Metal Forming – BSc 2024/25-1

Formability

Topics

- Concept of formability
- Formability of materials:
  - Bulk forming
  - Sheet forming
- Measurement techniques

Concept of formability

The plastic deformation is limited by:

- *plastic instability*
- *crack and fracture*

Instable plastic deformation:

In a certain point of the material the effect of hardening is abrogated by the softening.

The source of softening can be:

– change of geometry,
– change of the strain rate
– change of temperature.

Plastic instability

The plastic deformation is stable in a cylindrical tensile testing specimen if the force increases with increasing deformation:

$$dF > 0$$

Plastic instability occurs when: $dF = 0$

Force at this case: $F = \bar{\sigma} A$

Limit of stability: $dF = d(\bar{\sigma} A) = d\bar{\sigma} A + \bar{\sigma} dA = 0$

$$d\bar{\sigma} = -\bar{\sigma}\frac{dA}{A}$$ where $$-\frac{dA}{A} = d\bar{\varphi}$$

$$\frac{d\bar{\sigma}}{d\bar{\varphi}} = \bar{\sigma}$$ $\Rightarrow$ Next slide

Plastic instability

Assuming that: $\bar{\sigma} = \sigma_{flow} = C\bar{\varphi}^n \Rightarrow \frac{d\bar{\sigma}}{d\bar{\varphi}} = Cn\bar{\varphi}^{n-1}$

Limit of stability: $Cn\bar{\varphi}^{n-1} = C\bar{\varphi}^n \Rightarrow \boxed{\bar{\varphi}_{critical} = n}$

Plastic instability occurs when the critical strain is reached; it leads to local plastic deformation (contraction) and fracture of the sample.

Plastic instability can occur at forming of car body parts, as local thinning of the sheet.

It is beneficial if the value of *n* is higher.

Plastic strain to fracture

The limit of deformation. The formability of the material decreases during the forming process. If the strain reaches a critical value ($\bar{\varphi}_{fracture}$ - *strain at fracture*), fracture occurs.

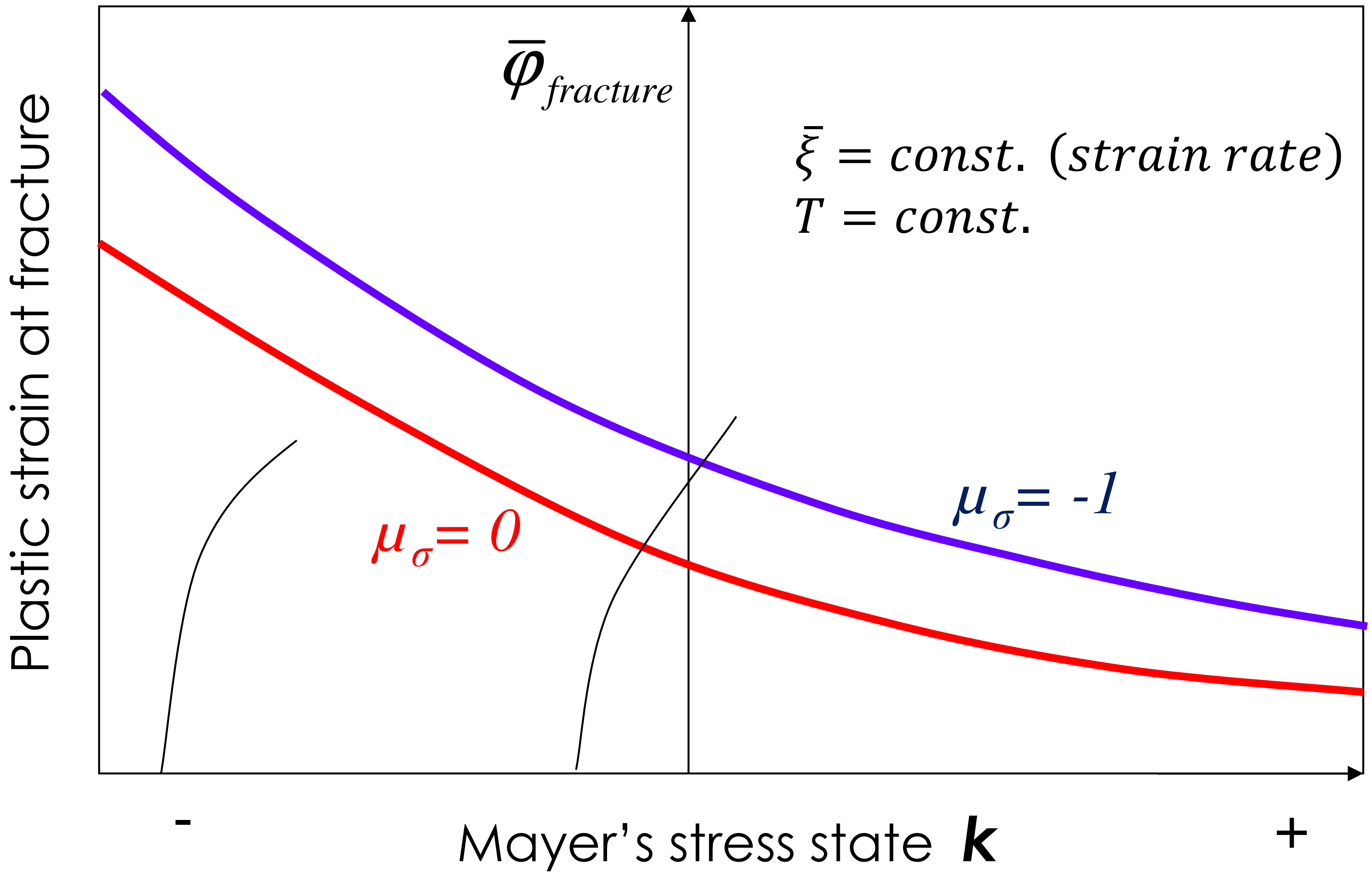
The limit of the deformation depends on the local ***temperature***, ***strain rate*** and ***stress state***. It can be characterized by two quantities:

– Lode parameter (μ_σ) $$\mu_\sigma = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3}$$

– Mayer's stress state (k) $$k = \frac{\sigma_1 + \sigma_2 + \sigma_3}{\bar{\sigma}}$$

Forming limit diagram

$$\bar{\varphi}_{fracture} = \left[a_2 - (a_1 - a_2)\mu_\sigma\right]\exp\left[b_2 - (b_1 - b_2)\mu_\sigma\right]k$$



Formability diagram

The occurrence of a fracture can be analyzed by the ***forming limit diagrams (FLD)***:

$$\overline{\varphi}_{fracture} = f\left(k\right)$$

The forming limit diagram of bulk forming processes can be determined by conducting experiments causing different stress states (tensile, upsetting, torsion, bending etc. tests).

The **increasing temperature** shifts the curves **upwards**.

The **increasing strain rate** shifts the curves **downwards**.

Bogatov fracture theory

For continuous forming

$$\Psi = \int_0^{\bar{\varphi}_f} \frac{a\bar{\varphi}^{a-1}}{\bar{\varphi}^a} d\bar{\varphi}$$

$$\bar{\varphi}_{critical} = f(k, \mu_\sigma, \bar{\xi}, T, \bar{x}_i)$$

For multistep forming

$$\Psi = \sum_{i=1}^{n} \int_0^{\bar{\varphi}_i} \frac{a\bar{\varphi}^{a-1}}{\bar{\varphi}^a} d\bar{\varphi}$$

$$a = a(k, \mu_\sigma, \bar{\xi}, T, \bar{x}_i)$$

Mayer's stress state (k)

$$k = \frac{\sigma_1 + \sigma_2 + \sigma_3}{\bar{\sigma}}$$

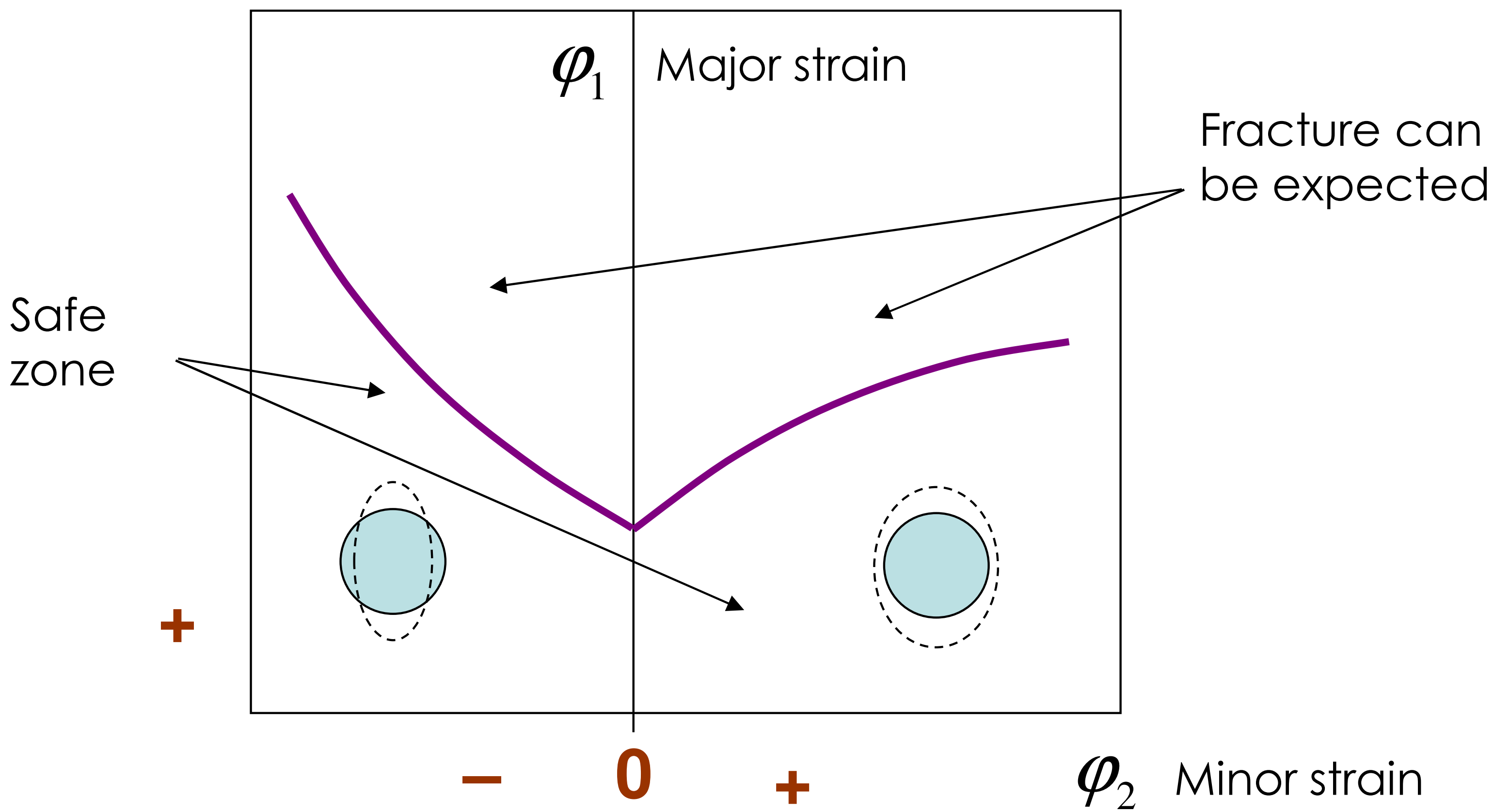
Lode parameter (μ_σ)

$$\mu_\sigma = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3}$$

$\Psi = 1 \;\Rightarrow$ fracture

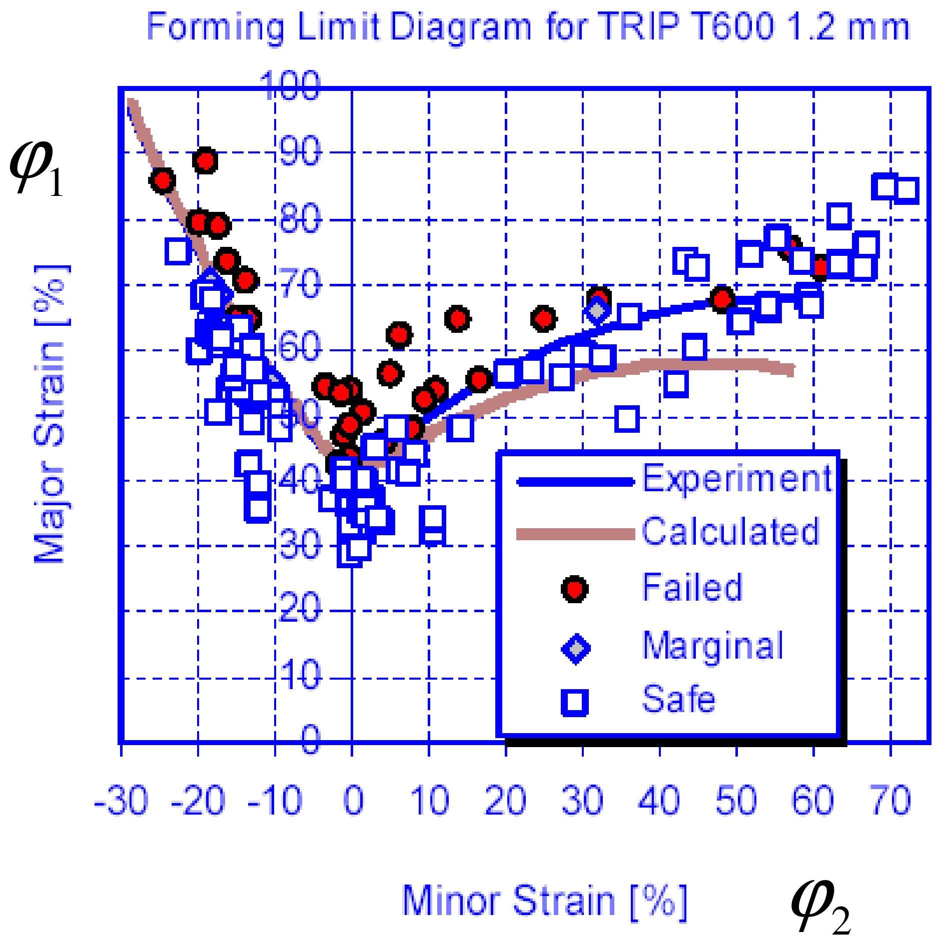
Forming limit diagram (FLD)

The formability for **sheet metal forming** techniques is characterized by the **forming limit diagram** (FLD).



Forming limit diagram (FLD)

Determination of the FLD using Nakazima test



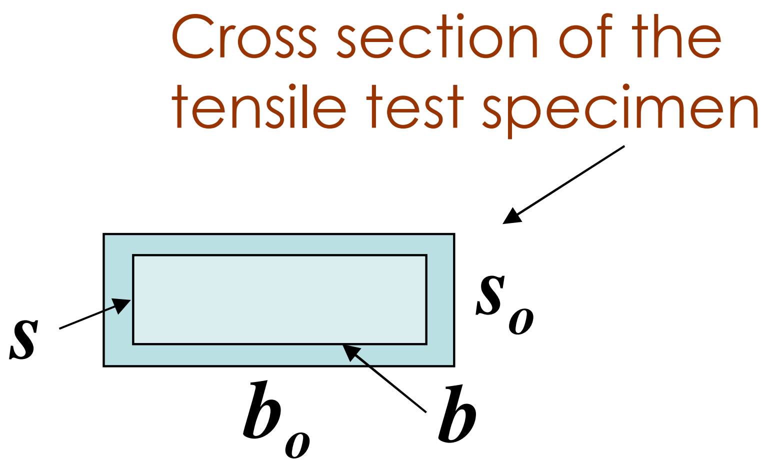
R and n values

Important quantities of sheet formability from tensile test:

- Lankford coefficient (R)
- hardening exponent (n).

The ***R-value*** characterises the ***normal anisotropy*** (perpendicular to the sheet's plane) of the sheet.

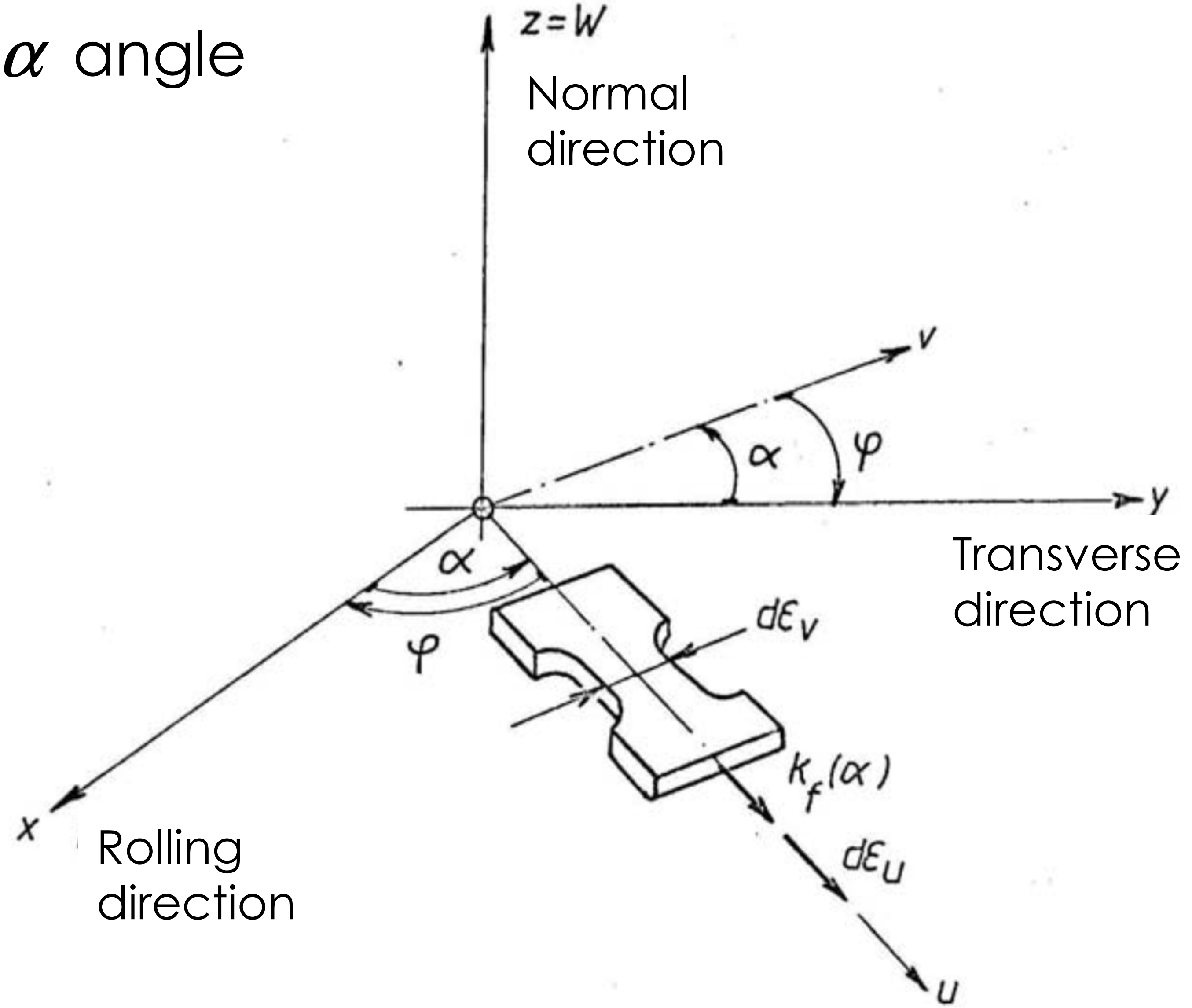
$$R_\alpha = \frac{d\varepsilon_v}{d\varepsilon_w} = \frac{\varepsilon_v}{\varepsilon_w} = \frac{\ln \frac{b}{b_0}}{\ln \frac{s}{s_0}}$$



b_o and s_o are the original, b and s the deformed dimensions. The α is the angle describing the specimen's orientation relative to the rolling direction of the sheet (see next slide).

R and n values

The α angle



R and n values

The ***Lankford coefficient*** is the weighted average of the R_α values measured in the directions 0°, 45° and 90° :

$$\bar{R} = \frac{R_0 + 2R_{45} + R_{90}}{4}$$ (normal anisotropy)

From the R_α values the ***planar anisotropy*** of the sheet also can be calculated:

$$\Delta R = \left| \frac{R_0 + R_{90}}{2} - R_{45} \right|$$ (planar anisotropy)

R and n values

The ***hardening exponent*** is the exponent of the flow curve which is also direction dependent:

$$\sigma = C\,\varphi^{n}$$

The weighted average of the ***n*** values measured in the directions 0, 45 and 90° :

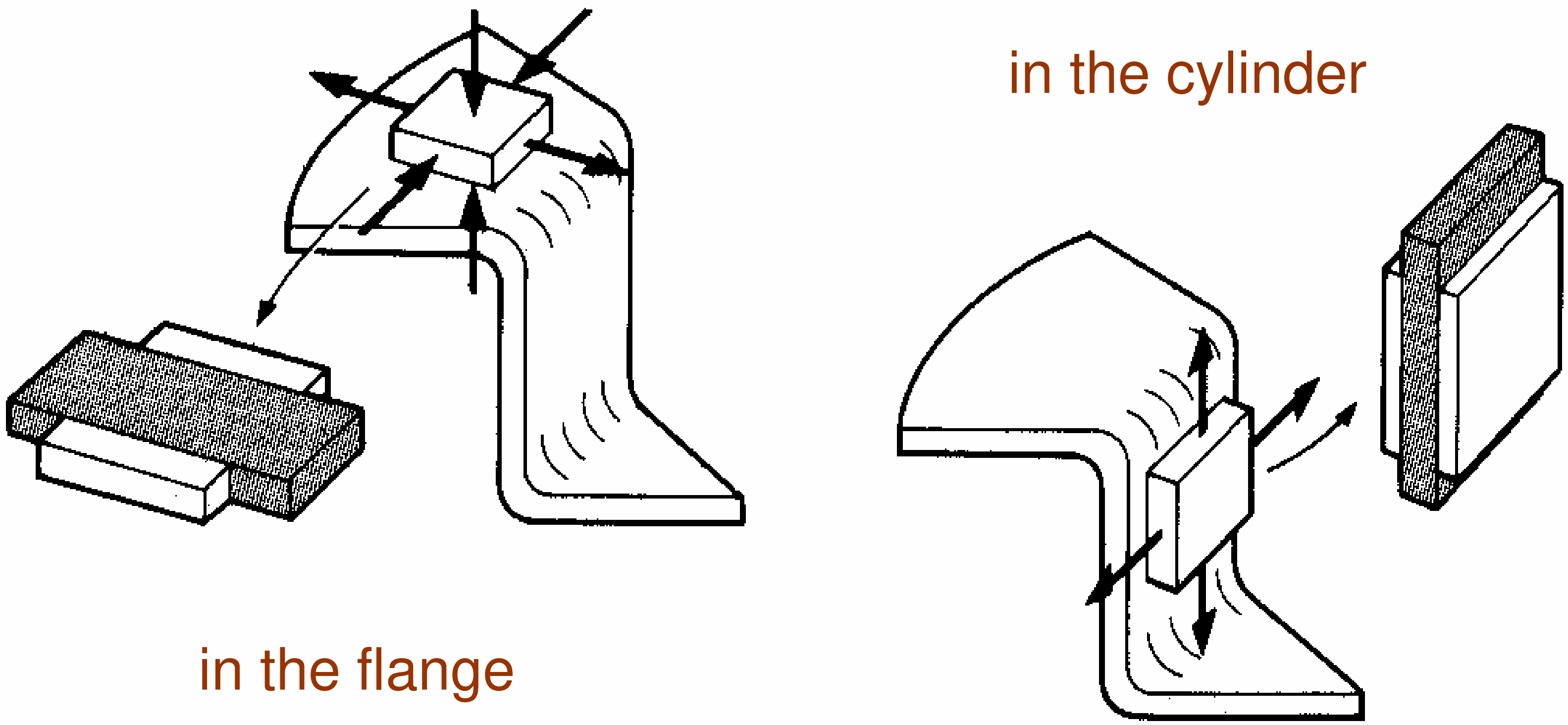
$$\bar{n} = \frac{n_0 + 2n_{45} + n_{90}}{4}$$

From the n_α values the ***planar anisotropy*** of the hardening can also be calculated:

$$\Delta n = \left| \frac{n_0 + n_{90}}{2} - n_{45} \right|$$

Connection of R and n values to deep drawing

Example: Stress and strain state during deep drawing

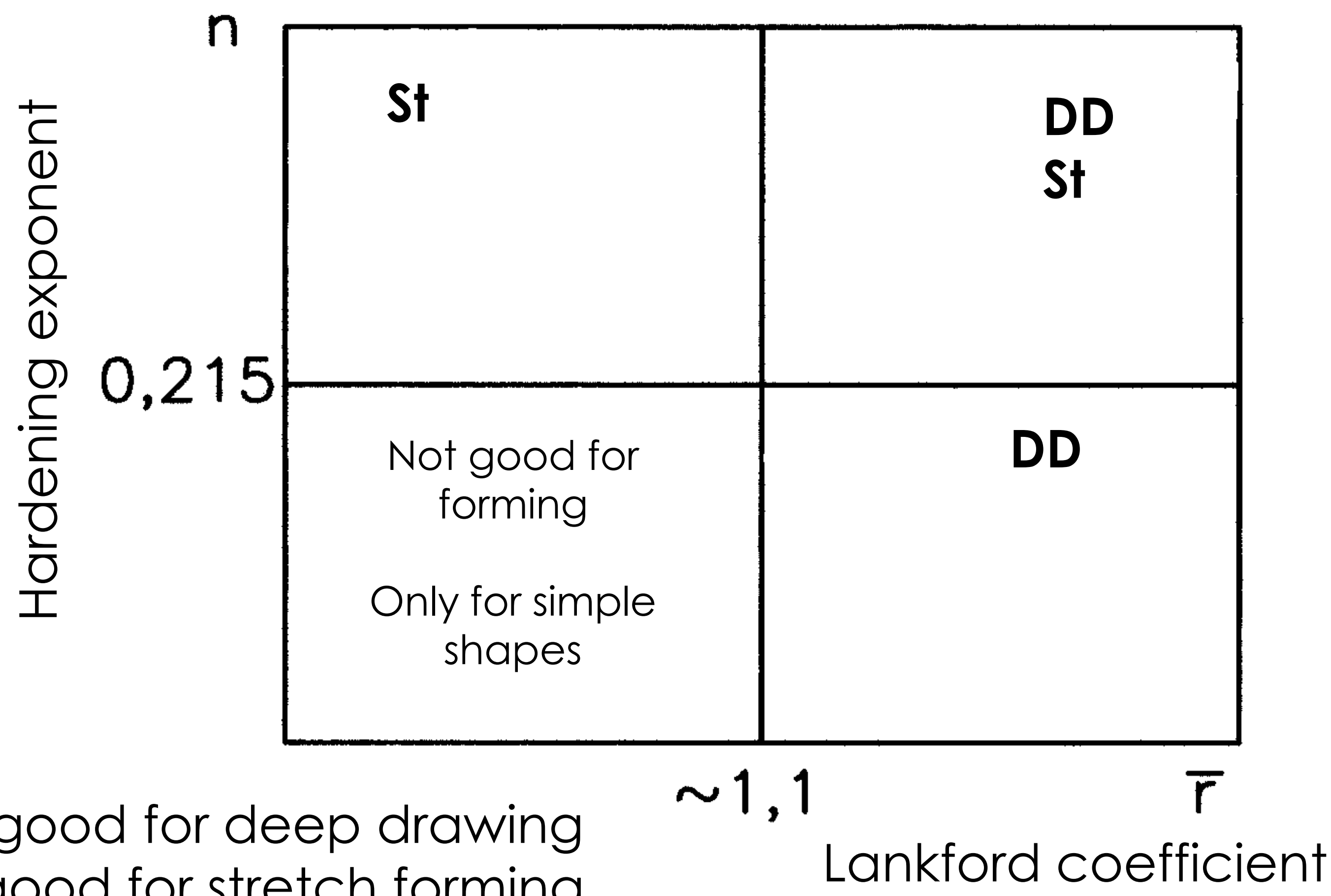


Wish: High normal anisotropy with low planar one

R and n values

Connection of R and n values to sheet forming technologies

Lillet diagram

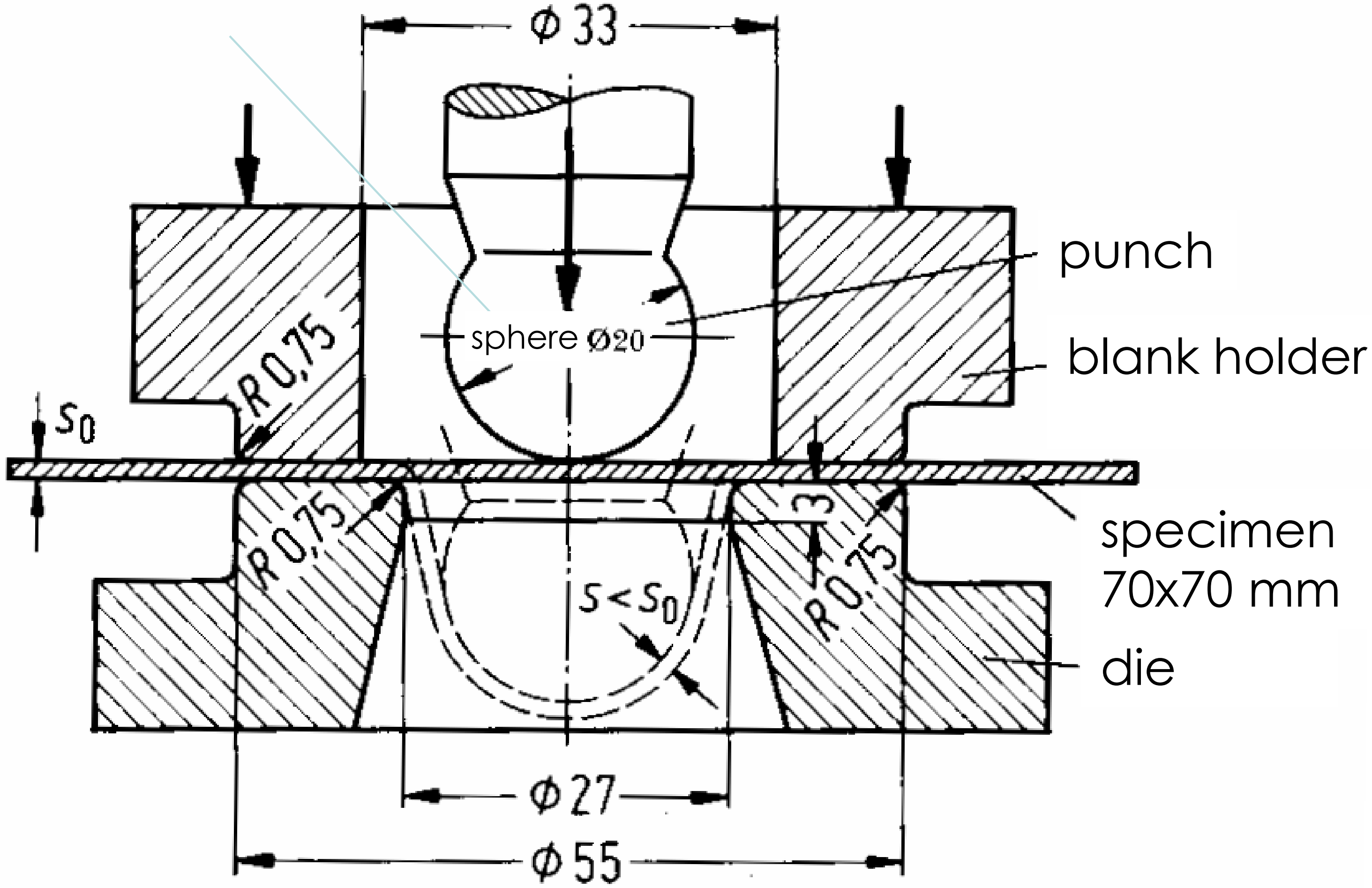


DD – good for deep drawing
St – good for stretch forming

R and n values for some materials

Jel	C N/mm²	n	R	$\bar{C}$	$\bar{n}$	$\bar{R}$
Carbon steel 0°	554,7	0,1714	1,817	552,8	0,164	1,59
Carbon steel 45°	584	0,1619	1,067			
Carbon steel 90°	488,6	0,1454	2,41			
AlMg3 0°	461.6	0.2914	0.613	405.4	0.2936	0.9675
AlMg3 45°	362.75	0.2647	1.05			
AlMg3 90°	434.4	0.2937	1.157			

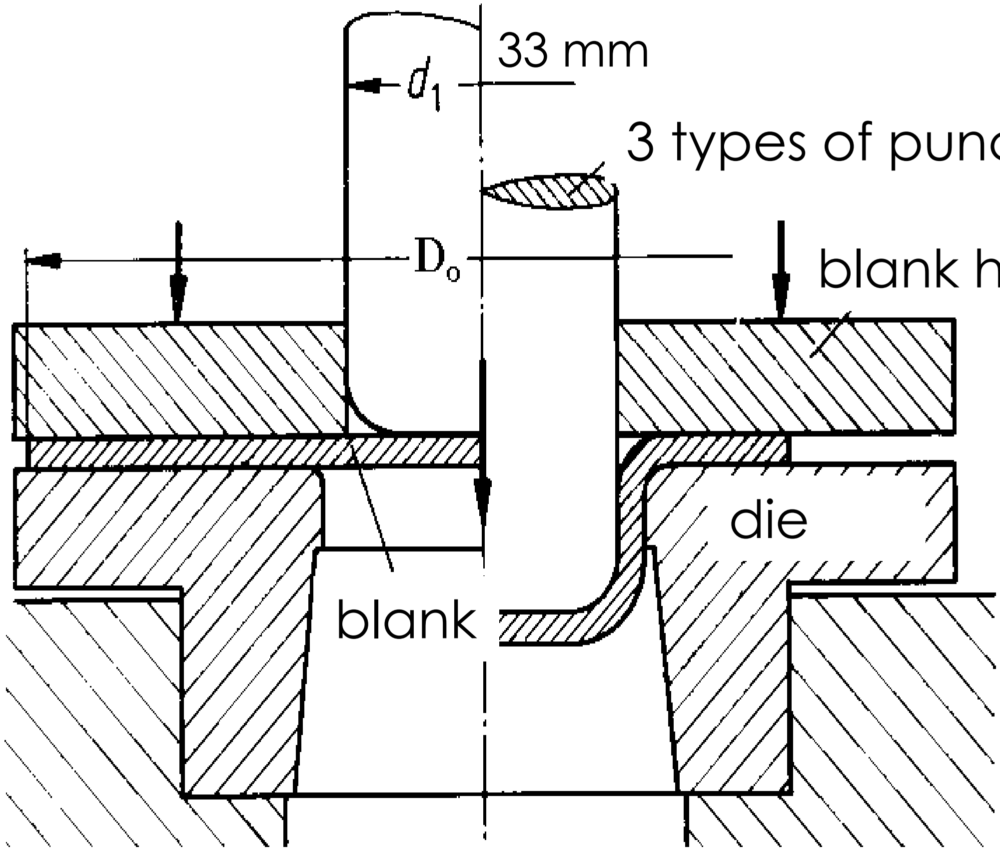
Technological tests - Erichsen test



Quantity: **displacement of the punch** from the contact till the crack of the specimen (mm)

Technological tests – deep drawing of a cup

Cup drawing

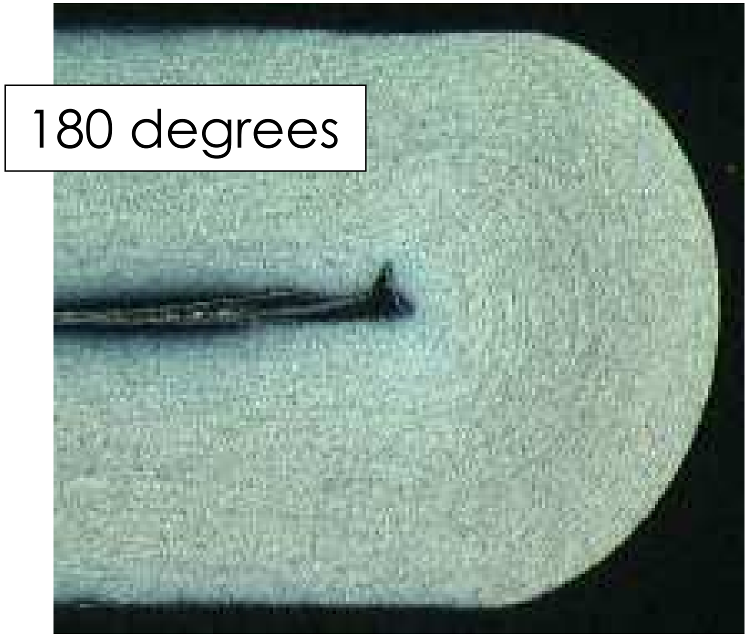


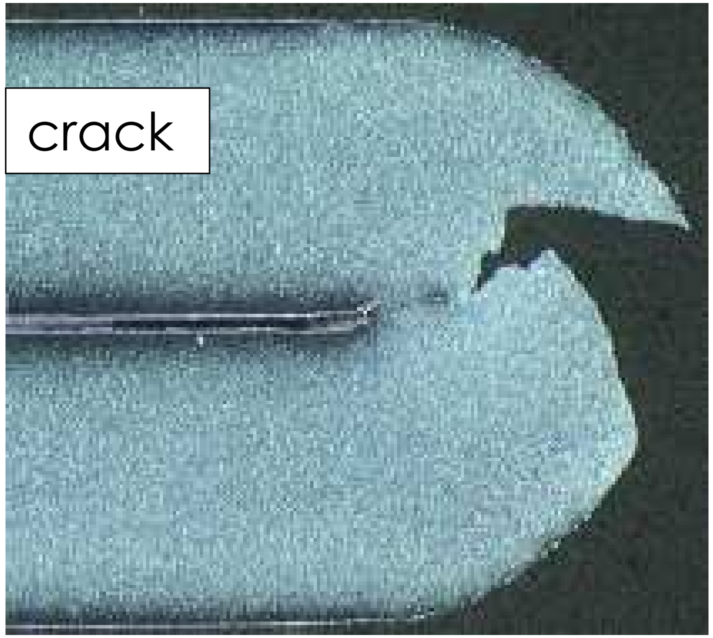
Quantity:

$$m = \frac{d_1}{D_{max}}$$

Starting from D_o = 58 mm blank diameter, by 2 mm steps till fracture (up to max. 74 mm).

Technological tests – bending





Quantity: bending angle till cracking

Thank you for your attention !