Deep Drawing, Formability

Deep drawing
Deep drawing of metal sheet is used to form containers

A flat blank is formed into a cup by forcing a punch against the center portion of a blank that rests on the die ring

Tooling: punch, blankholder ring, blank, die ring
Redrawing

Final shape of a container can be reached by more drawing steps, these operations are called as redrawings
Combined drawings

More drawing operations can be combined into one tool using multiple ram system in a hydraulic press
Other characteristics of deep drawing

• Easiest way is to draw cylindrical parts from circle disc, but…
• The process is capable of forming box (rectangular) shapes or shell-like containers
• Special variants are liquid pressure forming and rubber die forming
• These processes result in near net shapes for many purposes.
Deep drawing ratio

- Limiting Drawing Ratio (LDR) –
  \[ \beta = \frac{D_o}{d_n} \]
- where \( D_o \) is the diameter of the first (largest) blank and \( d_n \) is the smallest cup diameter that can be successfully drawn
- Drawing Ratio in general:
  \[ \beta_i = \frac{d_i}{d_{i+1}} \]
- First drawing \( \beta_1 = 2,2 \ldots 1,8 \)
  redrawing \( \beta_i = 1,4 \ldots 1,1 \)
(copper, aluminium, mild steel)
Calculation of blank diameter

- In case of cup-like components the blank is circular
- Area of blank equal to the area of cup:

\[ \frac{D_0^2 \pi}{4} = \frac{d_1^2 \pi}{4} + d_1 \pi h \]

\[ D_0 = \sqrt{d_1^2 + 4d_1h} \]
Calculation of drawing force

Drawing force: \[ F_{d,\text{max}} = n \pi d t UTS \]

Example:
Cup diameter: \( d = 45,7 \text{ mm} \)
Sheet thickness: \( t = 0,5 \text{ mm} \)
Ultimate Tensile Strength: \( UTS = 320 \text{ MPa} \)
Drawing coefficient: \( n = 0,7 \ldots 0,95 \)

\[ F_{d,\text{max}} = 0,9 \pi 45,7 \times 0,5 \times 320 = 20 \, 674 \, \text{N} \]
Drawing tool

Bélyeg
punch

Ráncgátló
blankholder

Munkadarab
alakítás
közbeni
állapotban

workpiece

Húzógyűrű
Die ring
Drawing errors (1)

Earing

Stress corrosion cracks

Other errors:
  Buckling and wrinkling
  Fracturing
Drawing errors (2)

Buckling and wrinkling, causing fracturing
Drawing errors (3)

Fracturing
Deep Drawing

Example
Analysis of a cup drawing

• The cup to be drawn:
  – Diameter: 60,3 mm
  – Height: 104,8 mm

• Blank diameter (earing is eliminated):

\[
D_0 = \sqrt{d_n^2 + 4d_n h_n}
\]

\[
D_0 = \sqrt{60,3^2 + 4 \cdot 60,3 \cdot 104,8}
\]

\[
D_0 = 170,1 \text{ mm}
\]
Calculation of drawing ratio

- Suggested drawing ratio
  - First drawing ~2
  - Second drawing 1,2…1,25
  - Third drawing 1,15…1,18
  - Further drawings 1,1…1,12 etc.

- Calculations by approximative (iterative) way
## Results

<table>
<thead>
<tr>
<th>Nr. of operations</th>
<th>Height in mm</th>
<th>Diameter in mm</th>
<th>Drawing ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0. blank</td>
<td>-</td>
<td>170.1</td>
<td>-</td>
</tr>
<tr>
<td>1. Cup drawing</td>
<td>65.1</td>
<td>85.7</td>
<td>1.98</td>
</tr>
<tr>
<td>2. Redrawing</td>
<td>85.7</td>
<td>69.9</td>
<td>1.23</td>
</tr>
<tr>
<td>3. Redrawing</td>
<td>104.8</td>
<td>60.3</td>
<td>1.16</td>
</tr>
</tbody>
</table>
Drawing force

• Cup drawing (first drawing)
  – Diameter: 85.7 mm
  – Thickness: 2 mm
  – UTS: 320 MPa

\[
F_{d_{\text{max}}} = n \cdot \pi \cdot d \cdot t \cdot UTS
\]
\[
F_{d_{\text{max}}} = 0.9 \cdot \pi \cdot 85.7 \cdot 2 \cdot 320
\]
\[
F_{d_{\text{max}}} = 155079 \, N \cong 155 \, kN
\]
Fluid forming uses only one solid die half.

Forming pressure is applied by the action of hydraulic fluid, which forces the blank to assume the shape of the rigid tool.

Sometimes a flexible membrane is used to separate blank and the fluid.
Strech drawing

Used for drawing car body panels

Blank is clamped, rigid die gives the shape of sheet metal

Change in thickness: $s_1 < s_0$
Formability Testing of Sheet Metals
Representation of Strain

- True or logarithmic strain: \( \varphi \)
- The integral of the incremental change in length \( dL \), divided by the actual length \( L \):

\[
\varphi = \frac{\int_{0}^{1} \frac{dL}{L}}{L} = \ln \frac{L_1}{L_0}
\]
Equivalent strain

- Strain in the direction of 3 axes:
  \[ \varphi_1 = \varphi_L \quad \varphi_2 = \varphi_w \quad \varphi_3 = \varphi_{th} \]
- Equivalent strain:
  \[ \varphi_e = \frac{\sqrt{2}}{3} \sqrt{(\varphi_1 - \varphi_2)^2 + (\varphi_2 - \varphi_3)^2 + (\varphi_1 - \varphi_3)^2} \]
True stress-strain (flow stress) curve

- Flow stress curve: \( \sigma_f = \sigma_f(\varphi_e) \)
  if temperature (T) and strain rate, is constant.

- In general
  \( n: \) strain hardening exponent;
  \( m: \) strain rate sensitivity

\[
\sigma_f = \sigma_f(\varphi_e; \dot{\varphi}_e; T)
\]

\[
\sigma_f = c \cdot \varphi_e^n \quad (if \quad \dot{\varphi}_e; T = \text{const.})
\]

\[
\sigma_f = c \cdot \varphi_e^n \cdot \dot{\varphi}_e^m \quad (if \quad T = \text{const.})
\]
Plastic strain ratio (r) Measurement

• Tensile test:

\[ \varphi_L = \ln\left(\frac{L_1}{L_0}\right); \]
\[ \varphi_w = \ln\left(\frac{w_1}{w_0}\right); \]
\[ \varphi_{th} = - (\varphi_L + \varphi_w) \quad (as \quad \varphi_L + \varphi_w + \varphi_{th} = 0) \]
Schematic Illustration of a Flat Tensile Specimen

\[ b = w; s = th \]

- **F** ... Tensile force
- **b** ... Specimen width
- **s** ... Specimen thickness
- **l** ... Reference length
Plastic strain ratio (r) Evaluation

• Calculation: $r = \frac{\phi_w}{\phi_{th}}$

• Definition: ratio of the true width strain divided to the true thickness strain

• The $r$ value frequently changes with direction in the sheet

• Test specimens should be machined parallel (0°), perpendicular (90°), and (45°) related to the rolling direction
Measure of anisotropy Test

Preparing tensile test specimen from a sheet

Geometry of tensile test specimen according to DIN EN 10 002 - 20*80

Source: IfU - Stuttgart
Measure of anisotropy

- Average normal anisotropy:

\[ r_m = \frac{r_0 + 2r_{45} + r_{90}}{4} \]

- Planar anisotropy:

\[ \Delta r = r_{45} - \frac{r_0 + r_{90}}{2} \]

The value \( r_m \) determines the limiting drawing ratio, and \( \Delta r \) is in correlation with the extent of earing.

A combination of high \( r_m \) and low \( \Delta r \) provides optimal drawability.
Anisotropy as a Function of the Rolling Direction

EN AW - 5182 w

EN AW - 6016-T4

r-value at $\varphi_3 = 0.11$
# Average normal anisotropy and hardening exponent of metals

<table>
<thead>
<tr>
<th>Material</th>
<th>n</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>0.2-0.5</td>
<td>1.0-1.4</td>
</tr>
<tr>
<td>Drawing steel</td>
<td>0.22-0.26</td>
<td>1.4-1.8</td>
</tr>
<tr>
<td>Austenitic steel</td>
<td>0.4-0.55</td>
<td>0.9-1.2</td>
</tr>
<tr>
<td>Copper</td>
<td>0.35-0.5</td>
<td>0.6-0.9</td>
</tr>
<tr>
<td>Aluminium</td>
<td>0.2-0.3</td>
<td>0.6-0.8</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.05</td>
<td>3.0-5.0</td>
</tr>
</tbody>
</table>
Forming Limit Diagram (1)
Forming Limit Diagram (2)

Forming Limit Diagram according to Goodwin and Keeler

- $\varphi_1 > \varphi_2$
- $\varphi_1 = \ln \frac{l_1}{l_0}$
- $\varphi_2 = \ln \frac{l_2}{l_0}$
- $\varphi_1 = \varphi_2$

- valid for $\varphi_1/\varphi_2 = \text{const.}$
Forming Limit Diagram (3)

- Sheet metal can be deformed only to a certain level – before local thinning (necking) and failure occur.
- FLD shows the limit of necking (or failure) as function of minor and major strain.
- Strains can be evaluated from the deformation of circle grids plotted on the surface of sheet metal.
Other formability tests

- Ball punch test (Erichsen test)
- Hydraulic bulge test
- Hemispherical dome test
- Cup drawing test (drawing test)
Ball punch test

Well known as Olsen or Erichsen test

The cup height at fracture is used as the measure of stretchability
Sketch showing the principle of the Erichsen Cupping Test
Ball punch test
Examples
Hydraulic bulge test

Material characterisation in biaxial stretching

Testing to much higher strain levels than those achievable in tensile testing

Research in plasticity theory
Hydraulic Bulge Test Assembly

1. Hydraulic pipes
2. Pressure gauge
3. Clamping tool
4. Ring piston
5. Die holder
6. Die
7. Sheet blank (starting state)
8. Path measuring gauge
Hemispherical dome test

Lubricated punch is used for deformation of sheet metal

The dome height at fracture is measured

The test yields reproducible results
Cup drawing test

Circular blanks of various diameters are used.

Tooling is standardised.

Limiting drawing ratio (LDR) is the ratio of the diameter of the largest blank that can be successfully drawn to the diameter of the punch.
Cup Drawing Test according to Swift

- $F_N$: blank holder force
- $F_{St}$: punch force
- $d_0$: punch diameter
- $s_0$: sheet thickness
- $D_0$: starting diameter of blank
- $D_a$: momentary flange outside diameter
- $r_M$: drawing ring radius
- $r_{St}$: punch edge radius

Source: IfU-Stuttgart
Cup drawing test
Examples