ=0.15)</td>
<td></td>
</tr>
</tbody>
</table>

15 mm of punch displacement (before necking)

![Graph with thickness distribution](image2)

19 mm of punch displacement (after necking)
Results and discussion

Thickness distribution after necking (19 mm of punch displacement)

- The **onset of necking** occurs always in the **same localization** but the instant for which it arises depends on the friction coefficient (friction postpones)

\[
\mu = 0.00 \text{ (Teflon)}
\]

\[
\mu = 0.10
\]

\[
\mu = 0.15
\]

\[
\mu = 0.00
\]

\[
\mu = 0.05
\]

\[
\mu = f(p)
\]
Conclusions

- Numerical study of the frictional contact conditions between the blank and the punch head in the hole expansion test
- Coulomb friction law comprising both constant and the pressure-dependent friction coefficients
- Results obtained with the pressure-dependent friction coefficient identical to the ones obtained considering a constant friction coefficient (evaluated at large contact pressure)
- Both the punch force and the hole diameter evolutions are only slightly affected by the friction coefficient
- Necking localization (near the diagonal direction) is independent of the friction coefficient
- Increasing the friction coefficient leads to a global decrease of the thickness strain in the flat region of the blank, postponing the onset of necking
Acknowledgements

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Thank you for your attention!