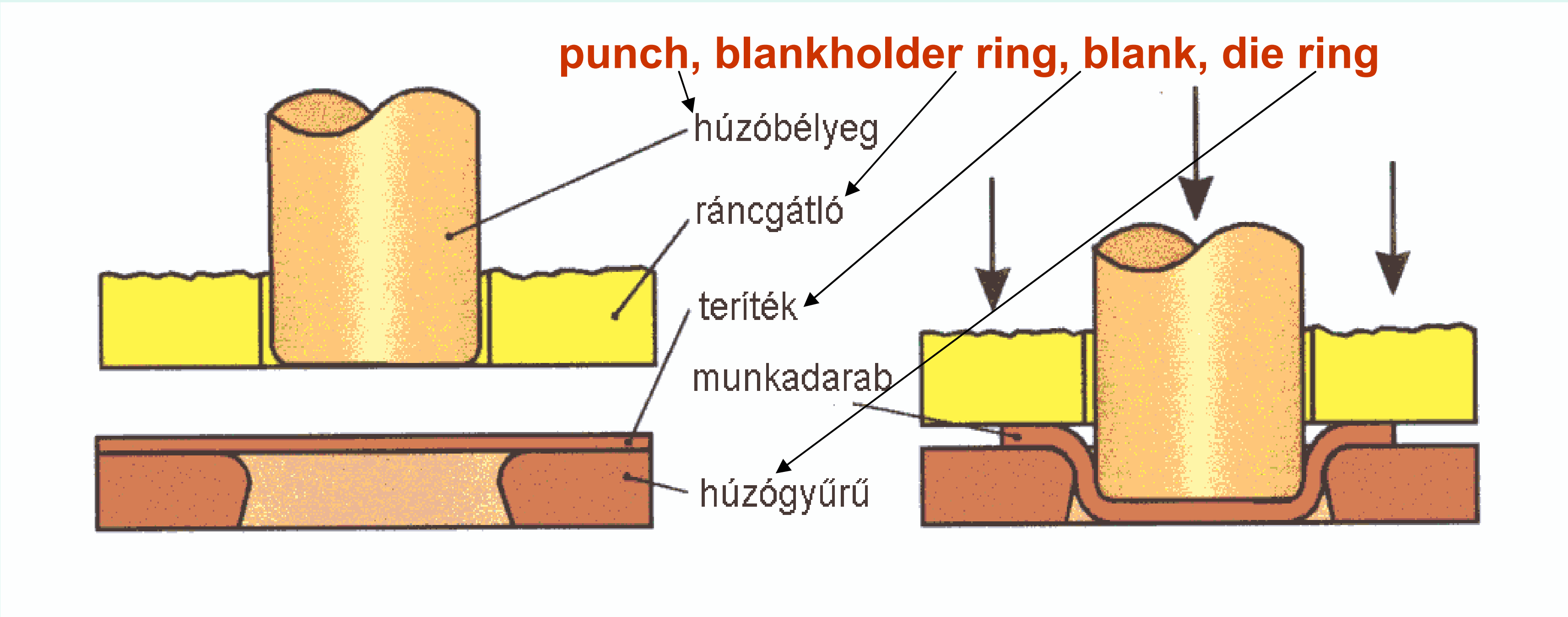
Deep Drawing, Formability

Deep drawing

Principle

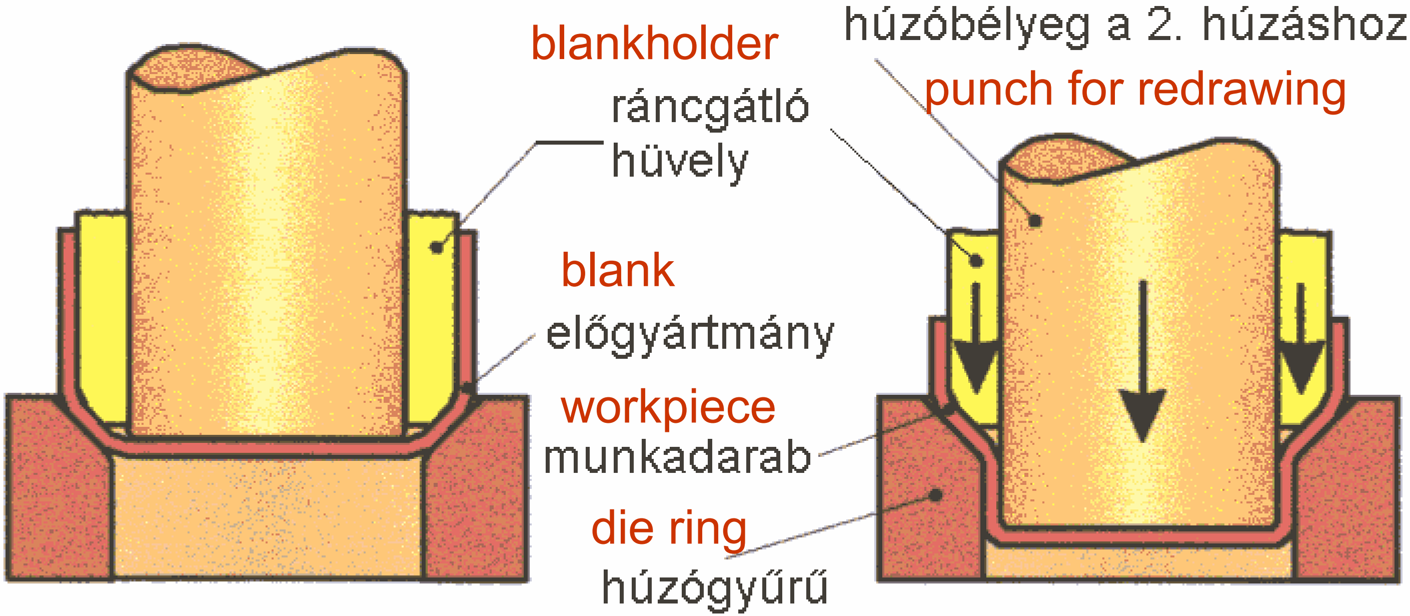


Deep drawing of metal sheet is used to form containers

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

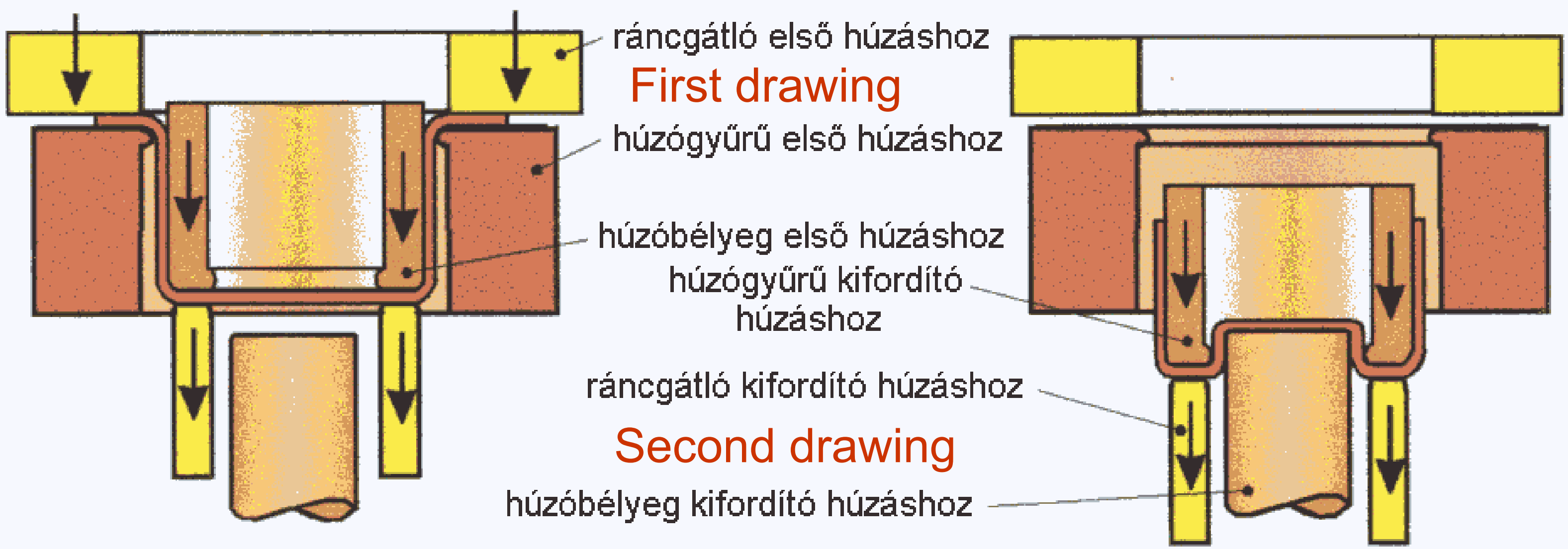
Tooling: punch, blankholder ring, blank, die ring

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) –

  $\beta = D_o/d_n$
- 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:

  $\beta_i = d_i/d_{i+1}$
- First drawing β_1 =2,2…1,8

  redrawing β_i =1,4…1,1

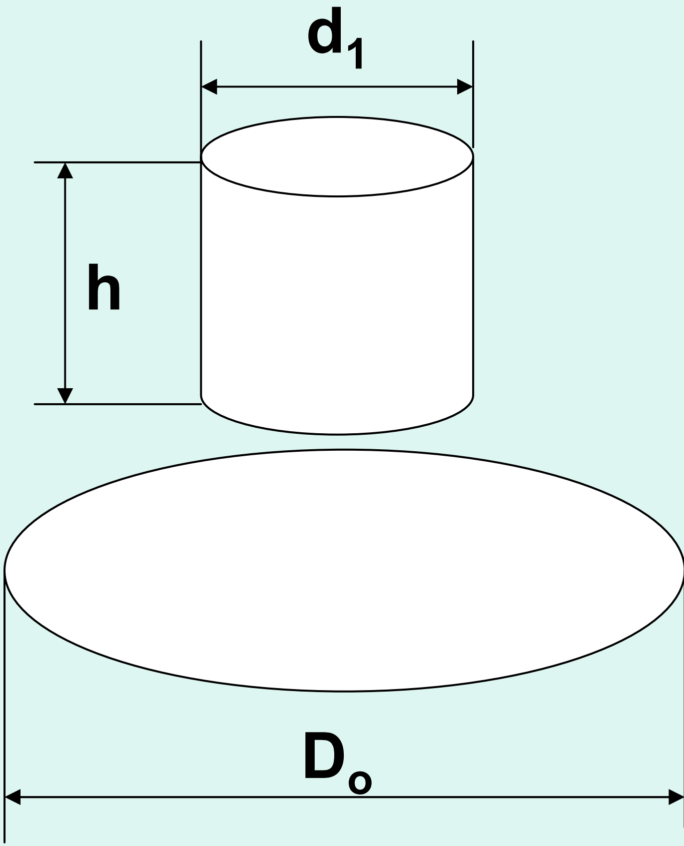
  (copper, aluminium, mild steel)

Calculation of blank diameter

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

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

$$D_0 = \sqrt{d_1^2 + 4d_1 h}$$



Calculation of drawing force

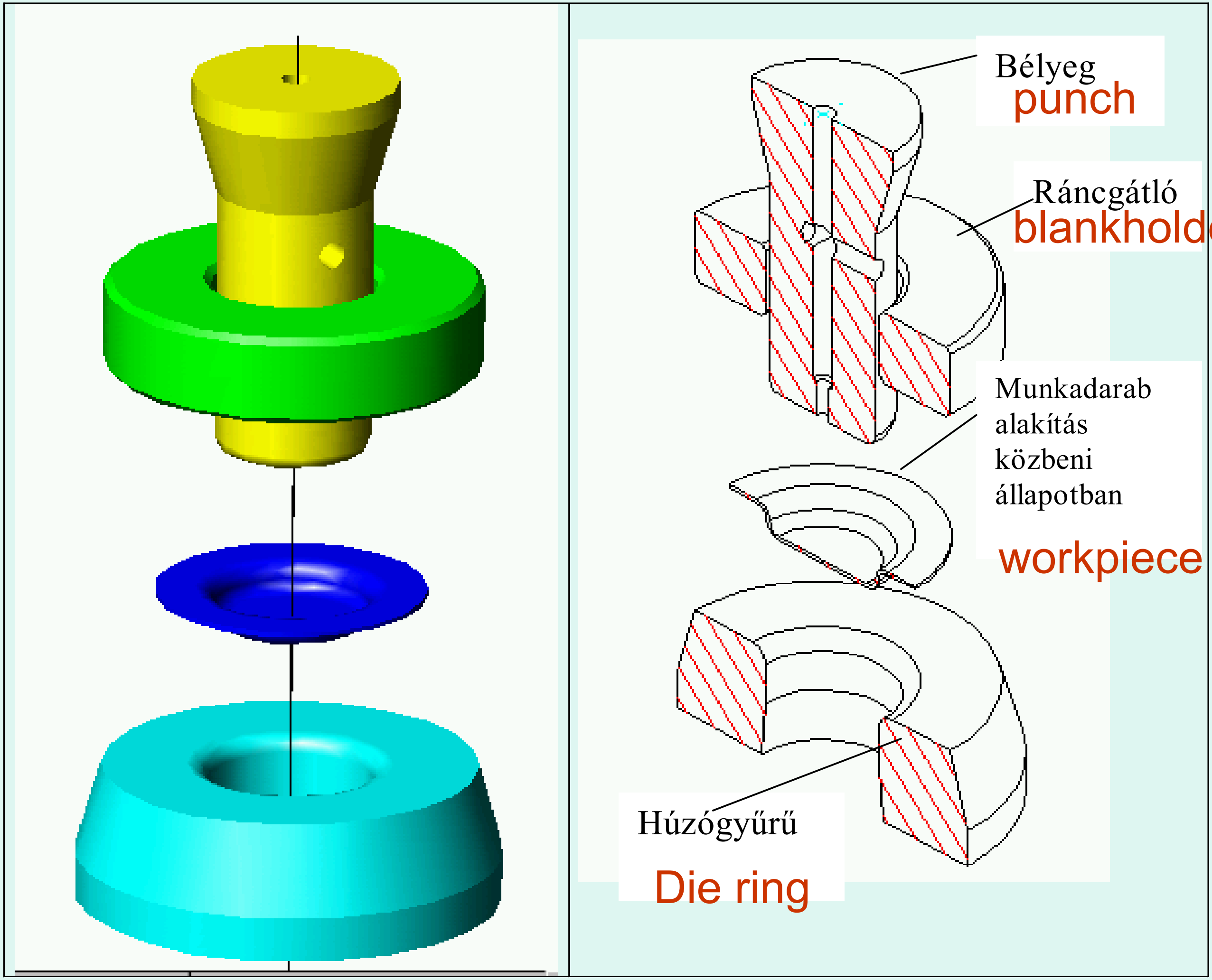
Drawing force: $F_{d,max} = n*\pi*d*t*UTS$

Example:

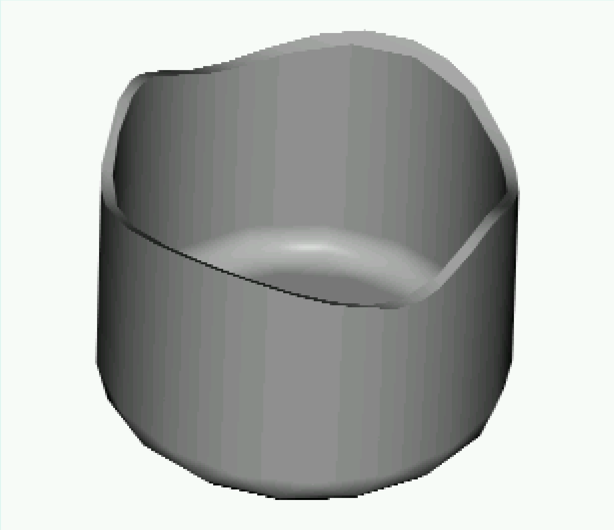
Cup diameter:	**d= 45,7 mm**
Sheet thickness:	**t = 0,5 mm**
Ultimate Tensile Strength:	**UTS = 320 MPa**
Drawing coefficient:	**n = 0,7…0,95**

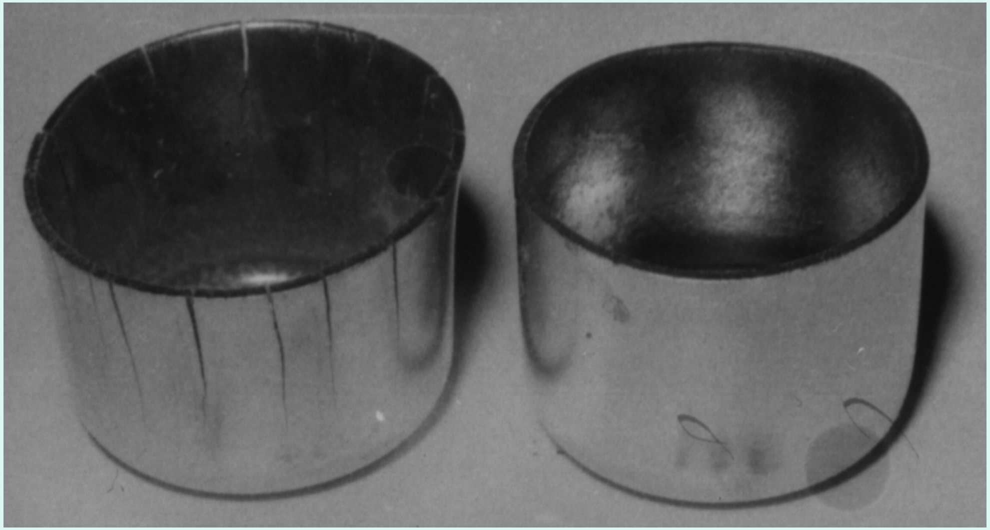
$$F_{d,max} = 0,9*\pi*45,7*0,5*320 = 20\ 674\ N$$

Drawing tool



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):**

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

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

$$D_0 = 170{,}1\ mm$$

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

Nr. of operations	Height in mm	Diameter in mm	Drawing ratio
0. blank	-	170,1	-
1. Cup drawing	65,1	85,7	1,98
2. Redrawing	85,7	69,9	1,23
3. Redrawing	104,8	60,3	1,16

Drawing force

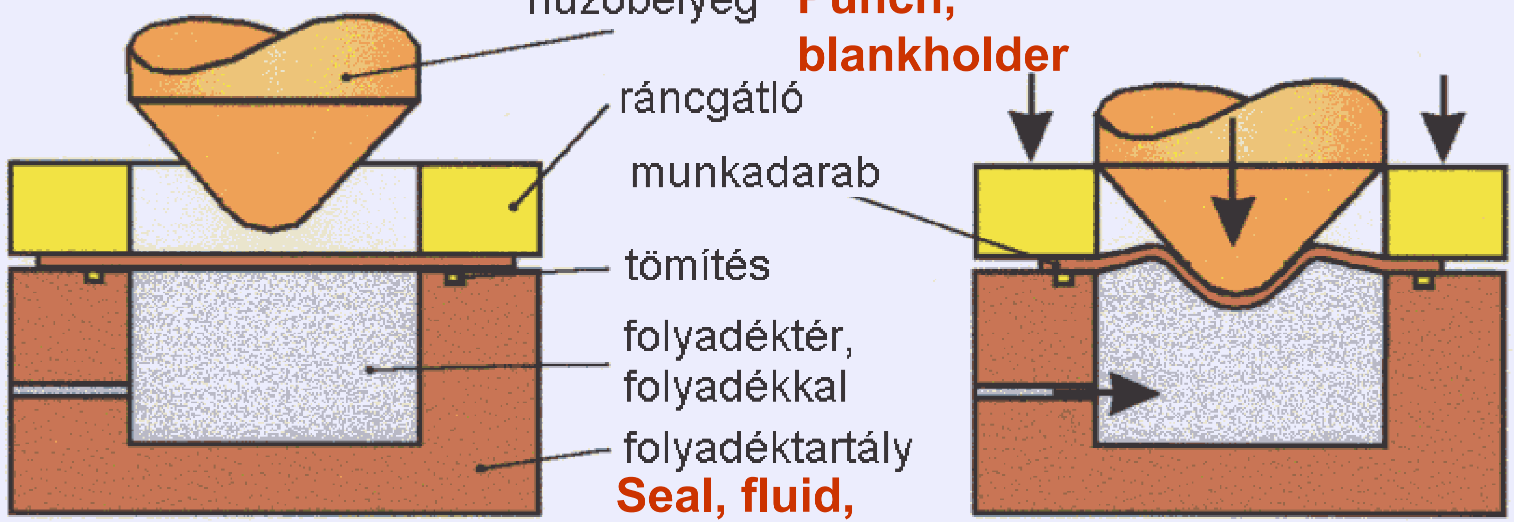
- Cup drawing (first drawing)
  - Diameter: 85,7 mm
  - Thickness: 2 mm
  - UTS: 320 MPa

$$F_{d\max} = n \cdot \pi \cdot d \cdot t \cdot UTS$$

$$F_{d\max} = 0{,}9 \cdot \pi \cdot 85{,}7 \cdot 2 \cdot 320$$

$$F_{d\max} = 155079\,N \cong 155\,kN$$

Fluid forming „hidromec” process

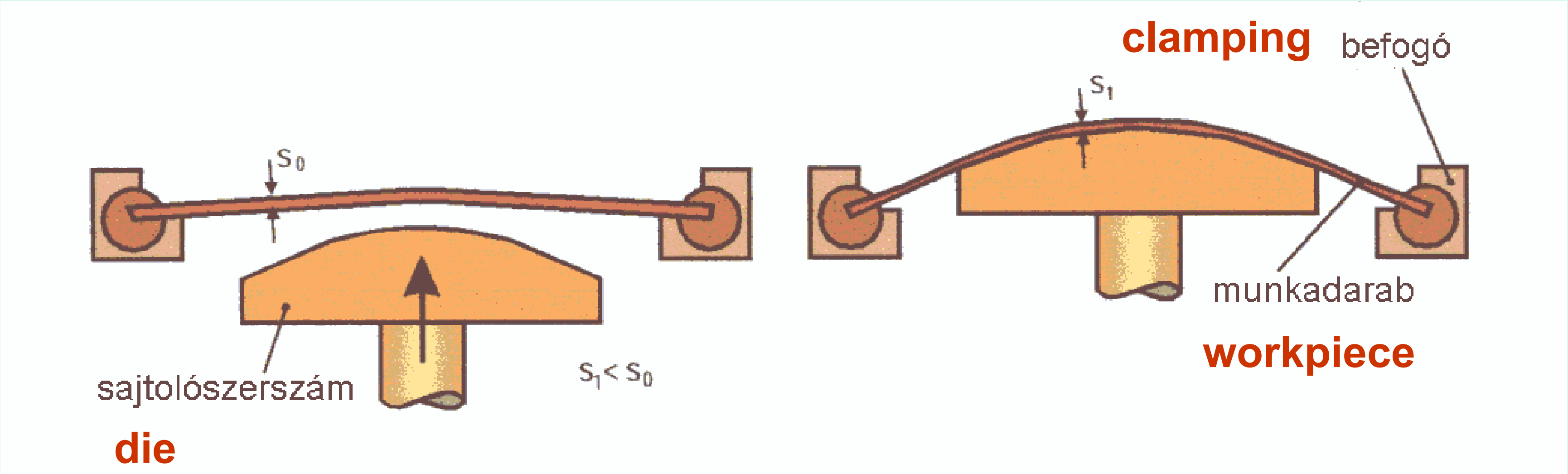


Fluid forming uses only one solid die half.

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

Sometimes a flexibile membran 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:** φ
- **The integral of the incremental change in length dL, divided by the actual length L:**

$$d\varphi = \frac{dL}{L} \qquad \varphi = \int_{L_0}^{L_1} \frac{dL}{L} = \ln \frac{L_1}{L_0}$$

Equivalent strain

- **Strain in the direction of 3 axes:**

$\varphi_1 = \varphi_L$ $\varphi_2 = \varphi_w$ $\varphi_3 = \varphi_{th}$

- **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, $\dot{\varphi}_e = \frac{d\varphi}{dt}$

  is constant.

- **In general**

  (n: strain hardening exponent;

  m: strain rate sensitivity)

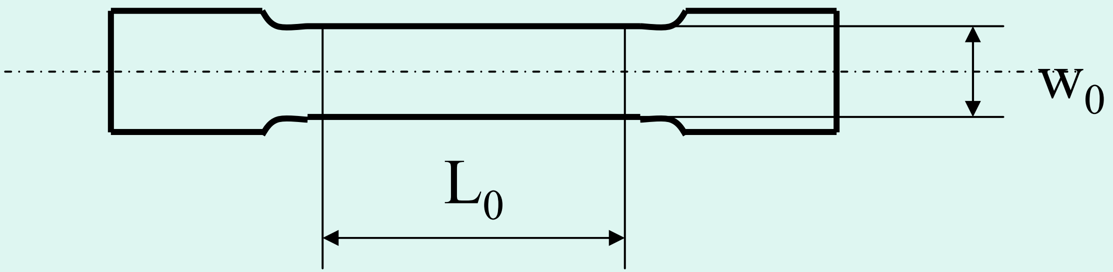
$$\sigma_f = \sigma_f\left(\varphi_e;\dot{\varphi}_e;T\right)$$

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

$$\sigma_f = c\cdot\varphi_e^n\cdot\dot{\varphi}_e^m\,(if\ T = const.)$$

Plastic strain ratio (r) Measurement

- **Tensile test:**

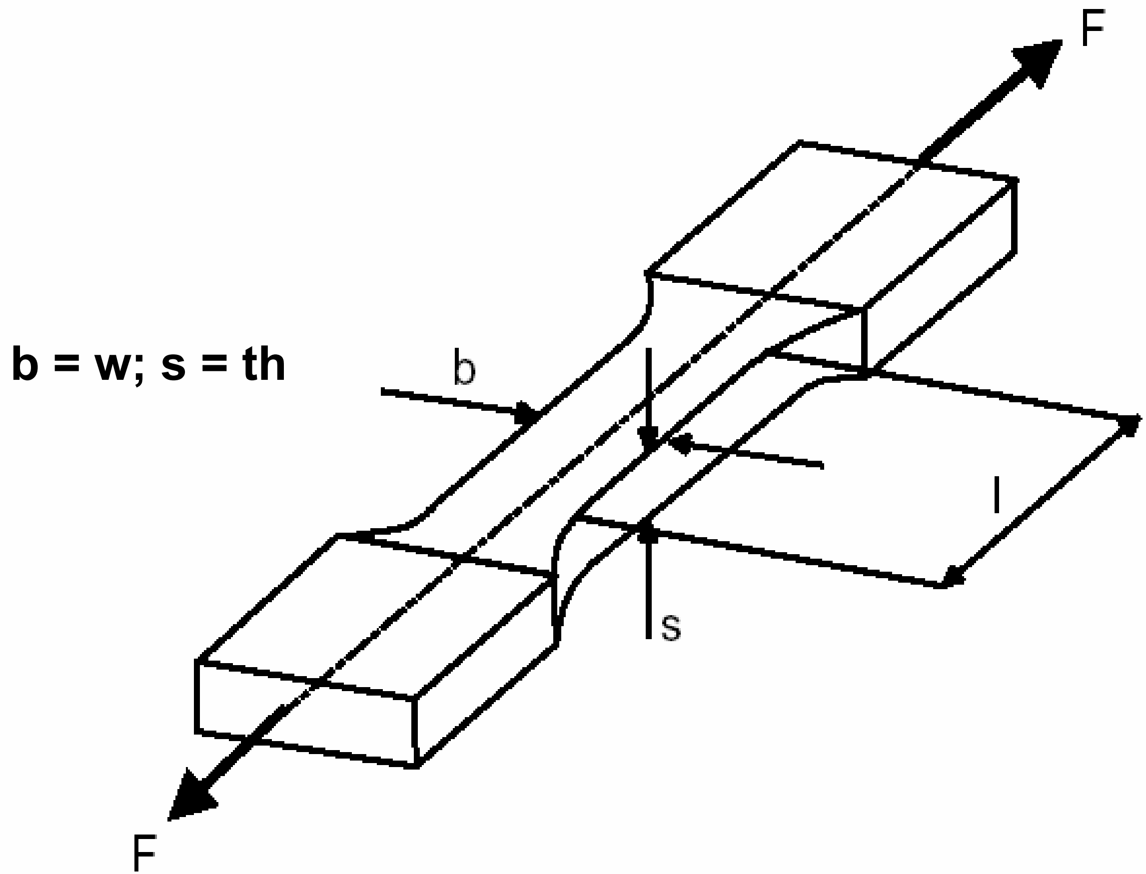


$$\varphi_L = \ln(L_1/L_0);$$

$$\varphi_w = \ln(w_1/w_0);$$

$$\varphi_{th} = -(\varphi_L + \varphi_w) \quad (\text{ as } \varphi_L + \varphi_w + \varphi_{th} = 0)$$

Schematic Illustration of a Flat Tensile Specimen

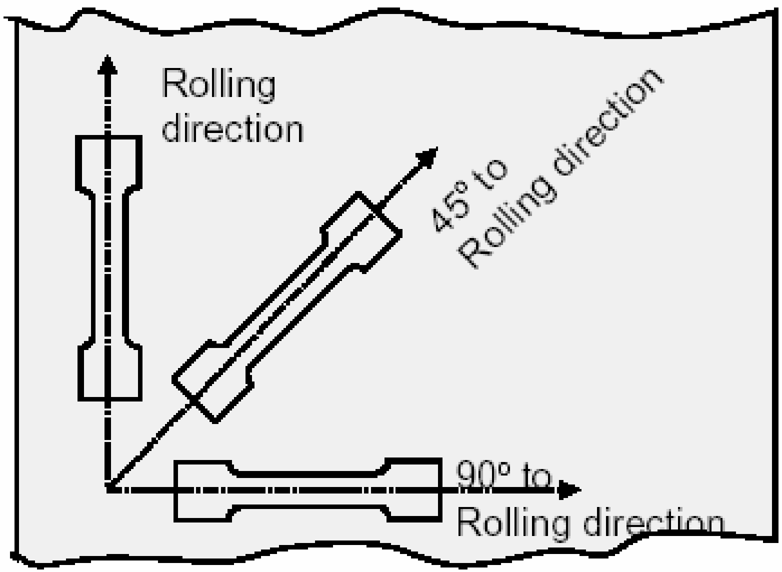


F ... Tensile force
b ... Specimen width
s ...Specimen thickness
l ... Reference length

Plastic strain ratio (r) Evaluation

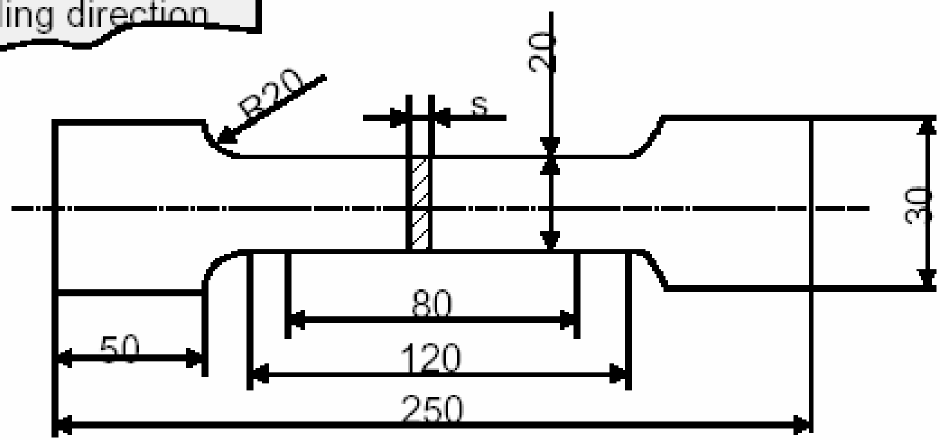
- Calculation: $r = \varphi_w / \varphi_{th}$
- Definition: ratio of the true width strain devided to the true thickness strain
- The r value frequently changes with direction in the sheet
- Test specimens should be machined parallel (0°), perpendicular (90°), and (45°) related to the rolling direction

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:**

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

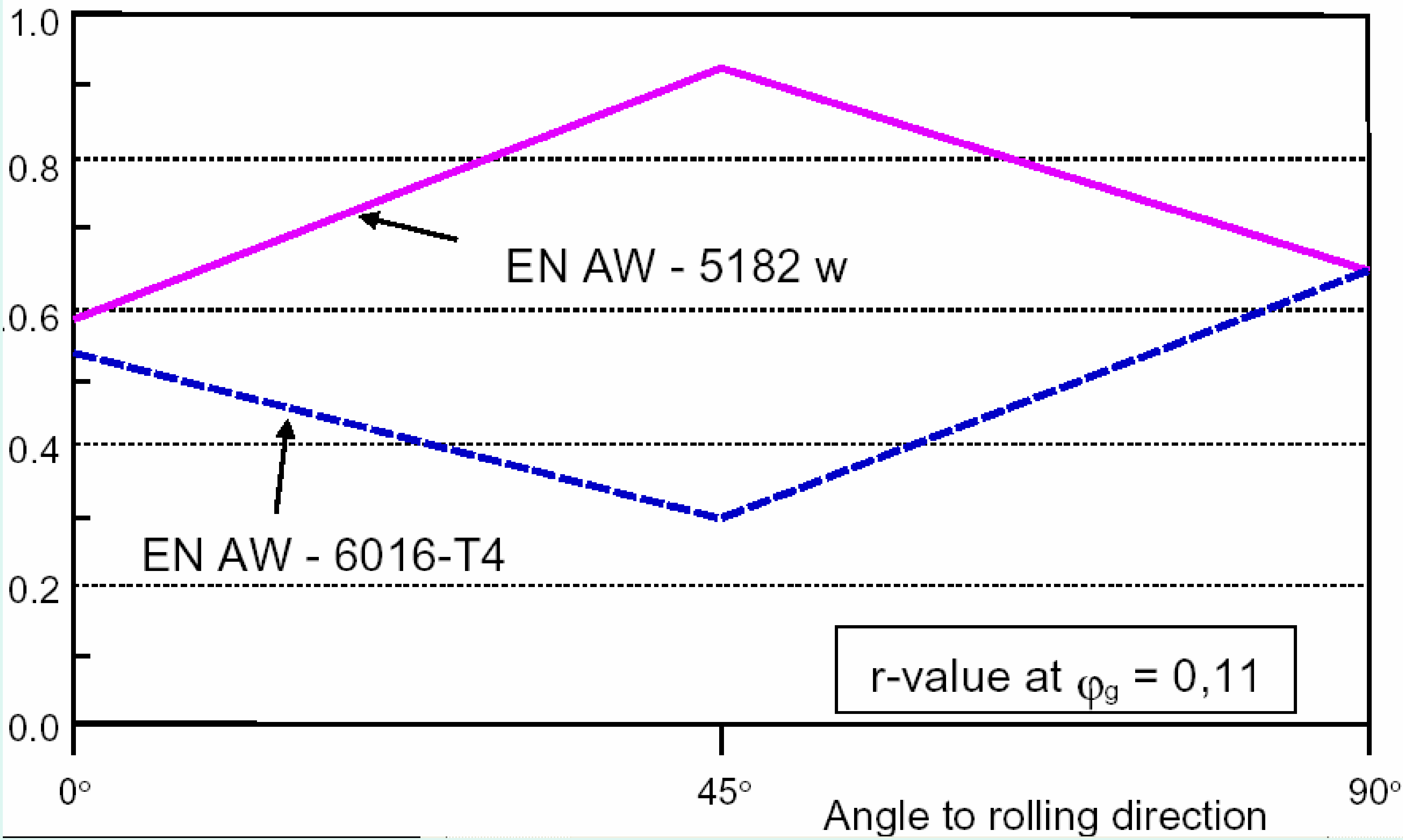
- **Planar anisotropy:**

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

The value r_m determines the limiting drawing ratio, and Δr is in correlation with the extent of earing.

A combination of high r_m and low Δr provides optimal drawability.

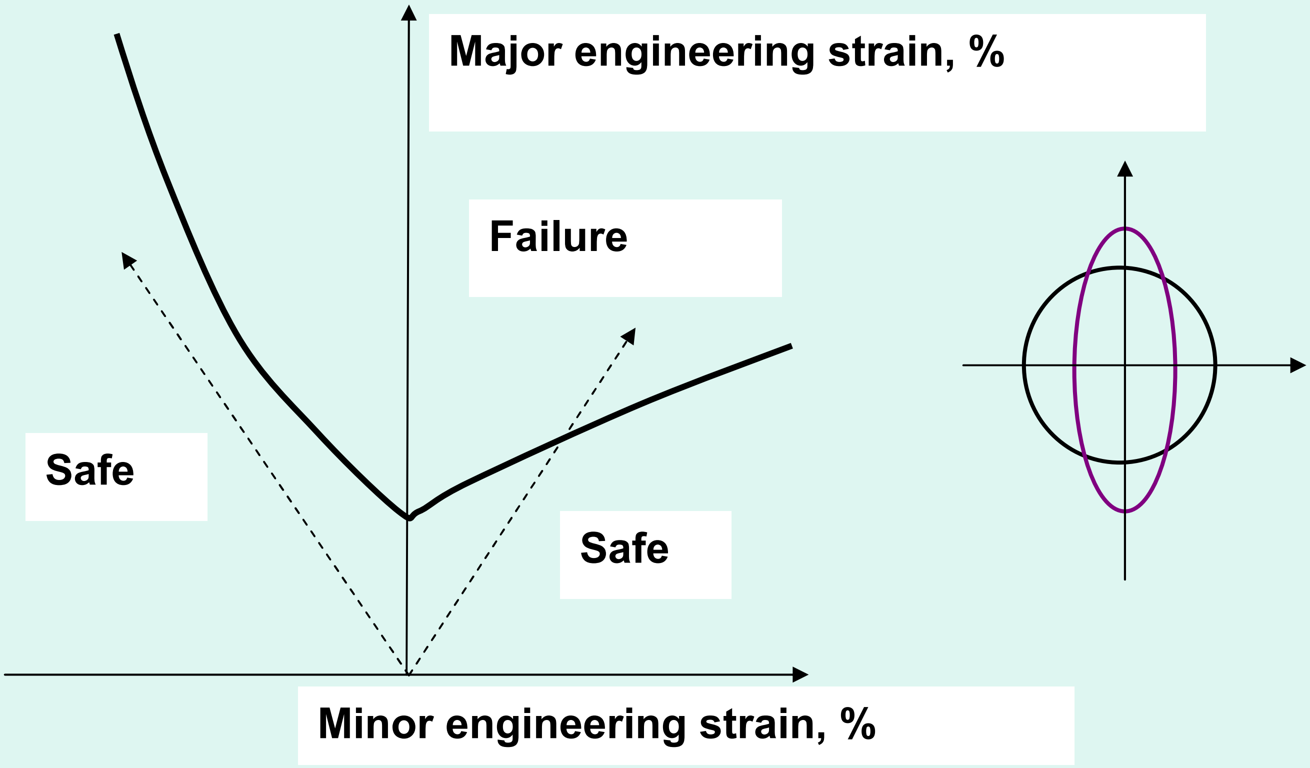
Anisotropy as a Function of the Rolling Direction



Average normal anisotropy and hardening exponent of metals

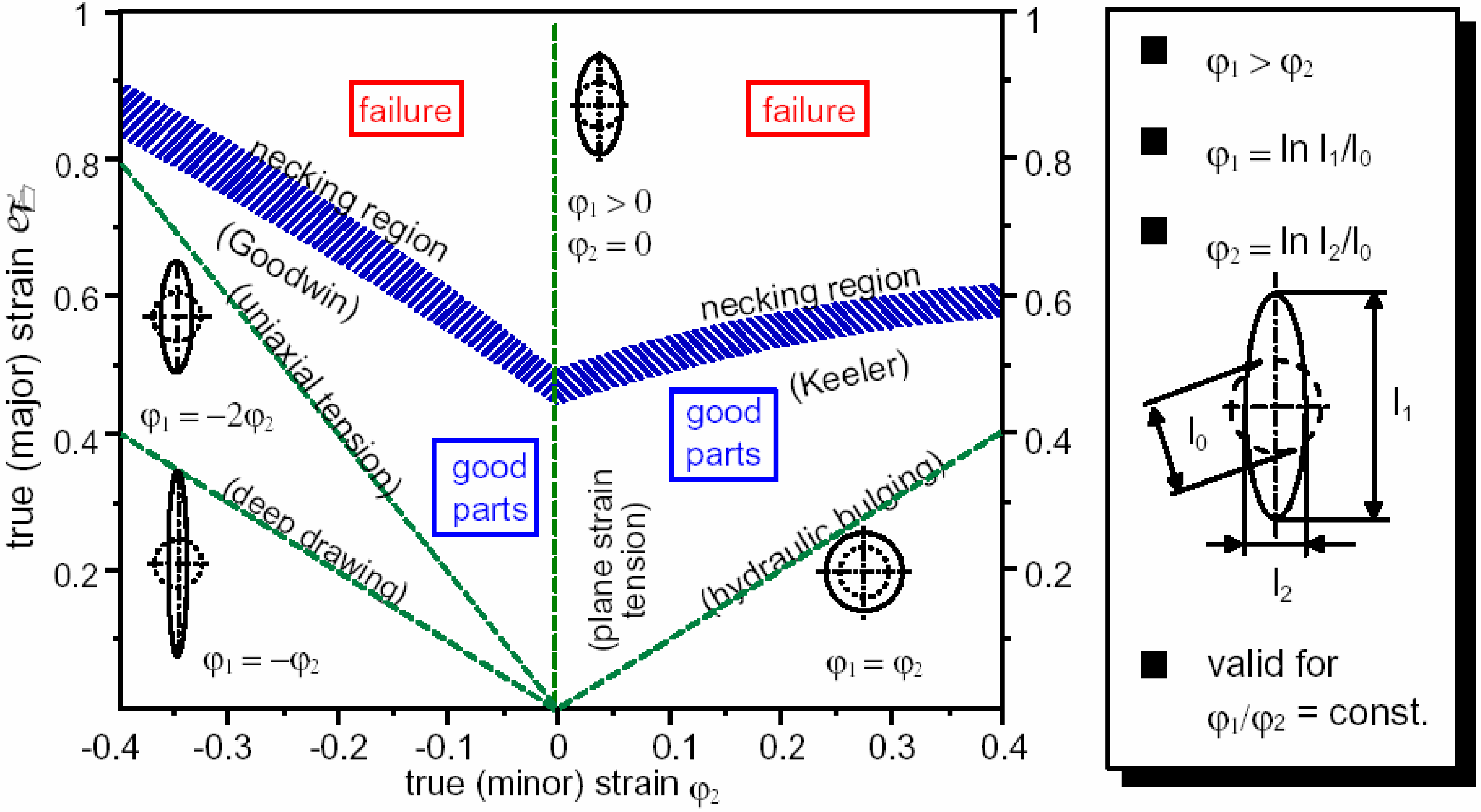
	n	r
Mild steel	0,2-0,5	1,0-1,4
Drawing steel	0,22-0,26	1,4-1,8
Austenitic steel	0,4-0,55	0,9-1,2
Copper	0,35-0,5	0,6-0,9
Aluminium	0,2-0,3	0,6-0,8
Titanium	0,05	3,0-5,0

Forming Limit Diagram (1)



Forming Limit Diagram (2)

Forming Limit Diagram according to Goodwin and Keeler



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

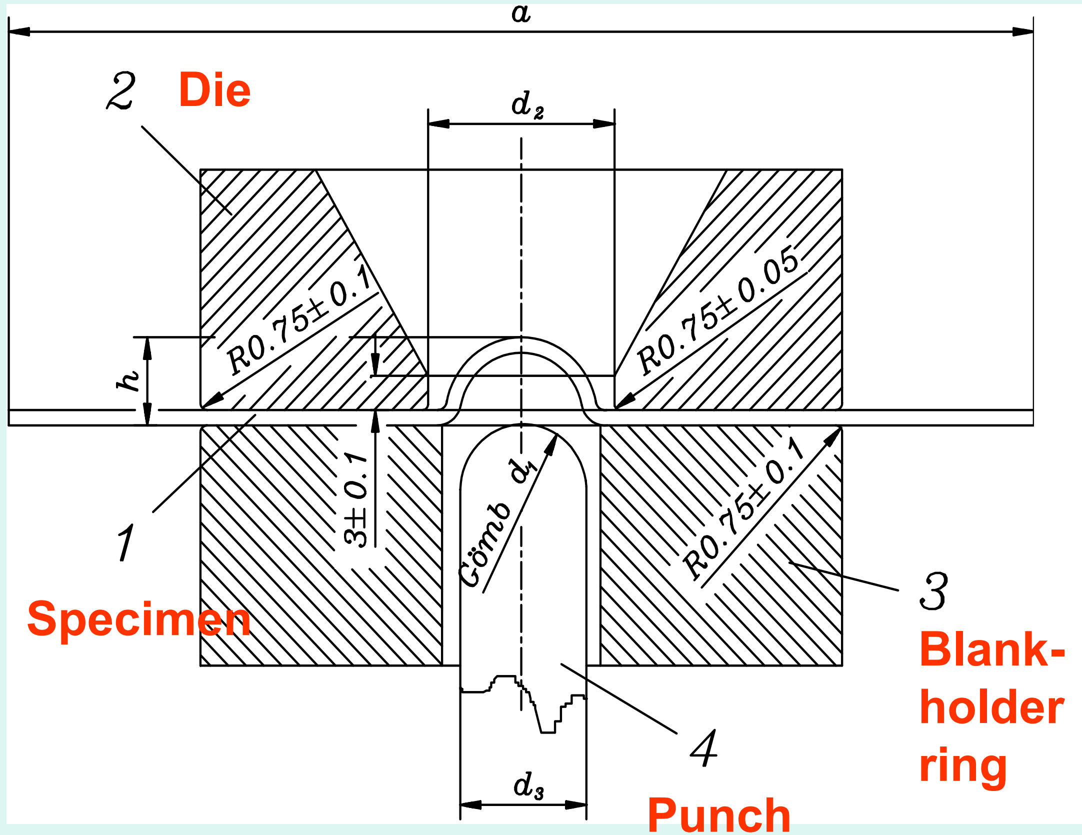
Other formability tests

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

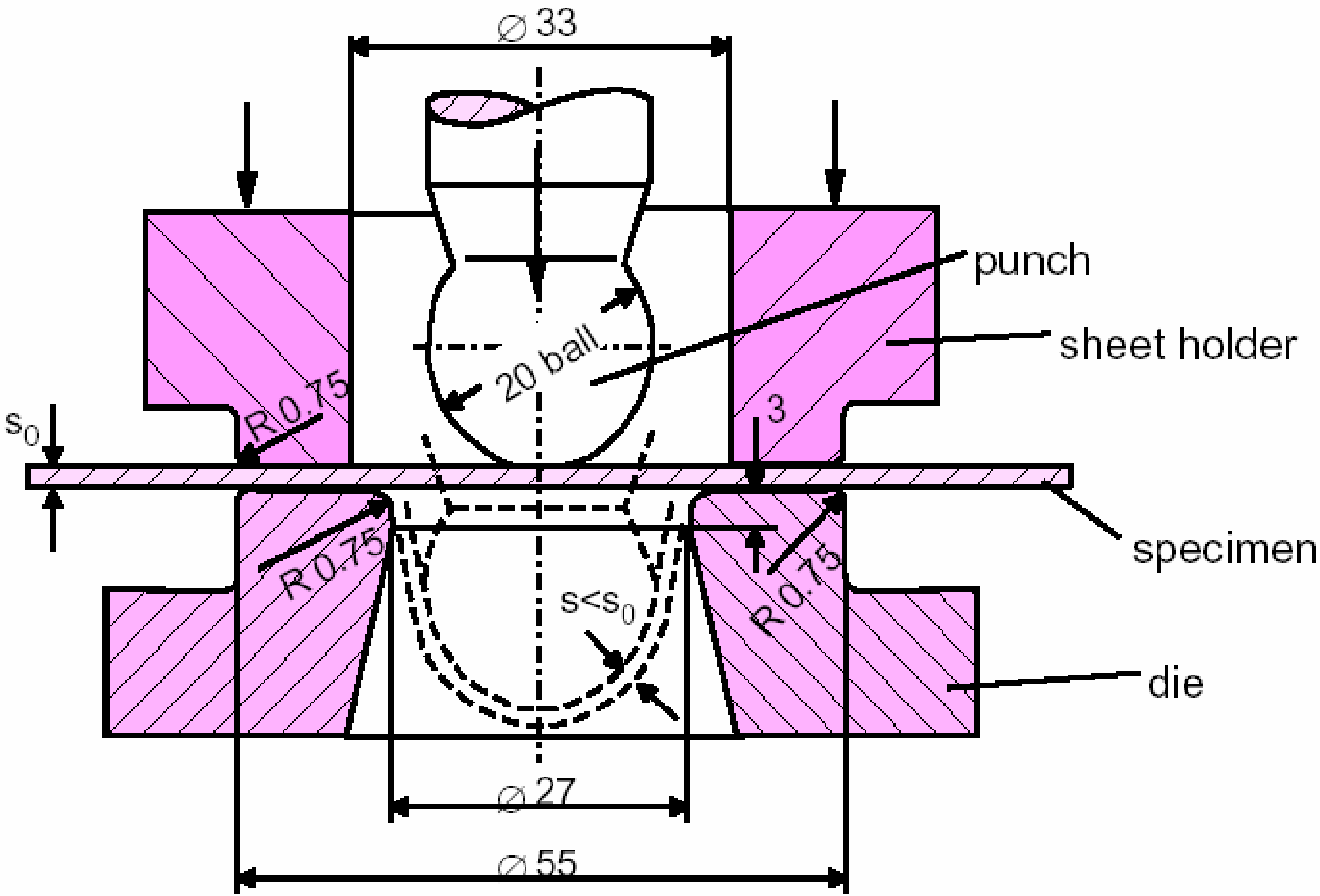
Ball punch test

Well known as Olsen or Erichsen test

The cup height at fracture is used as the measure of strechability



Sketch showing the principle of the Erichsen Cupping Test



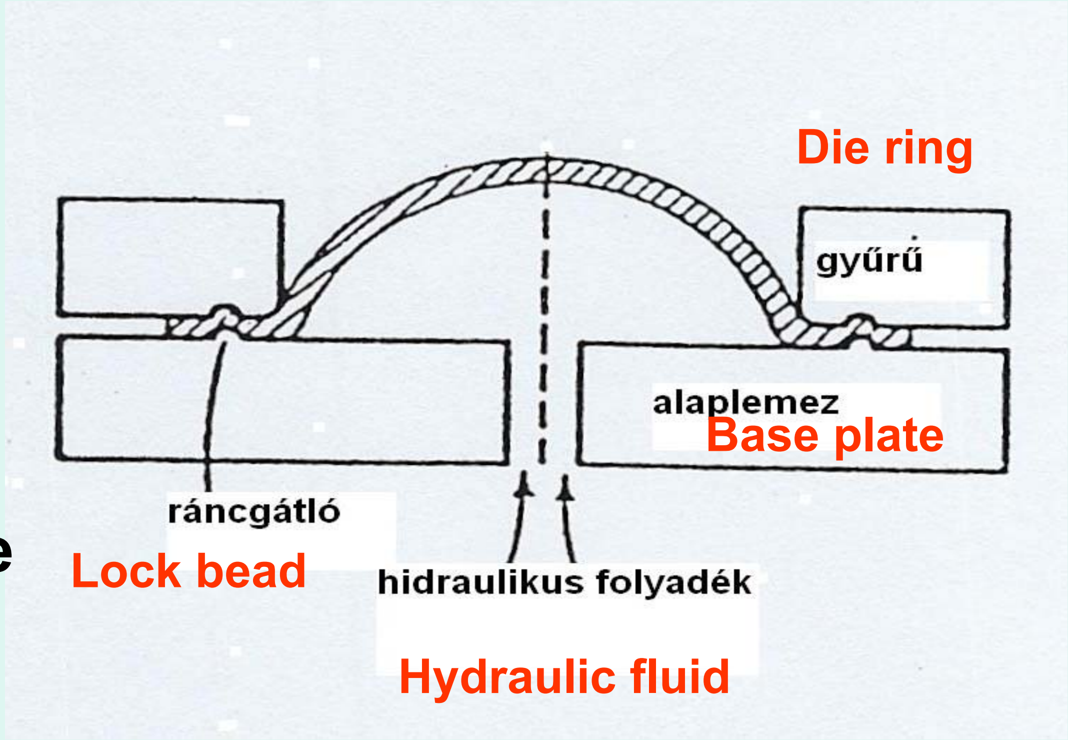
Ball punch test
Examples

Hydraulic bulge test

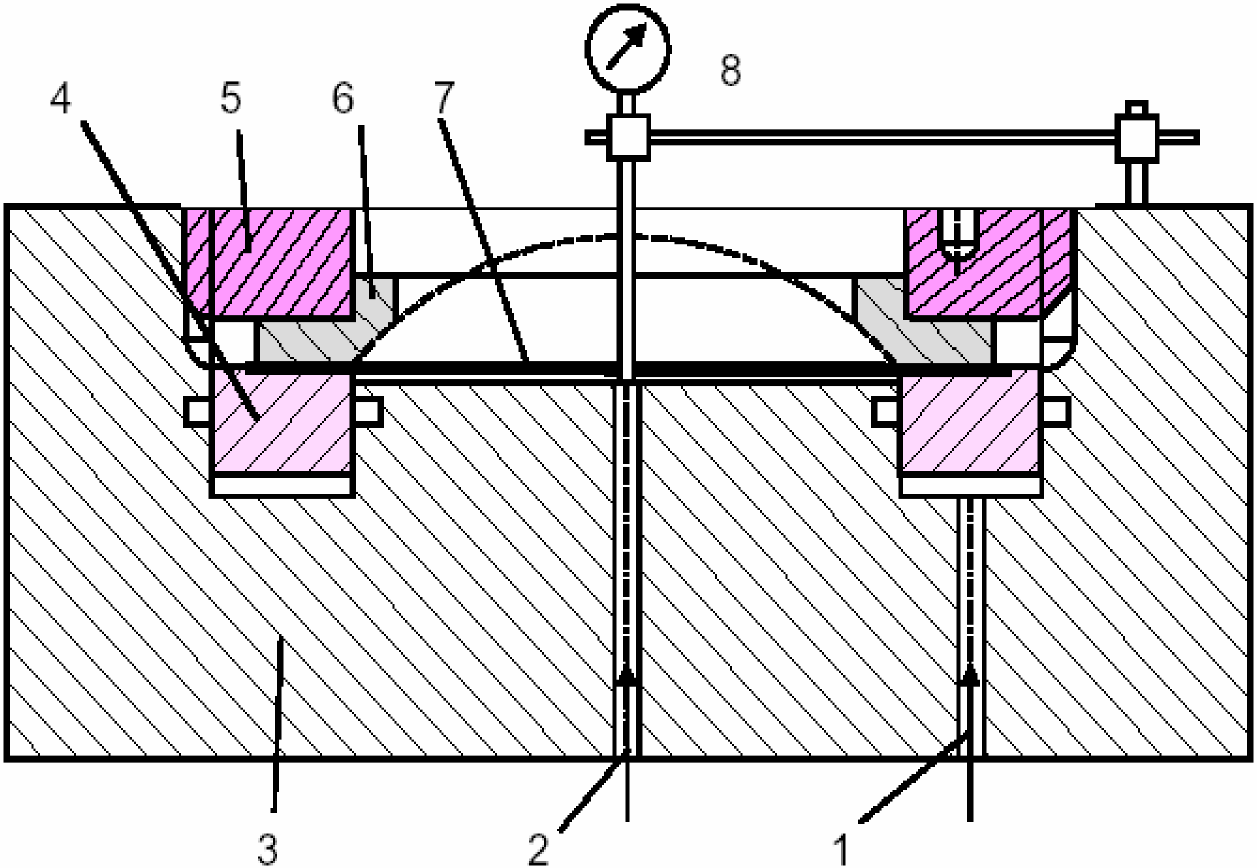
Material characterisation in biaxial streching

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

Research in plasticity theory



Hydraulic Bulge Test Assembly



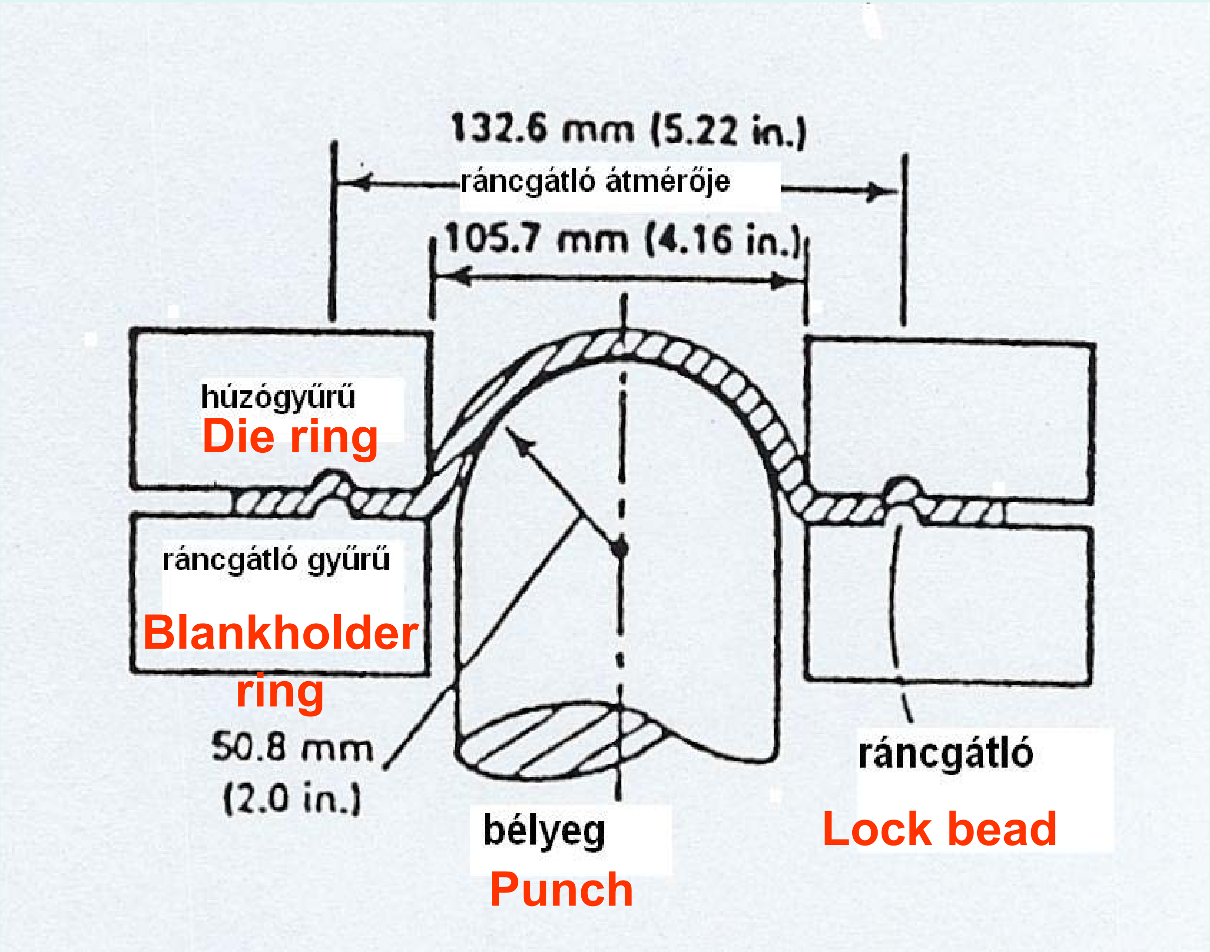
1 hydraulic pipes
2 pressure gauge
3 clamping tool
4 ring piston
5 die holder
6 die
7 sheet blank (starting state)
8 path measuring gauge

Hemispherical dome test

Lubricated punch is used for deformation of sheet metal

The dome height at fracture is measured

The test yields reproducible results

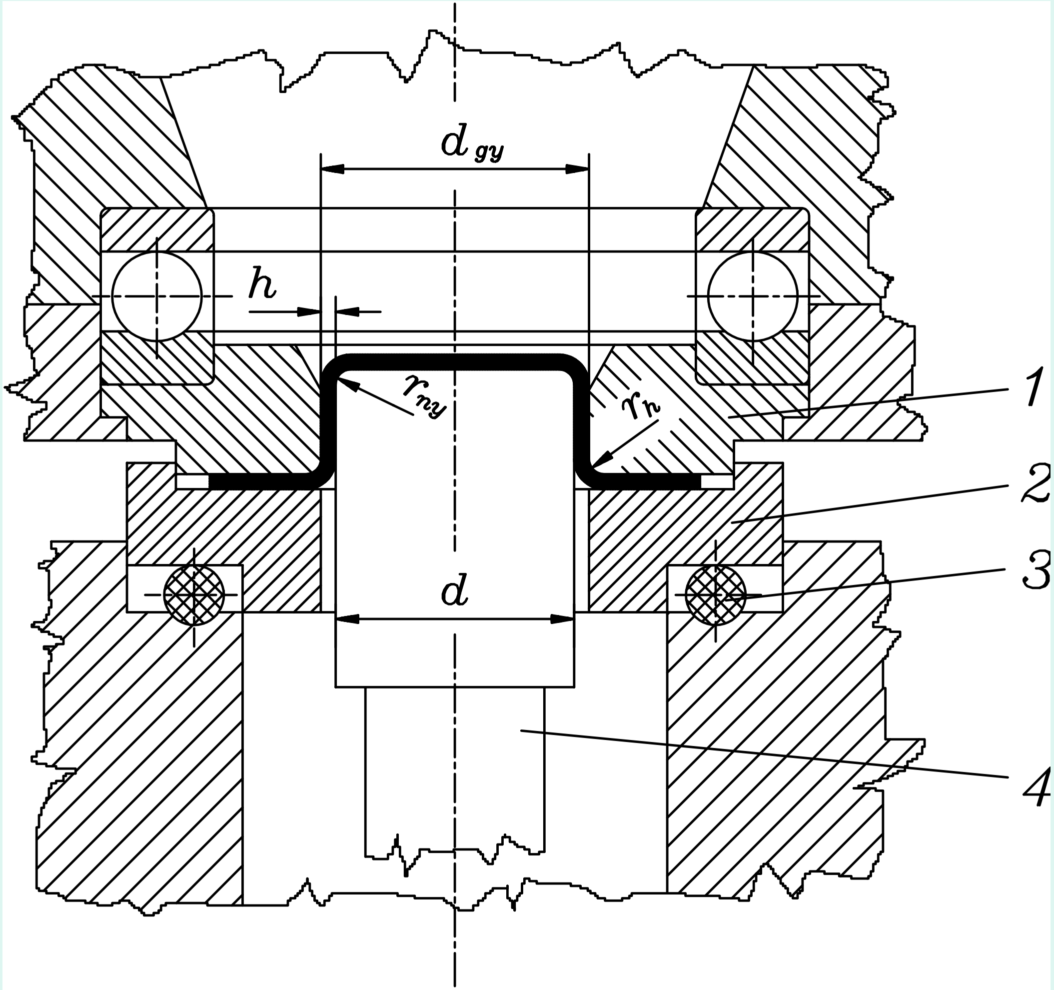


Cup drawing test

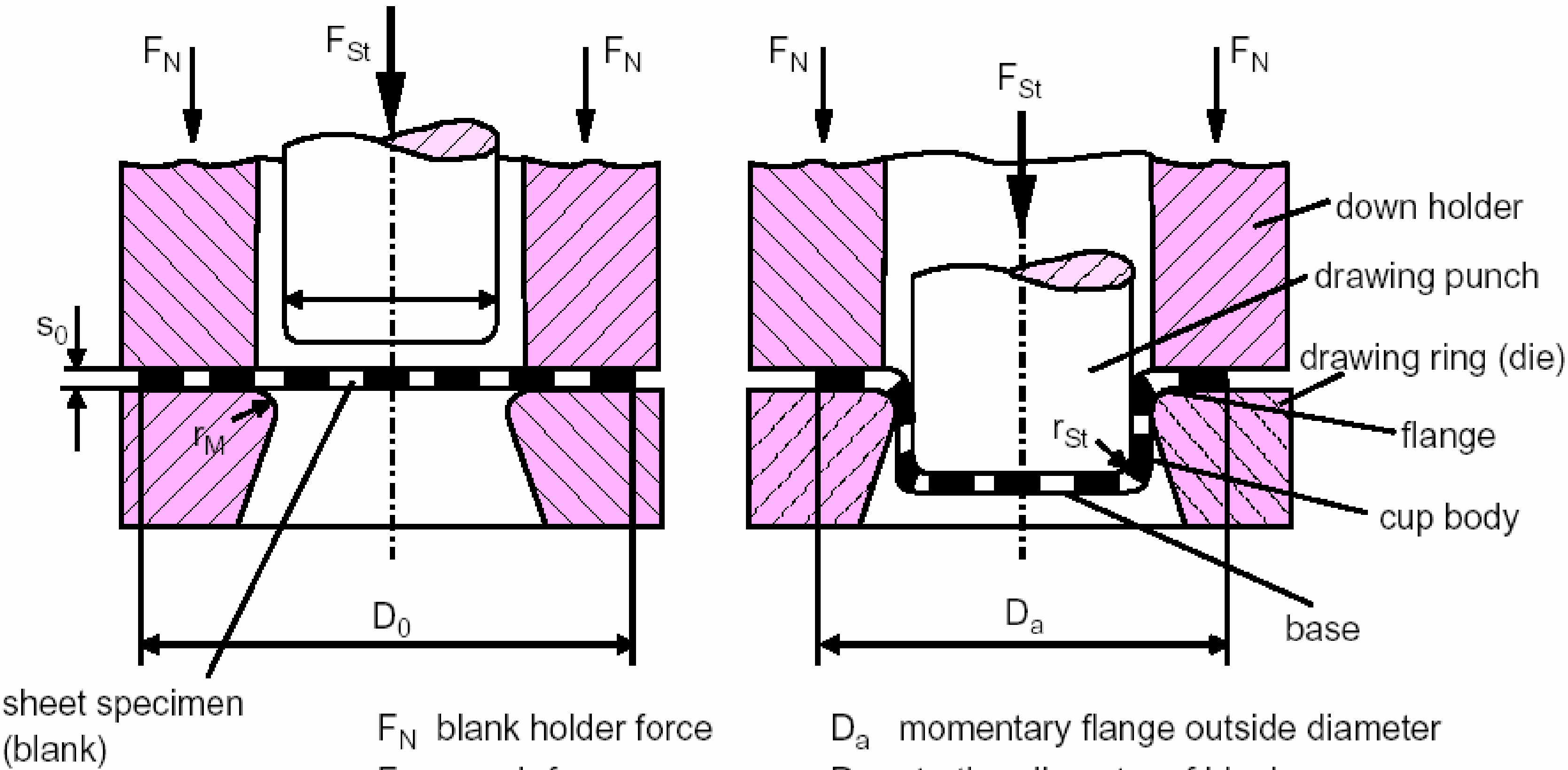
Circular blanks of various diameters are used

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

Source: IfU-Stuttgart

Cup drawing test
Examples