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Plate and sheet forming

Context: Materials for transport applications

- 3 credits
- Evaluation:
  - Oral exam
  - Presentation
  - Executive summary report
  - Active contribution in seminars
- Compulsory reading
  - Davies, Materials for automotive bodies, Elsevier. 2003
  - Yamagata, The science and technology of materials in automotive engines, Woodhead Publishing. 2005
- Additional literature
  - Banabic, Sheet Metal Forming Processes, Springer, 2010
  - Illig, Thermoforming: a practical guide, Hanser Verlag, 2001
  - Matthews & Rawling, Composite Materials, Elsevier, 1999

1 general aspects of plasticity

Strength and stiffness

- Stiffness
  - Determined by composition and atom binding energy
- Strength
  - Determined by
    - Composition
    - Microstructure
    - Point defects (intersitial or substitutional atoms, vacancies)
    - Dislocations
  - Affected by
    - Mechanical treatment (cold forming)
    - Heat treatment (annealing, hardening, tempering …)

Ductility

- Importance
  - Forming
  - Crash behavior
- Determined by
  - Composition
  - Microstructure
  - Point defects (interstitial or substitutional atoms, vacancies)
  - Dislocations
- Affected by
  - Mechanical treatment (cold forming)
  - Heat treatment (annealing, hardening, tempering …)

Plasticity: strain definitions

- Engineering strain / technical strain / Cauchy strain

$$e = \frac{\Delta L}{L_0} = \lambda - 1$$

- True strain / logarithmic strain / Hencky strain

$$\varepsilon = \ln\left(\frac{L_1}{L_0}\right) = \ln(\lambda)$$

- Green strain

$$\varepsilon_G = \frac{1}{2}\left(\frac{L_1^2 - L_0^2}{L_0^2}\right) = \frac{1}{2}\left(\lambda^2 - 1\right)$$

- Euler-Almansi strain

$$\varepsilon_E = \frac{1}{2}\left(\frac{L_1^2 - L_0^2}{L_1^2}\right) = \frac{1}{2}\left(1 - \frac{1}{\lambda^2}\right)$$

Stress definitions

- Cauchy stress tensor

$$\boldsymbol{\sigma} = \sigma_{ij} = \begin{bmatrix} \mathbf{T}^{(\mathbf{e}_1)} \\ \mathbf{T}^{(\mathbf{e}_2)} \\ \mathbf{T}^{(\mathbf{e}_3)} \end{bmatrix} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} \equiv \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} \equiv \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix},$$

- Principal stresses

$$|\sigma_{ij} - \lambda\delta_{ij}| = -\lambda^3 + I_1\lambda^2 - I_2\lambda + I_3 = 0$$

$$\sigma_{ij} = \begin{bmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{bmatrix}$$

$$\begin{aligned} I_1 &= \sigma_{11} + \sigma_{22} + \sigma_{33} \\ &= \sigma_{kk} \\ I_2 &= \begin{vmatrix} \sigma_{22} & \sigma_{23} \\ \sigma_{32} & \sigma_{33} \end{vmatrix} + \begin{vmatrix} \sigma_{11} & \sigma_{13} \\ \sigma_{31} & \sigma_{33} \end{vmatrix} + \begin{vmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{vmatrix} \\ &= \sigma_{11}\sigma_{22} + \sigma_{22}\sigma_{33} + \sigma_{11}\sigma_{33} - \sigma_{12}^2 - \sigma_{23}^2 - \sigma_{31}^2 \\ &= \frac{1}{2}\left(\sigma_{ii}\sigma_{jj} - \sigma_{ij}\sigma_{ji}\right) \\ I_3 &= \det(\sigma_{ij}) \\ &= \sigma_{11}\sigma_{22}\sigma_{33} + 2\sigma_{12}\sigma_{23}\sigma_{31} - \sigma_{12}^2\sigma_{33} - \sigma_{23}^2\sigma_{11} - \sigma_{31}^2\sigma_{22} \end{aligned}$$

Plane stress condition

- Principal stresses in plane stress condition

$$\sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$

- Maximum and minimum shear stress

$$\tau_{max}, \tau_{min} = \pm\sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}$$

  - In principal stress terms:

$$\tau_{\max} = \frac{1}{2}\left|\sigma_{\max} - \sigma_{\min}\right|$$

Tresca yield criterion (1864)

Hydrostatic and distortional stress

$$\sigma_{ij} = s_{ij} + \pi\delta_{ij}$$

- Hydrostatic:
  - deforms the body (changes the volume)
  - Does not cause plastic deformation

$$\pi\delta_{ij} \qquad \pi = \frac{\sigma_{kk}}{3} = \frac{\sigma_{11} + \sigma_{22} + \sigma_{33}}{3} = \tfrac{1}{3} I_1 .$$

- Distortional stress component:
  - distorts the body
  - Plastic deformation

$$s_{ij} = \sigma_{ij} - \frac{\sigma_{kk}}{3}\delta_{ij},$$

$$\begin{bmatrix} s_{11} & s_{12} & s_{13} \\ s_{21} & s_{22} & s_{23} \\ s_{31} & s_{32} & s_{33} \end{bmatrix} = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix} - \begin{bmatrix} \pi & 0 & 0 \\ 0 & \pi & 0 \\ 0 & 0 & \pi \end{bmatrix}$$

$$= \begin{bmatrix} \sigma_{11} - \pi & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} - \pi & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} - \pi \end{bmatrix}.$$

Von Mises stress / octahedral stress

- Invariants of the distortional stress tensor

$$
\begin{aligned}
J_1 &= s_{kk} = 0, \\
J_2 &= \tfrac{1}{2} s_{ij} s_{ji} \\
&= \tfrac{1}{2}(s_1^2 + s_2^2 + s_3^2) \\
&= \tfrac{1}{6}\left[(\sigma_{11}-\sigma_{22})^2 + (\sigma_{22}-\sigma_{33})^2 + (\sigma_{33}-\sigma_{11})^2\right] + \sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2 \\
&= \tfrac{1}{6}\left[(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2\right] \\
&= \tfrac{1}{3} I_1^2 - I_2, \\
J_3 &= \det(s_{ij}) \\
&= \tfrac{1}{3} s_{ij} s_{jk} s_{ki} \\
&= s_1 s_2 s_3 \\
&= \tfrac{2}{27} I_1^3 - \tfrac{1}{3} I_1 I_2 + I_3.
\end{aligned}
$$

- Von Mises stress $\sigma_{VM} = \sqrt{\frac{1}{2}\left[(\sigma_I - \sigma_{II})^2 + (\sigma_{II} - \sigma_{III})^2 + (\sigma_{III} - \sigma_I)^2\right]} = \sqrt{3J_2}$

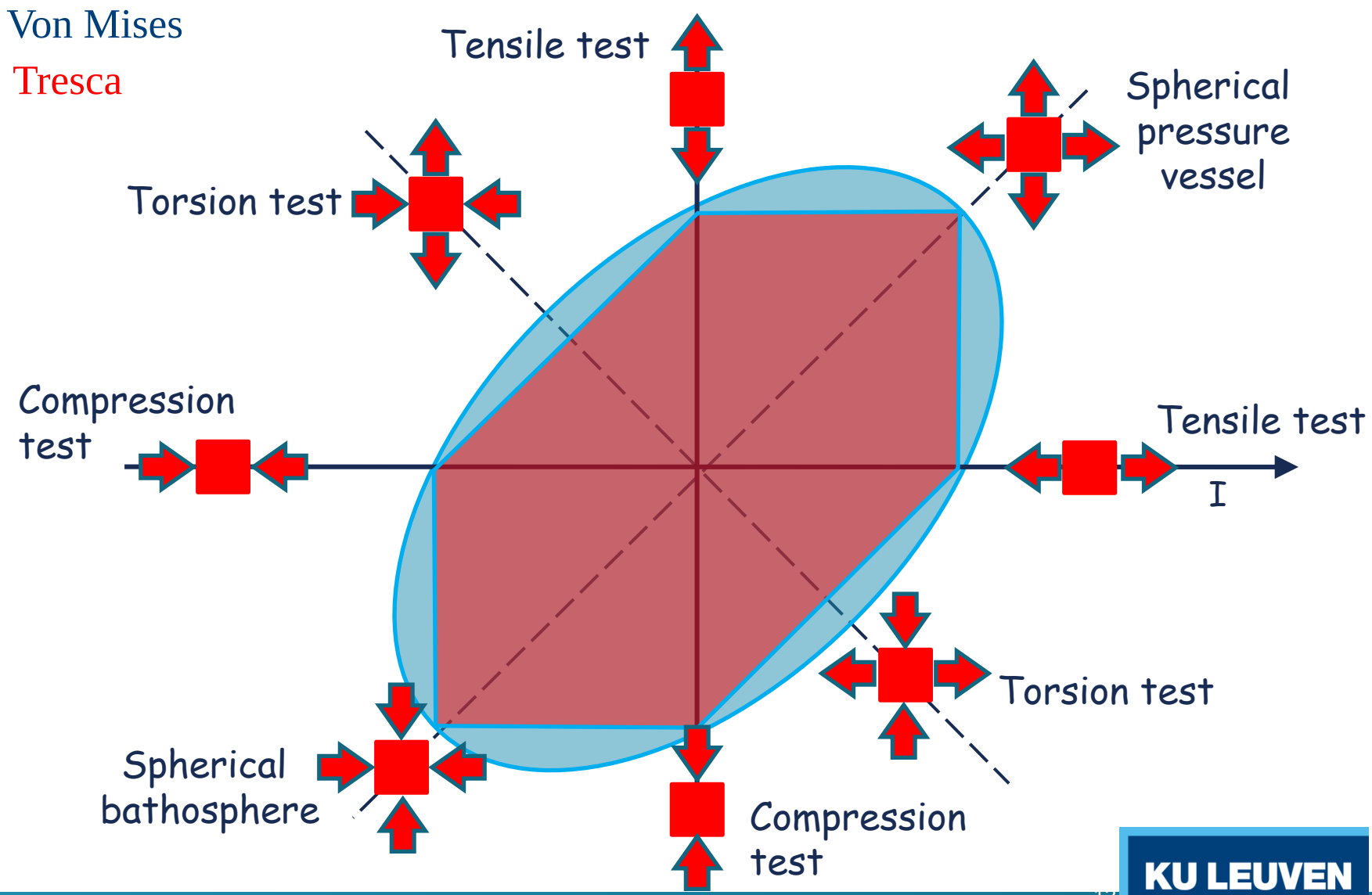
- Octahedral stress: $\tau_{oct} = \frac{1}{3}\sqrt{(\sigma_I - \sigma_{II})^2 + (\sigma_{II} - \sigma_{III})^2 + (\sigma_{III} - \sigma_I)^2} = \sqrt{\frac{2}{3} J_2}$

Huber-Mises-Hencky yield criterion

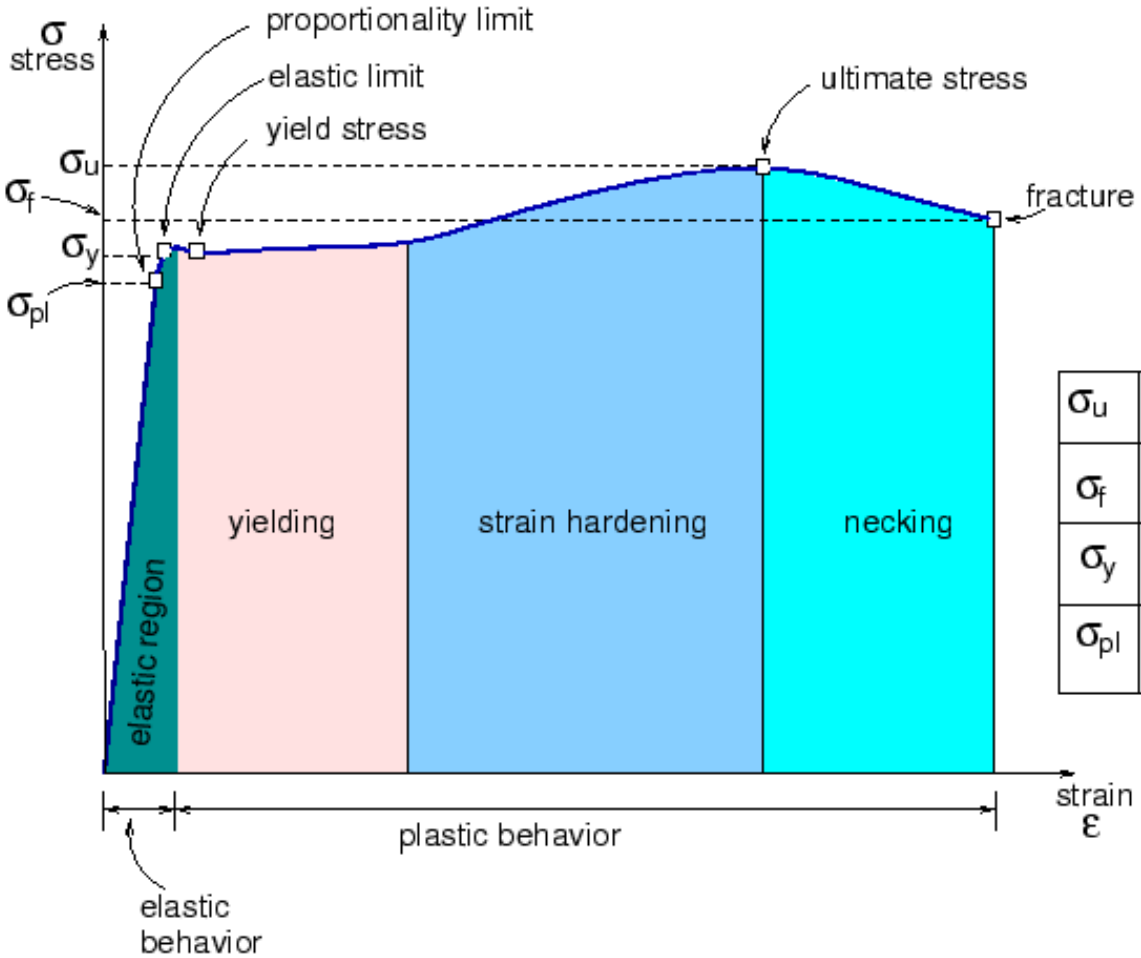
- Yielding starts when J_2 reaches a critical value

General	$2\sigma_y^2 = (\sigma_{11}-\sigma_{22})^2 + (\sigma_{22}-\sigma_{33})^2 + (\sigma_{33}-\sigma_{11})^2 + 6(\sigma_{12}^2+\sigma_{23}^2+\sigma_{31}^2)$
Principal stress	$2\sigma_y^2 = (\sigma_I - \sigma_{II})^2 + (\sigma_{II} - \sigma_{III})^2 + (\sigma_{III} - \sigma_I)^2$
Plane stress general	$\sigma_y^2 = \sigma_{11}^2 - \sigma_{11}\sigma_{22} + \sigma_{22}^2 + 3\sigma_{12}^2$
Plane stress principal	$\sigma_y^2 = \sigma_I^2 - \sigma_I\sigma_{II} + \sigma_{II}^2$
Pure shear	$\sigma_y = \sqrt{3}\lvert\sigma_{12}\rvert$
uniaxial	$\sigma_y = \sigma_1$

Graphic representation



Uniaxial loading



σ_u	Ultimate stress
σ_f	Fracture stress
σ_y	Yield stress
σ_{pl}	Proportionality limit

2 Forming processes

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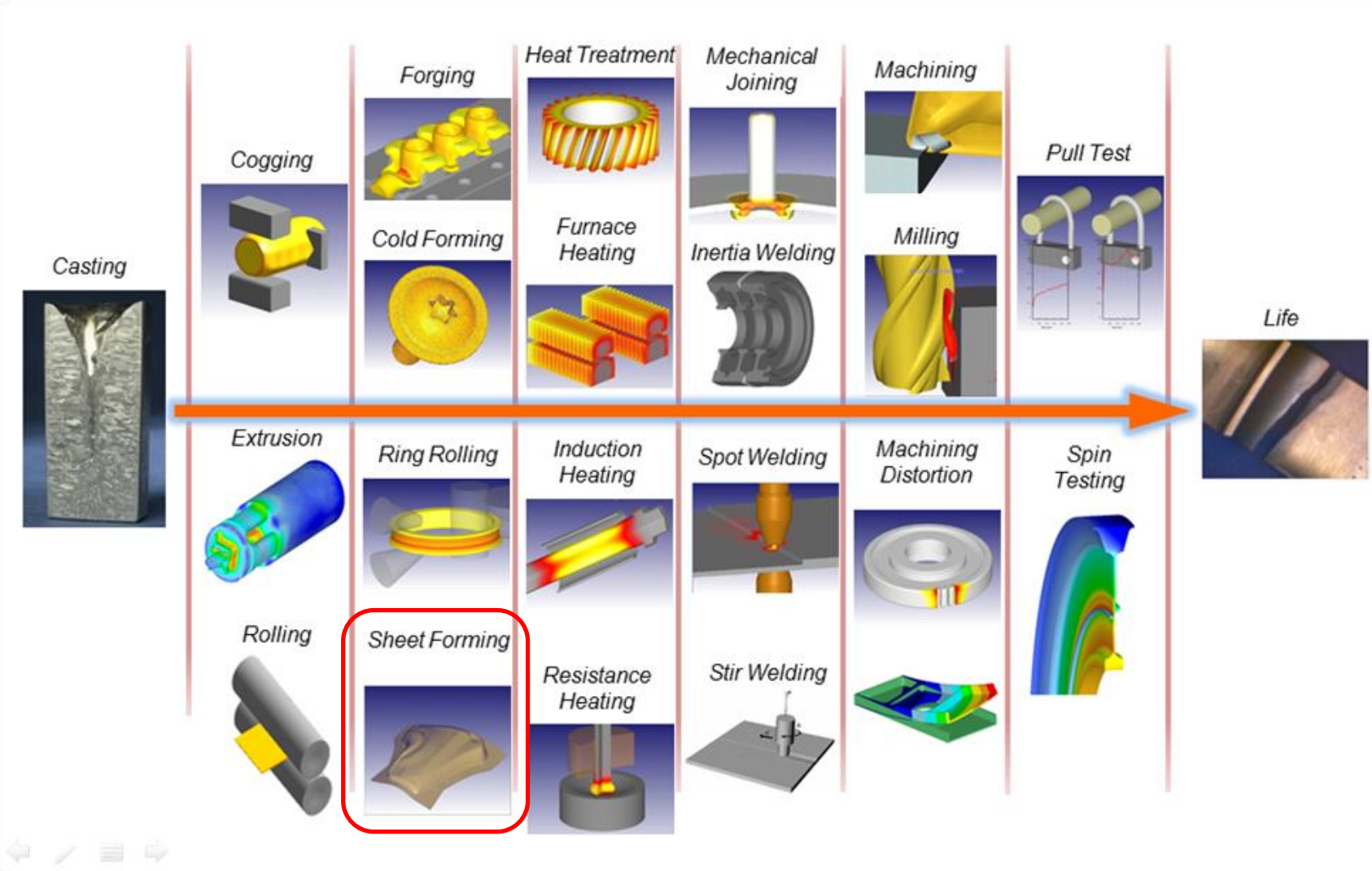
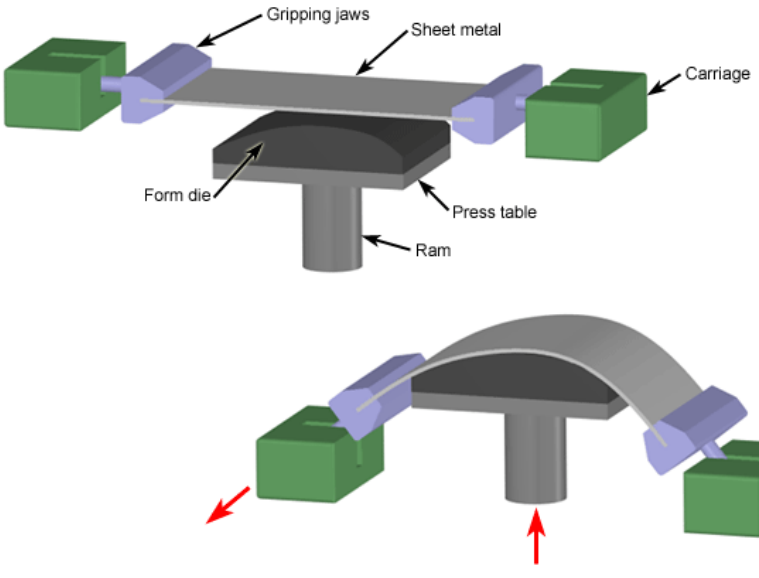
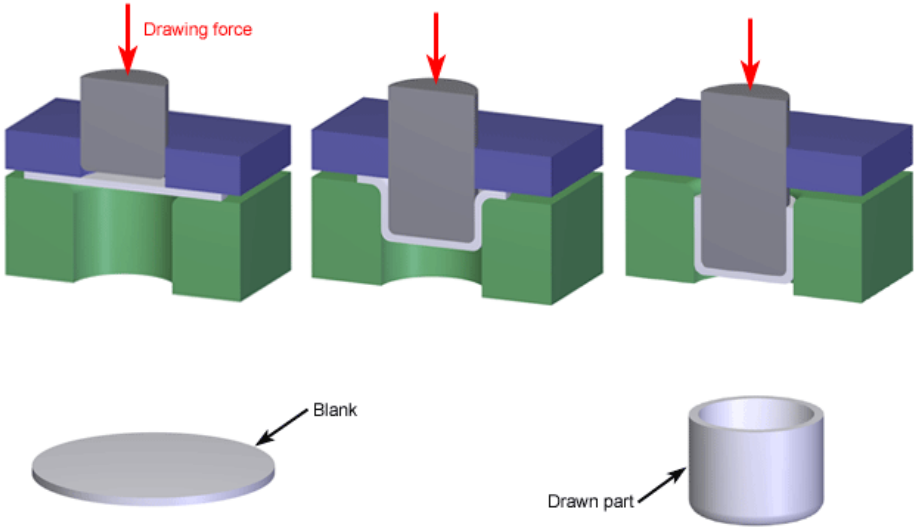
Shaping processes

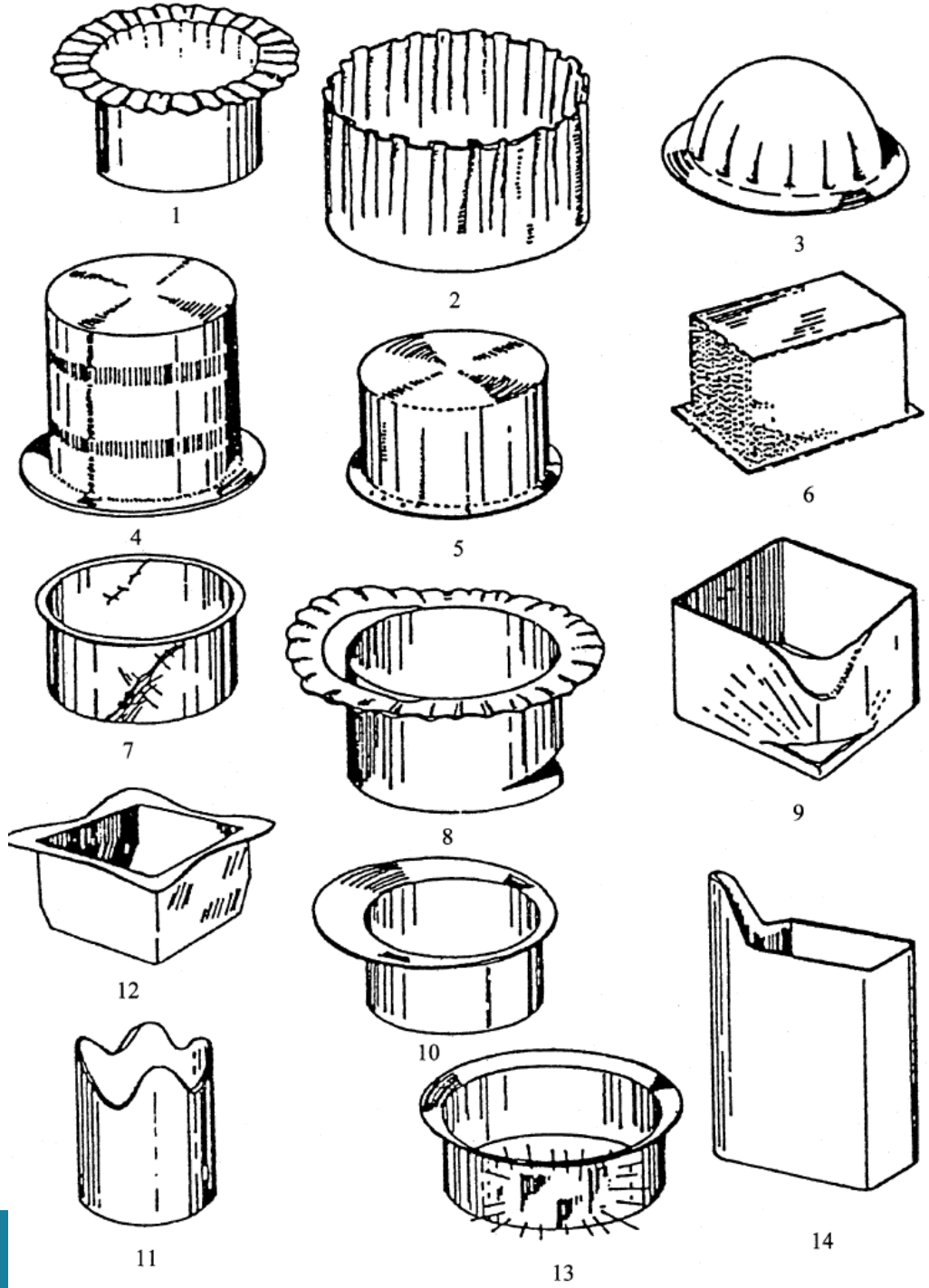


Stretch forming – deep drawing

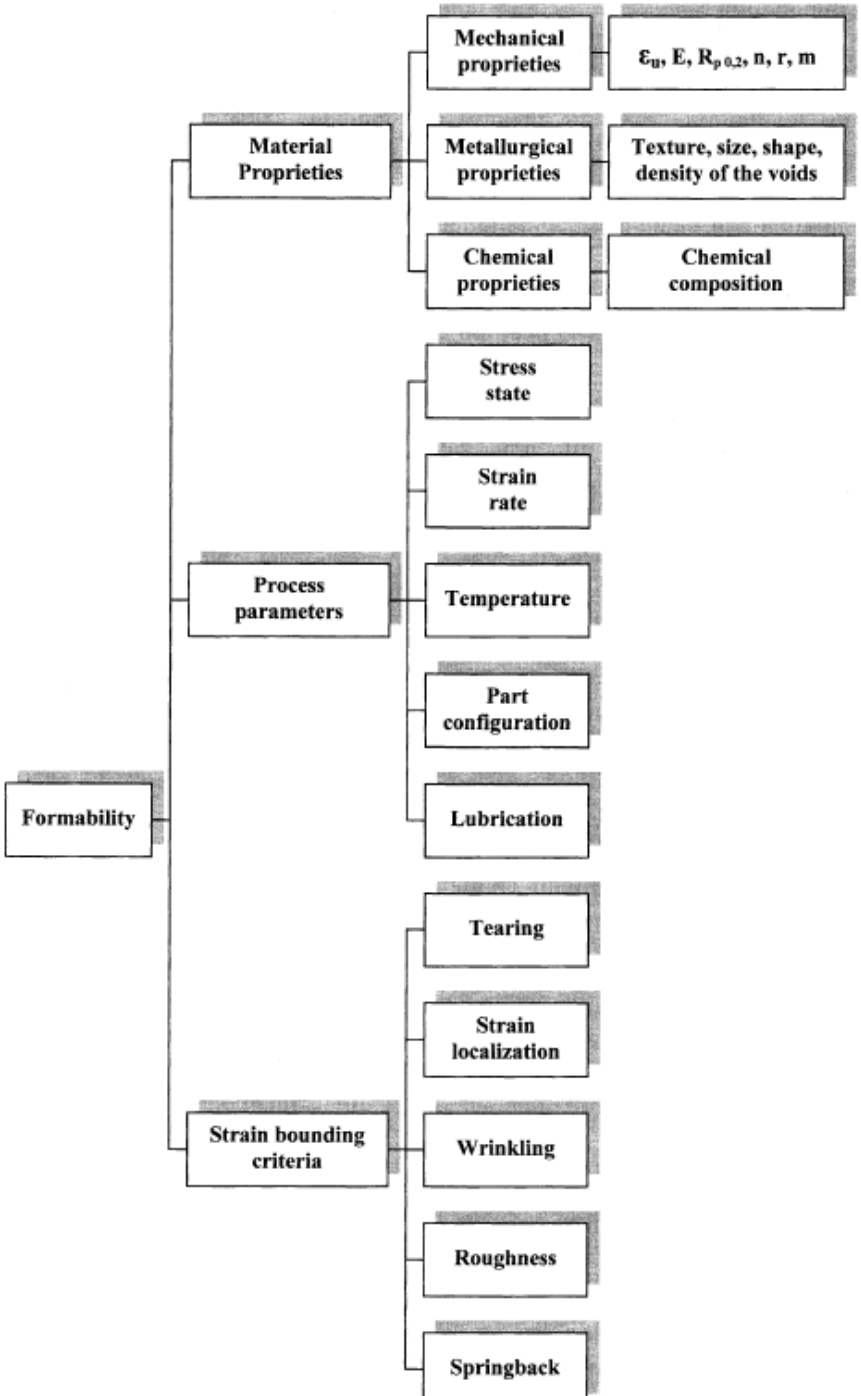




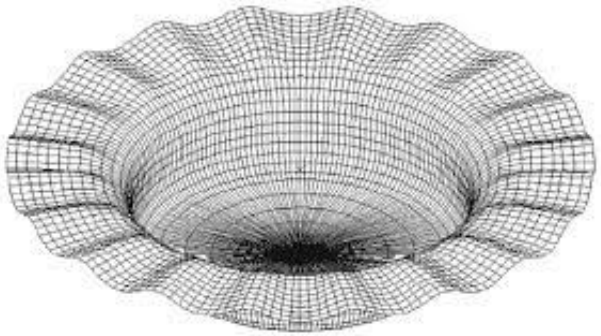
Defects in deep drawing

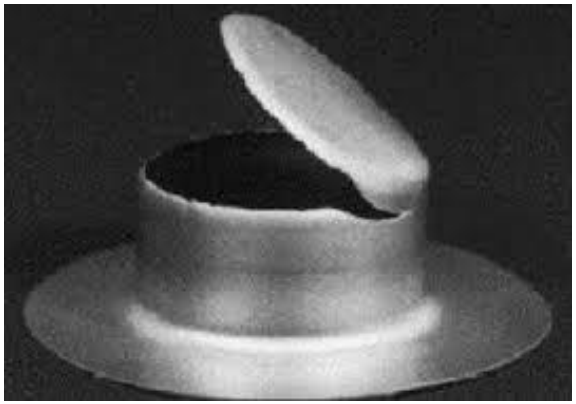


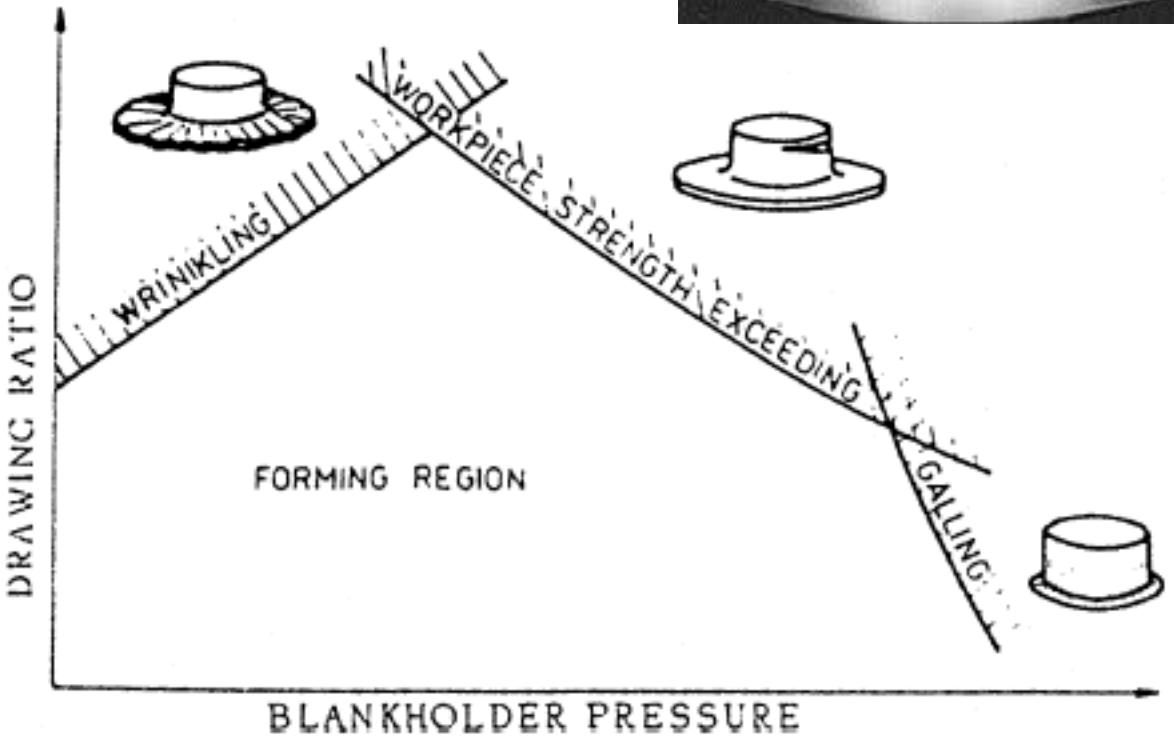
Parameters influencing formability

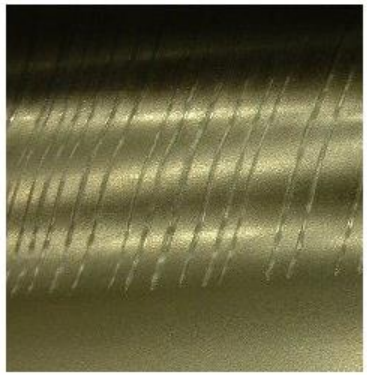


Example









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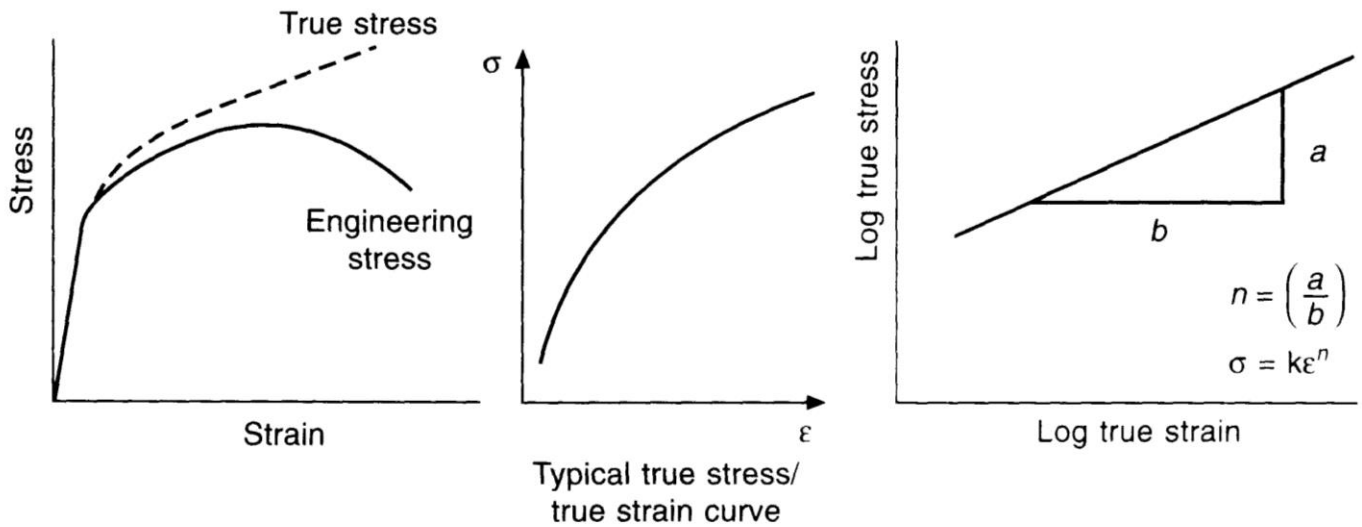
3 formability of metals

Formability definitions

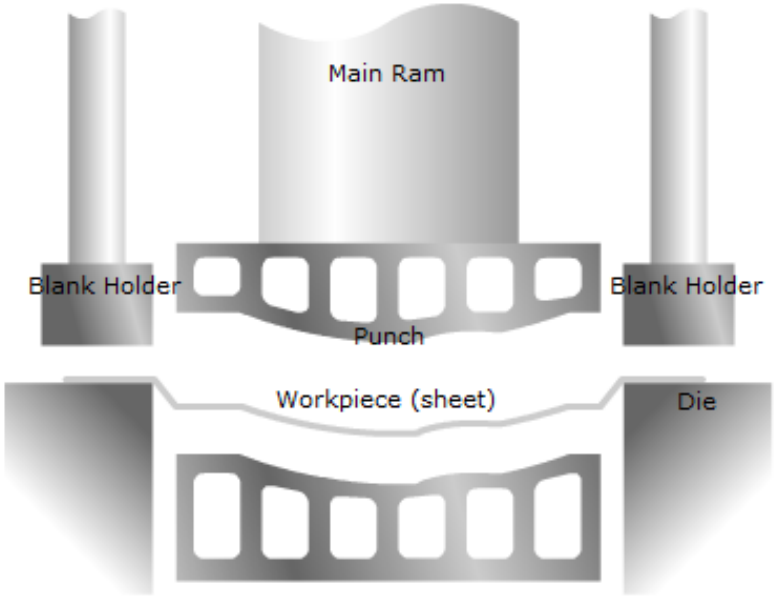
- Work-hardening factor ‘n’
  - Strengthening during plastic deformation



  - Related to stretching
  - Important for energy absorption and impact

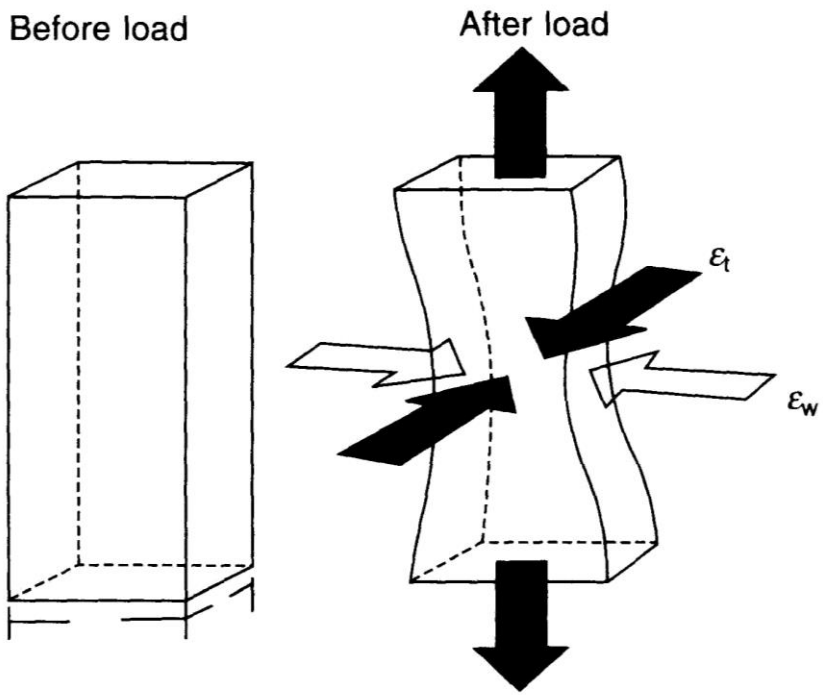
Importance of work hardening n

- Importance:
  - Stretch forming
  - Energy absorption
- Determined by microstructure; dislocations, point defects :
  - composition
  - Heat treatment



Formability definitions

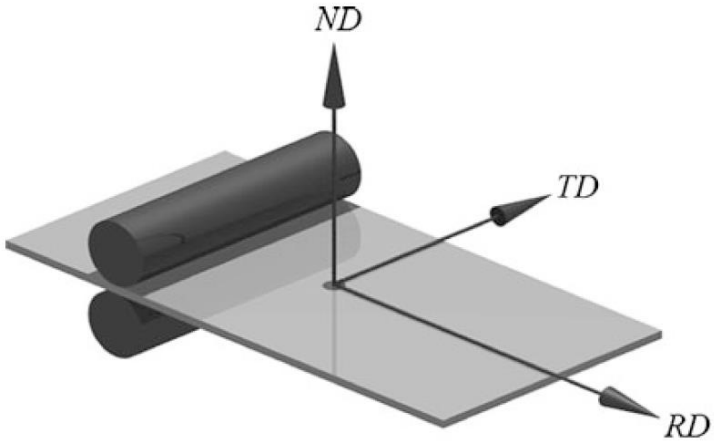
- Anisotropy factor r
  - Related to part thinning during deformation

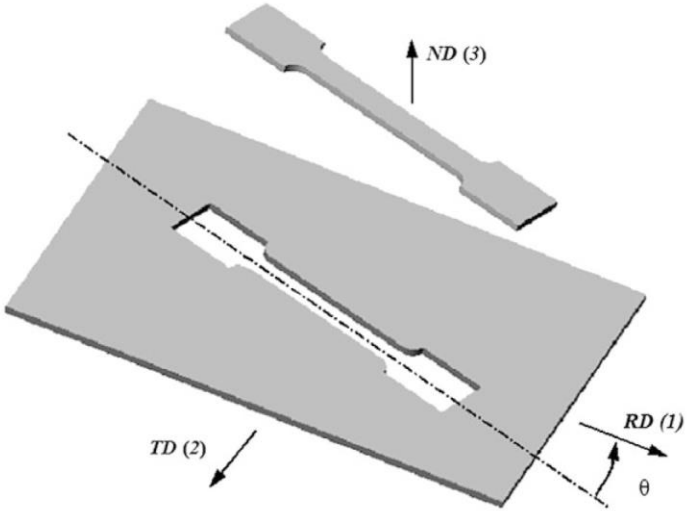


$$r = \frac{\varepsilon_w}{\varepsilon_t} = \frac{\text{True strain in width direction}}{\text{True strain in thickness direction}}$$

$$r = \frac{\varepsilon_w}{\varepsilon_t} = \frac{\varepsilon_w}{-\varepsilon_w - \varepsilon_l}$$

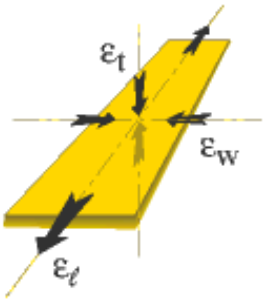
Directional dependence of r

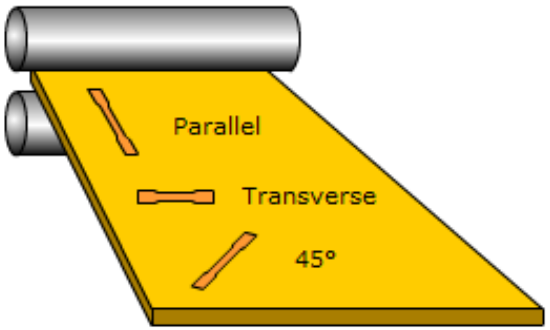




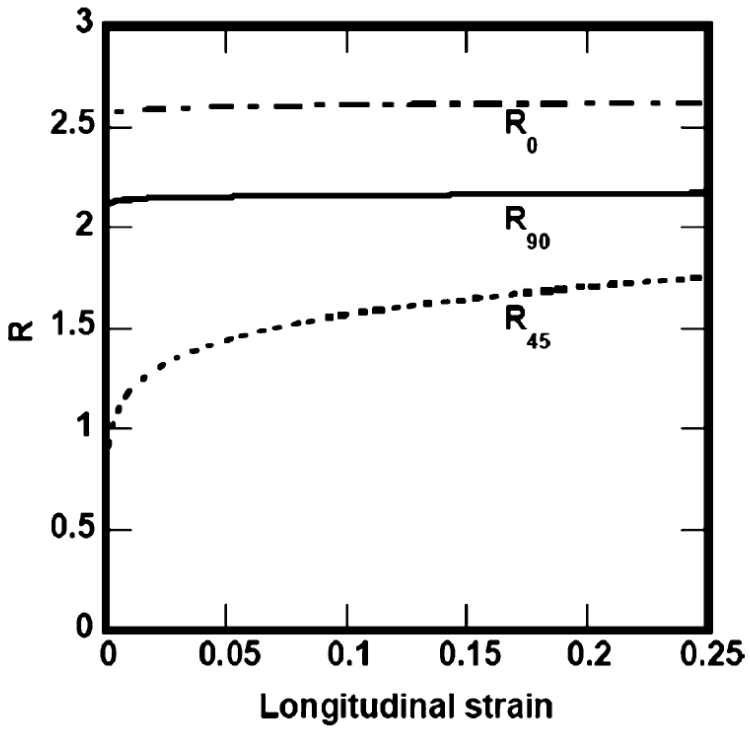
Coefficient of normal anisotropy

$$\overline{r_m} = \frac{r_{0°} + 2r_{45°} + r_{90°}}{4}$$





- Depends on strain

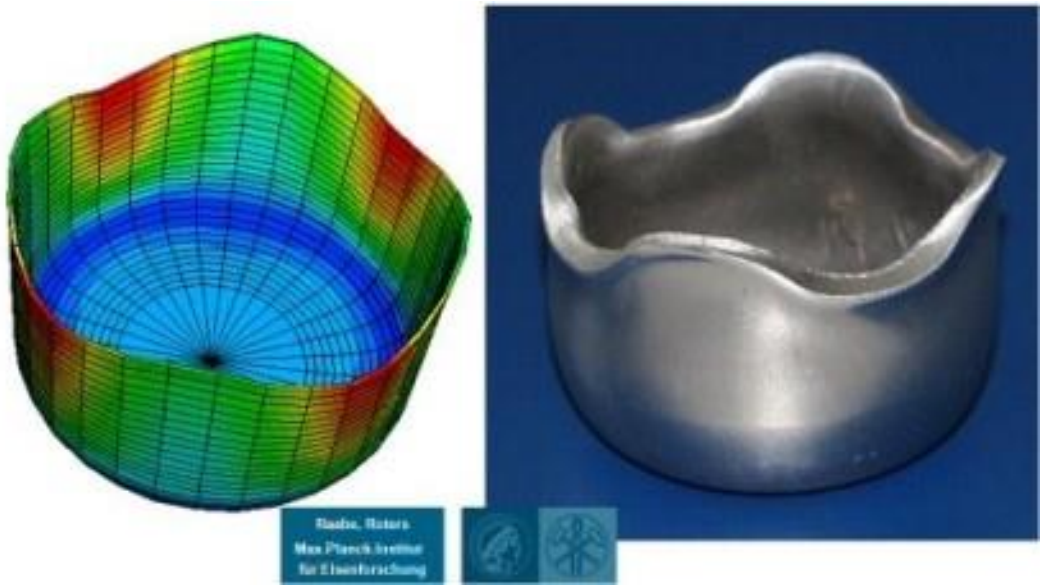


Planar anisotropy

- Variation of normal anisotropy

$$\Delta r = \frac{r_{0^\circ} - 2r_{45^\circ} + r_{90^\circ}}{4}$$

- Responsible for earing



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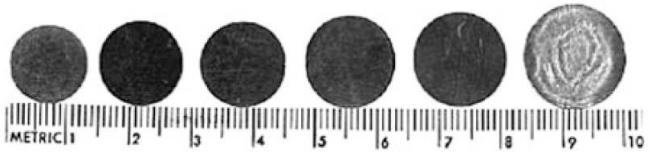
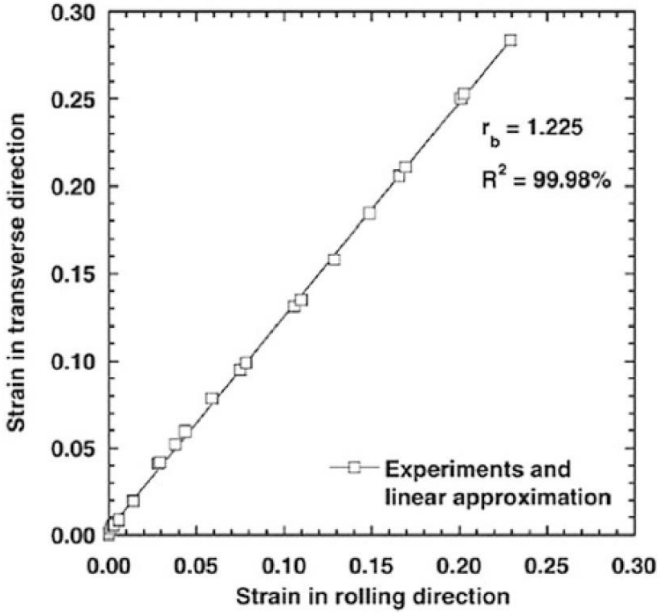
Biaxial anisotropy coefficient

$$r_b = \frac{\varepsilon_{TD}}{\varepsilon_{RD}}$$

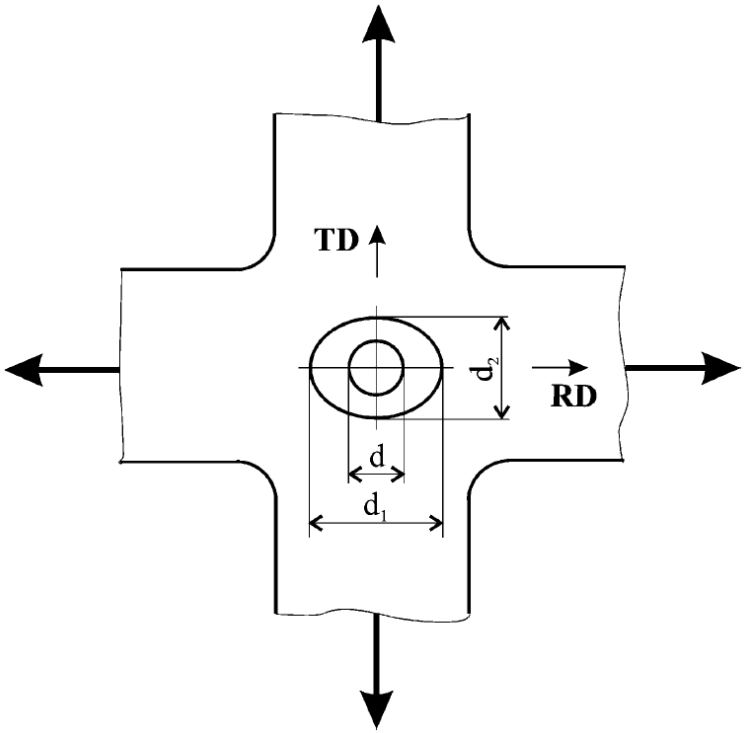
- Barlat
  - Flatwise compression





Pöhland

° Biaxial tension



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Consequences of anisotropy

- Tresca and Von Mises criteria no longer valid
- More yield stresses needed

- Yield criterion for anisotropic materials: Hill1948

$$F(\sigma_2-\sigma_3)^2+G(\sigma_3-\sigma_1)^2+H(\sigma_1-\sigma_2)^2+\left(2L\sigma_{23}^2+2M\sigma_{13}^2+2N\sigma_{12}^2\right)=1$$

$$2F=\frac{1}{Y^2}+\frac{1}{Z^2}-\frac{1}{X^2} \qquad 2L=\frac{1}{R^2}$$

$$2G=\frac{1}{X^2}+\frac{1}{Z^2}-\frac{1}{Y^2} \qquad 2M=\frac{1}{S^2}$$

$$2H=\frac{1}{X^2}+\frac{1}{Y^2}-\frac{1}{Z^2} \qquad 2N=\frac{1}{T^2}$$

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Hill 1990

$$\varphi = |\sigma_{11} + \sigma_{22}|^m + \left(\sigma_b^m / \tau^m\right) \left|(\sigma_{11} - \sigma_{22})^2 + 4\sigma_{12}^2\right|^{m/2} + \left|\sigma_{11}^2 + \sigma_{22}^2 + 2\sigma_{12}^2\right|^{(m/2)-1}$$

$$\cdot \left\{-2a\left(\sigma_{11}^2 - \sigma_{22}^2\right) + b\left(\sigma_{11} - \sigma_{22}\right)^2\right\} = (2\sigma_b)^m$$

σ_b: yield stress in biaxial tension

τ: yield stress in pure shear

$$m = \frac{\ln\left[2\left(r_{45} + 1\right)\right]}{\ln \dfrac{2\sigma_b}{\sigma_{45}}}$$

$$a = \frac{(r_0 - r_{90})\left[1 - \left((m-2)/2\right) \cdot r_{45}\right]}{(r_0 + r_{90}) - (m-2) \cdot r_0 \cdot r_{90}};$$

$$b = \frac{m \cdot \left[2 \cdot r_0 \cdot r_{90} - r_{45} \cdot (r_0 + r_{90})\right]}{(r_0 + r_{90}) - (m-2) \cdot r_0 \cdot r_{90}}.$$

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Further developments

- New criteria for the complex steel alloys for automotive

Table 2.3 The mechanical parameters needed for the identification of several yield criteria

Author, year	σ_0	σ_{30}	σ_{45}	σ_{75}	σ_{90}	σ_b	r_0	r_{30}	r_{45}	r_{75}	r_{90}	r_b	3D	A1	A2
Hill's family															
Hill 1948	x						x		x		x		x		
Hill 1979	x					x	x						x	x	
Hill 1990	x		x		x	x			x					x	
Hill 1993	x				x	x	x				x			x	x
Lin, Ding 1996	x				x	x	x		x		x			x	x
Hu 2005					x	x	x		x		x		x	x	x
Leacock 2006					x	x	x		x		x			x	x
Hershey's family															
Hosford 1979	x						x				x		x	x	
Barlat 1989	x						x				x			x	
Barlat 1991	x		x		x	x							x	x	
Karafillis Boyce 1993	x		x		x		x		x		x		x	x	x
Barlat 1997	x		x		x	x	x		x		x		x	x	x
BBC 2000	x		x		x	x	x		x		x		x	x	x
Barlat 2000	x		x		x	x	x		x		x			x	x
Bron, Besson 2003	x		x		x	x	x		x		x	x	x	x	x
Barlat 2004	x		x		x	x	x		x		x	x	x	x	x
BBC 2005	x		x		x	x	x		x		x	x	x	x	x
Drucker's family															
Cazacu–Barlat 2001	x	x	x	x	x	x	x	x	x	x	x		x	x	x
Cazacu–Barlat 2003	x	x	x	x	x	x	x	x	x	x	x		x	x	x
C-P – B 2006	x	x	x	x	x	x	x	x	x	x	x		x	x	x
Polinomial criteria															
Comsa 2006	x		x		x	x	x		x		x	x	x	x	x
Soare 2007 (Poly 4)	x	x	x		x	x	x		x		x	x	x	x	x

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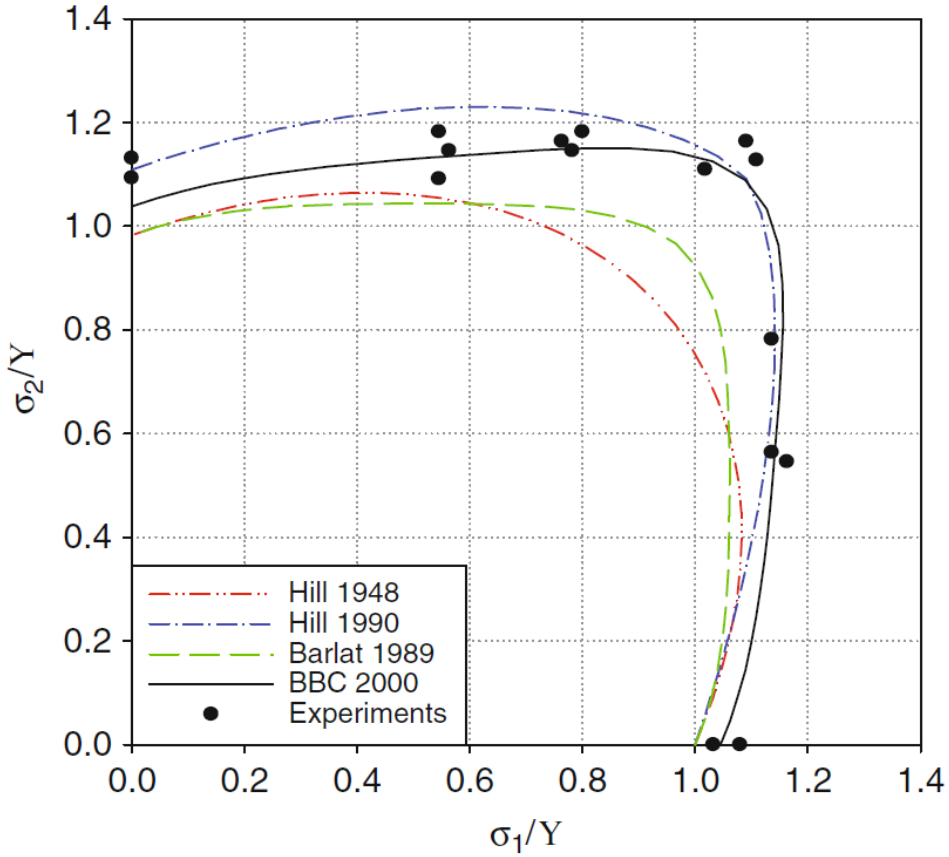
Experimental correlation



- Further reading: *D. Banabic, Sheet Metal Forming Processes, Springer, 2010*

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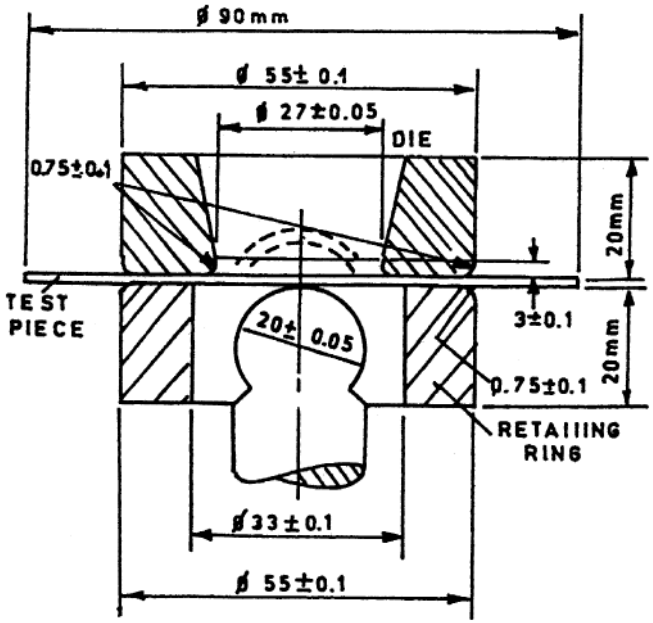
4 Determination of formability

- Tensile tests
  - n
  - r
  - Plasticity during necking

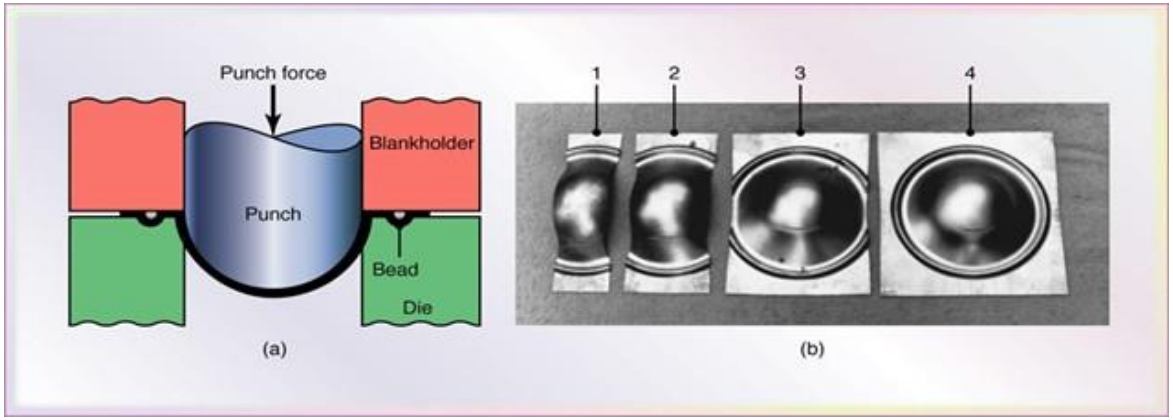
- Forming limit tests
  - Punch stretching methods: Erichsen test, Hecker test
  - Deep drawing methods: Swift test
  - Forming limit methods: Nakazima test

Punch stretching methods

- Erichsen test
  - Indentation depth (mm)



- Hecker test



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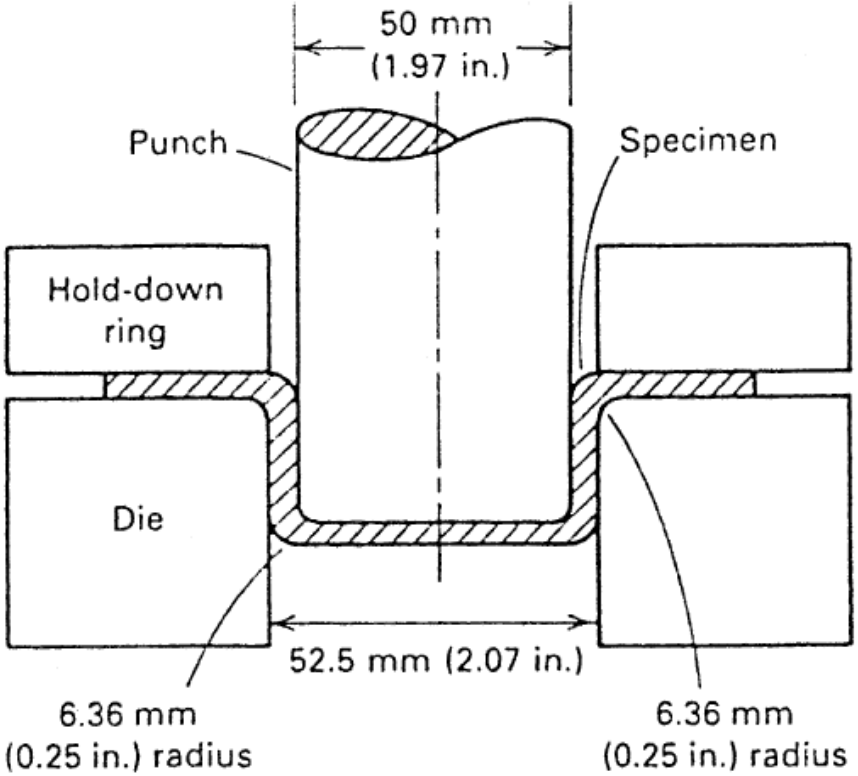
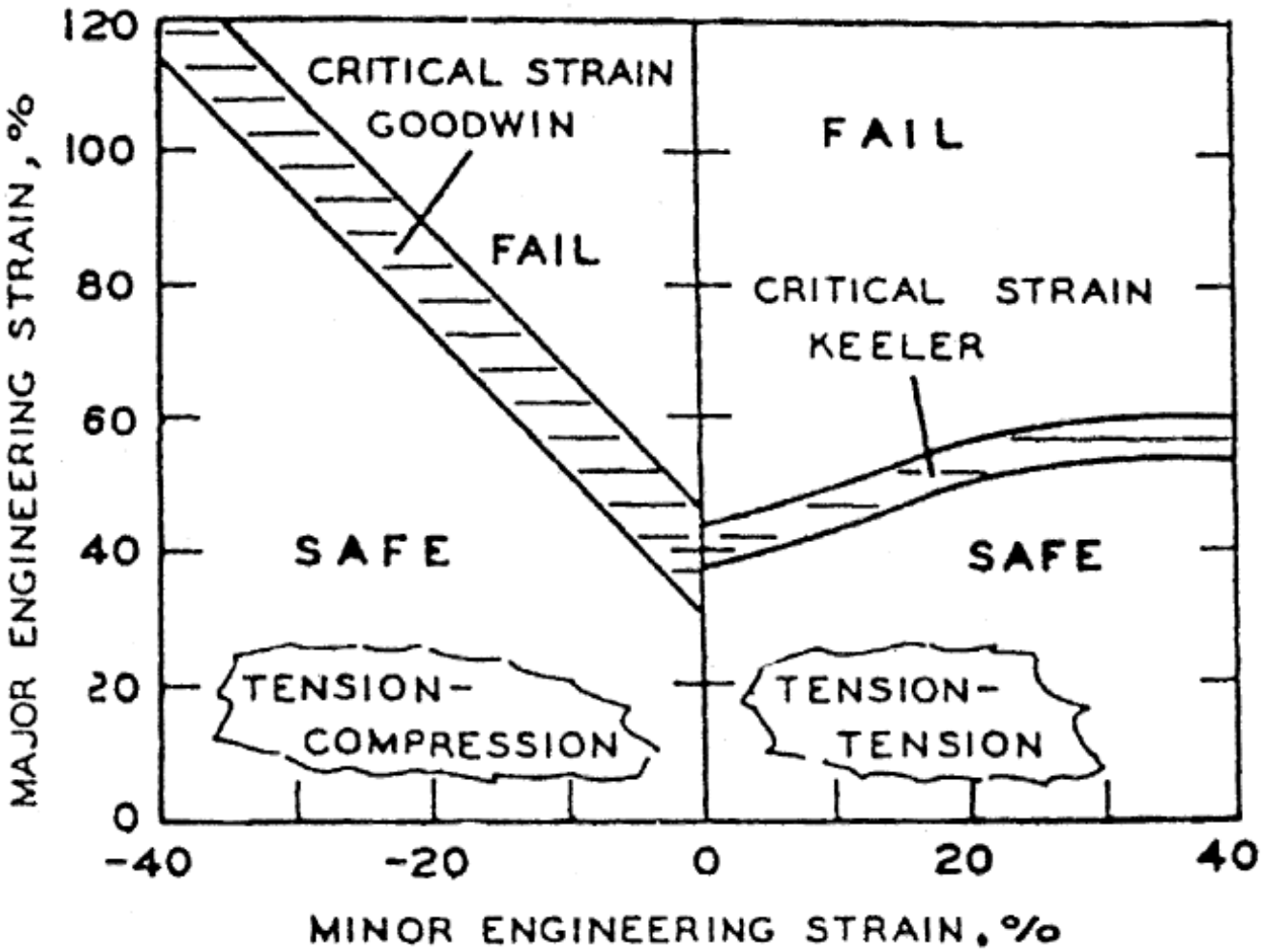
Deep drawing methods

- Swift test
  - Limit drawing ratio

$$\mathrm{LDR} = \frac{D_{max}}{d}$$

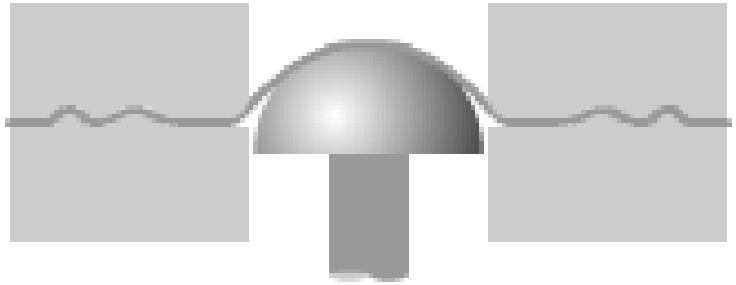


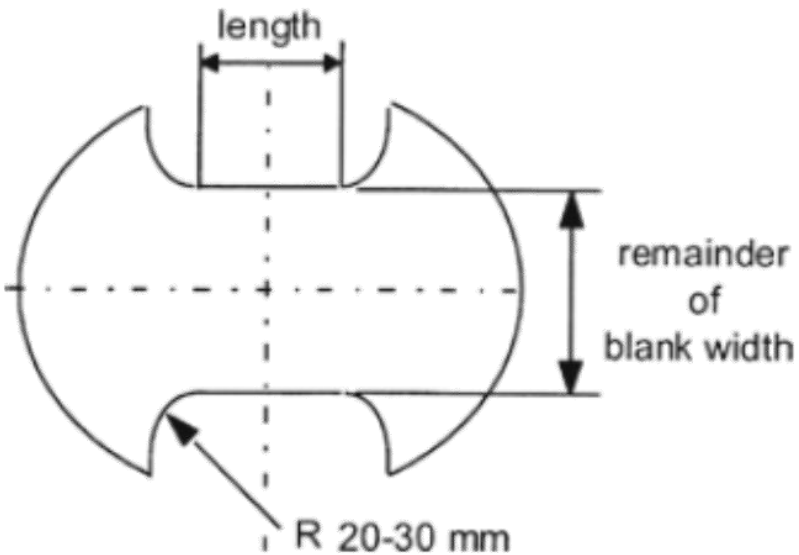
Forming limit strain diagram



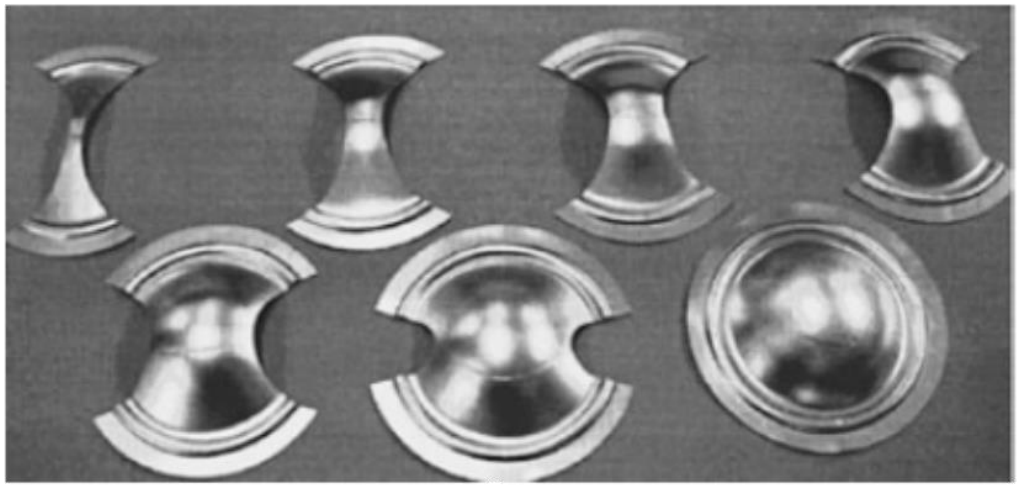
Nakazima test

- Forming test with varying boundary conditions





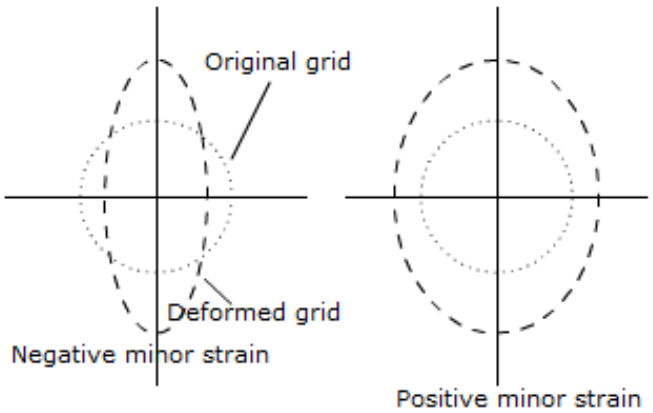
a)

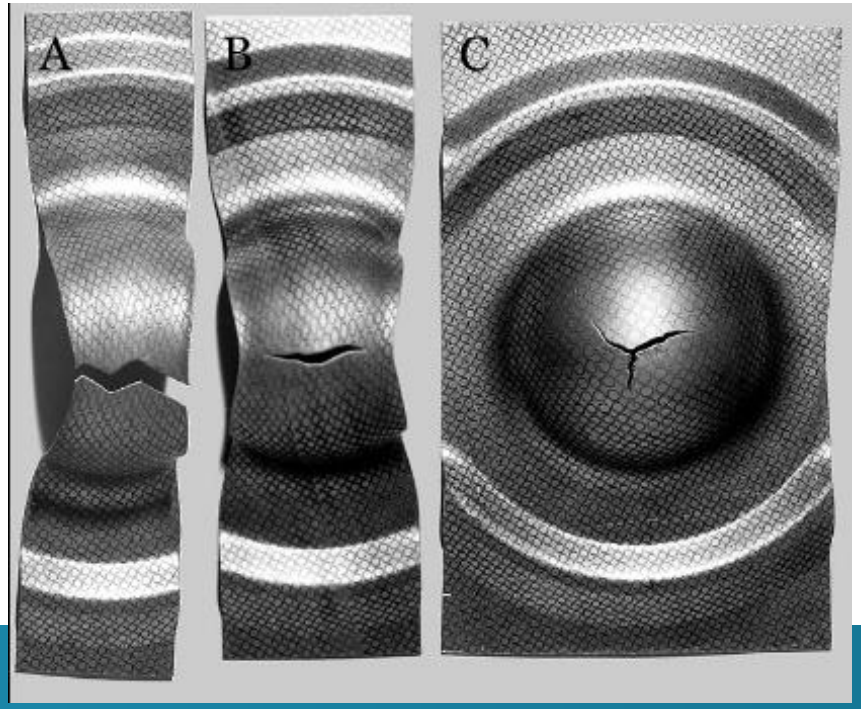


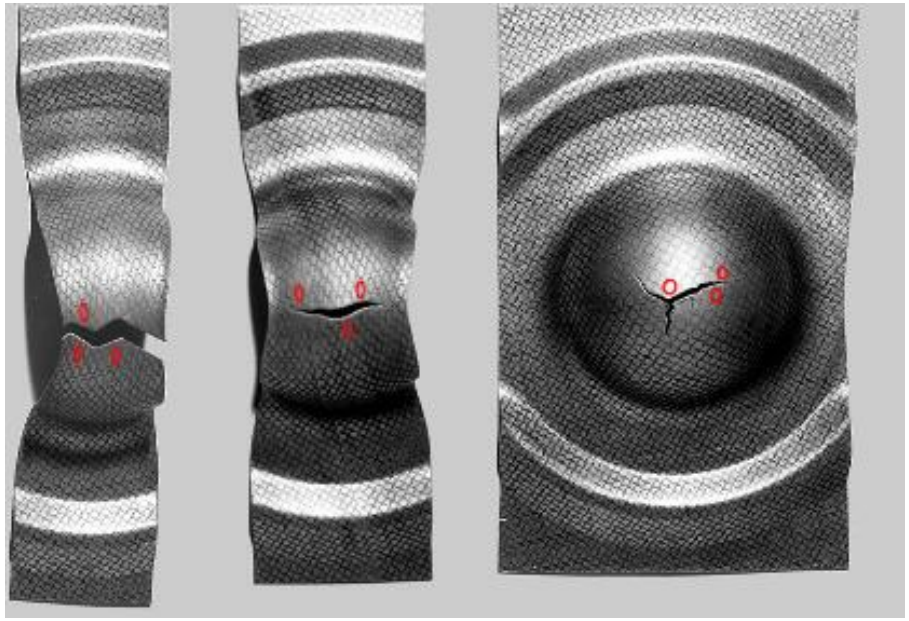
b)

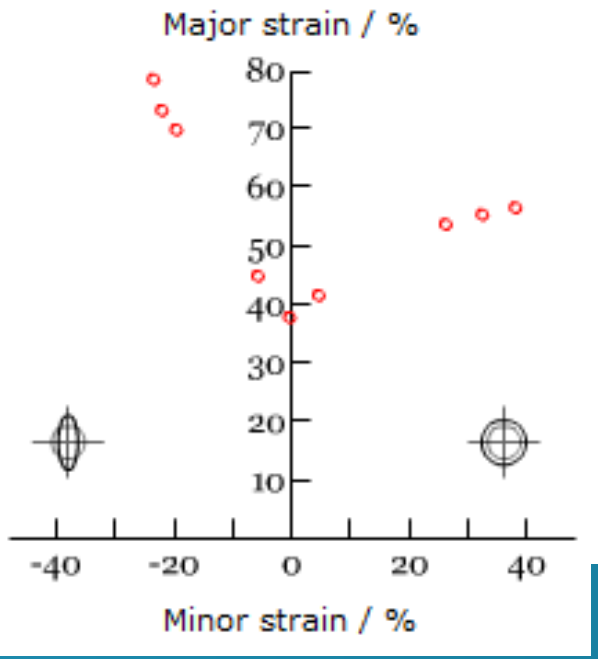
Determination of deformability limits: Hecker method

- Deformation of a printed circular grid
  - Largest strain ε_1
    - Always positive
  - Smallest strain ε_2
    - Positive or negative

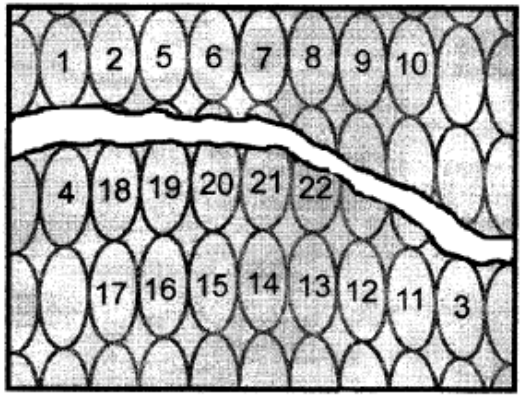




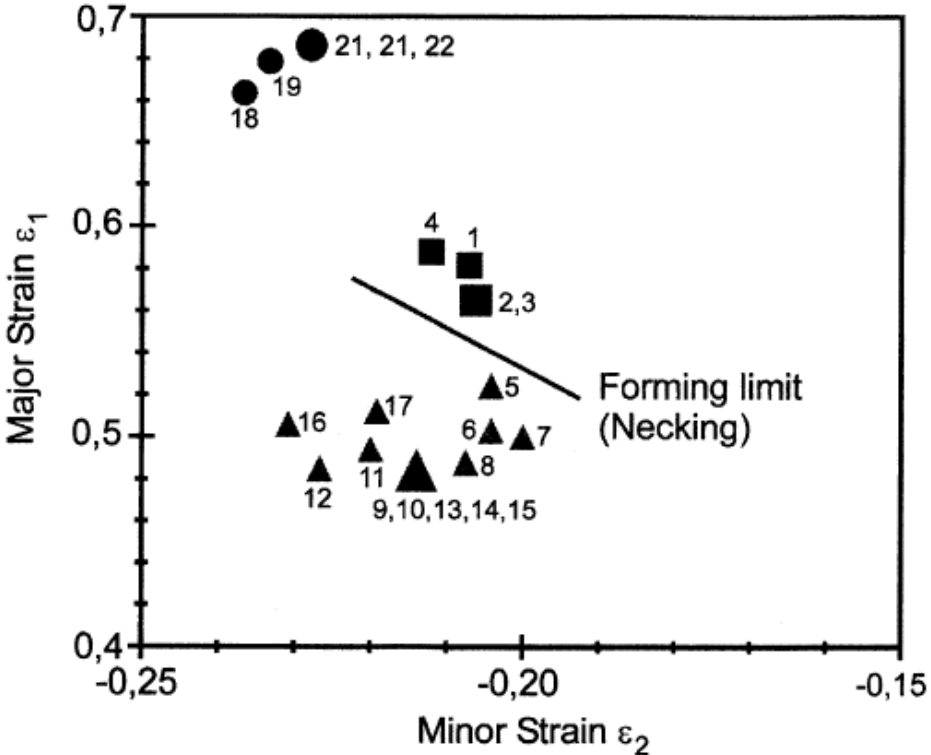


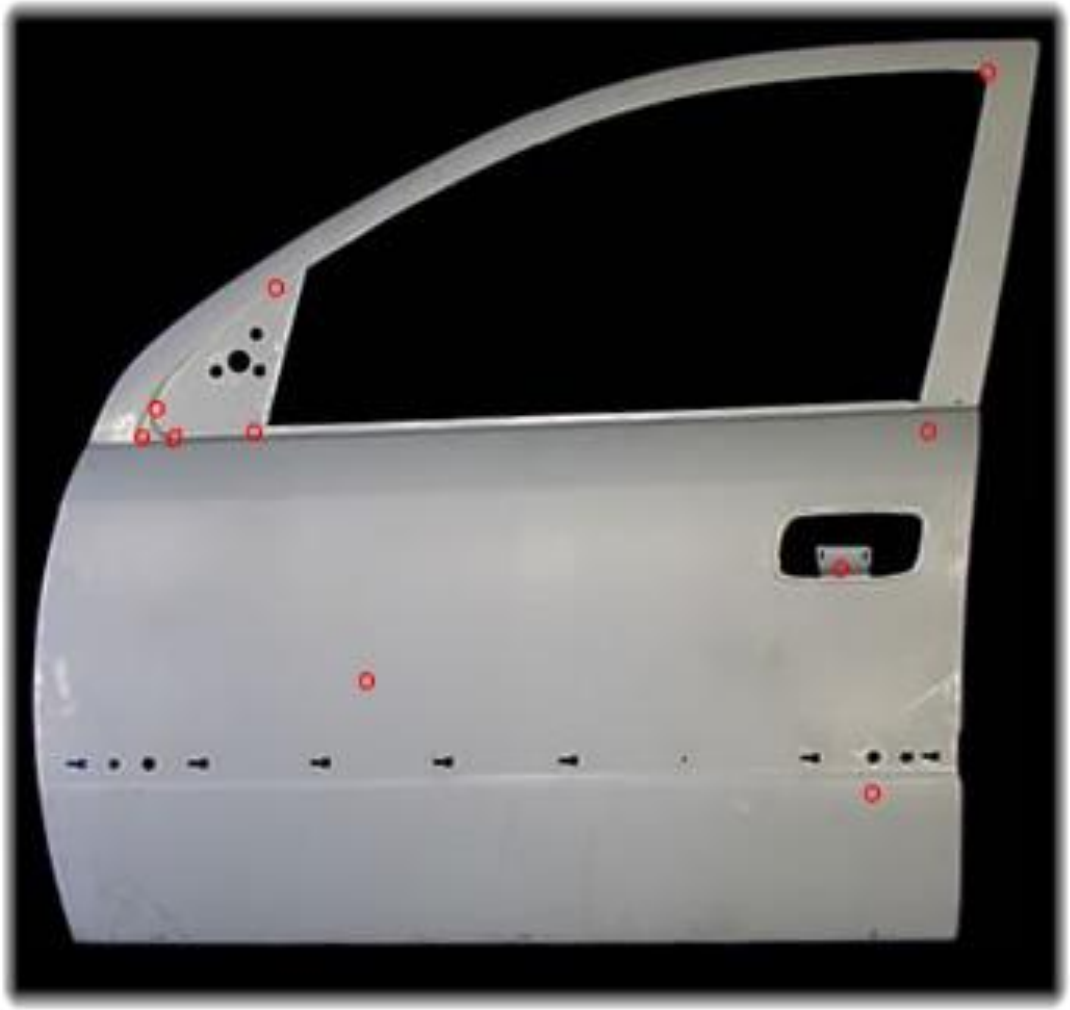


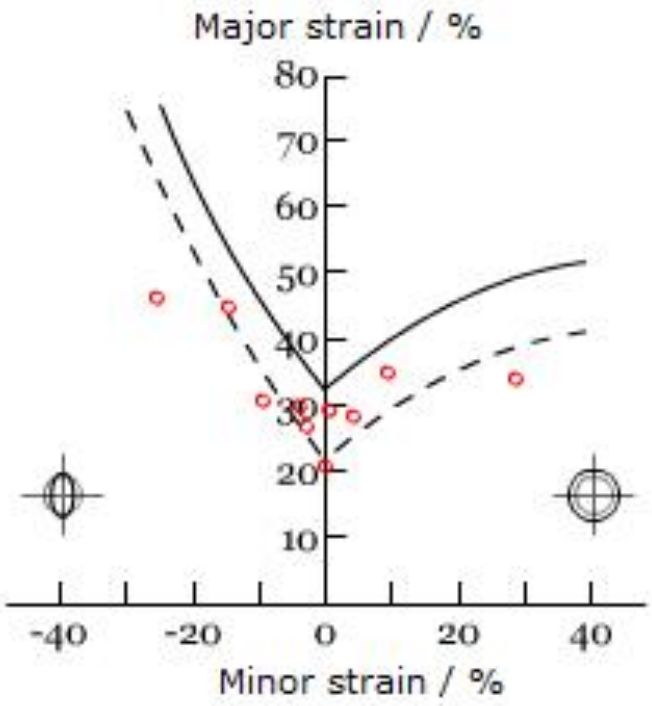
Replica of Fractured Specimen



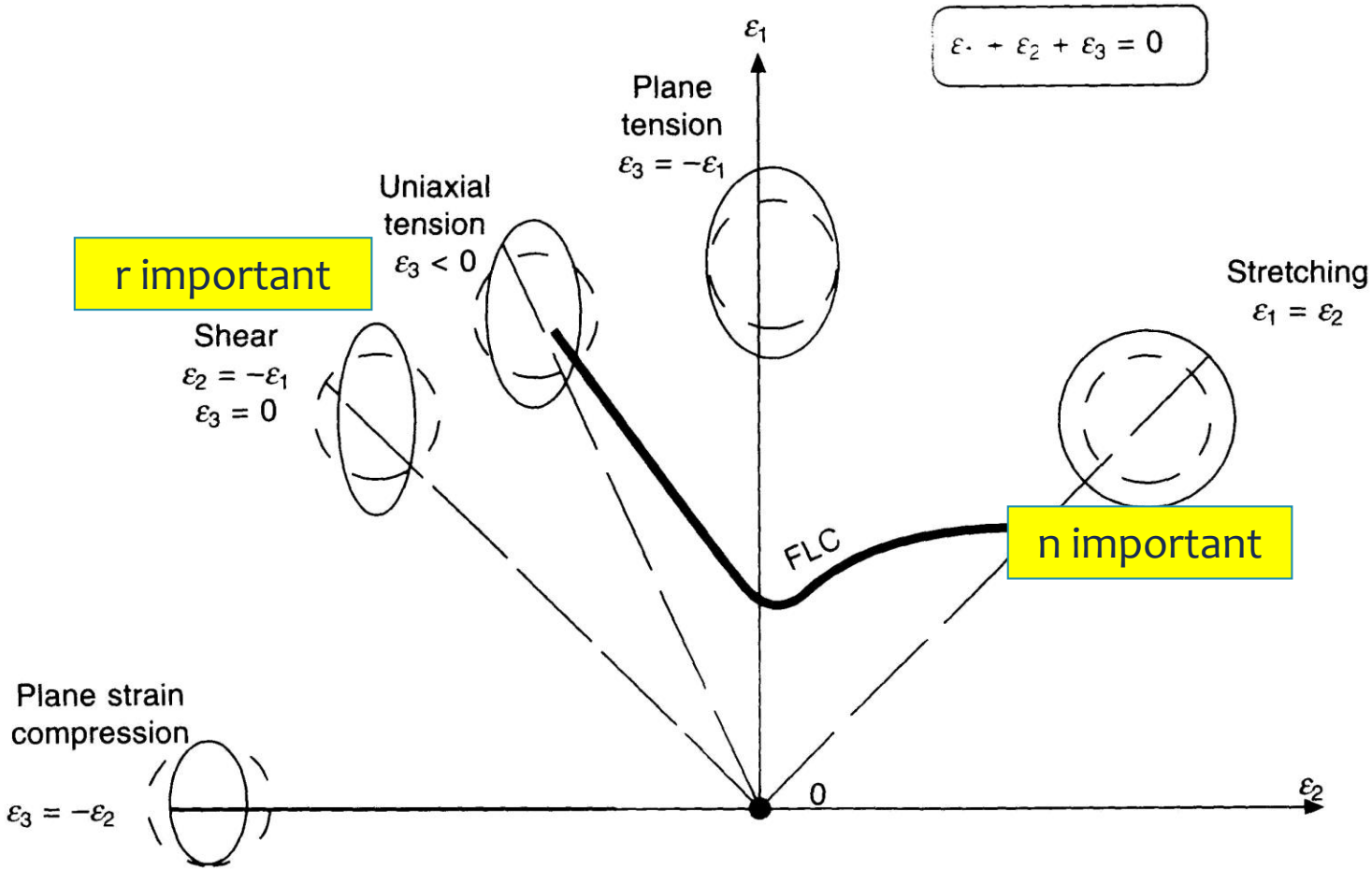
Type I ● Fractured (18 ... 22)
Type II ■ Necked or Fracture Affected (1 ... 4)
Type III ▲ Acceptable (5 ... 17)



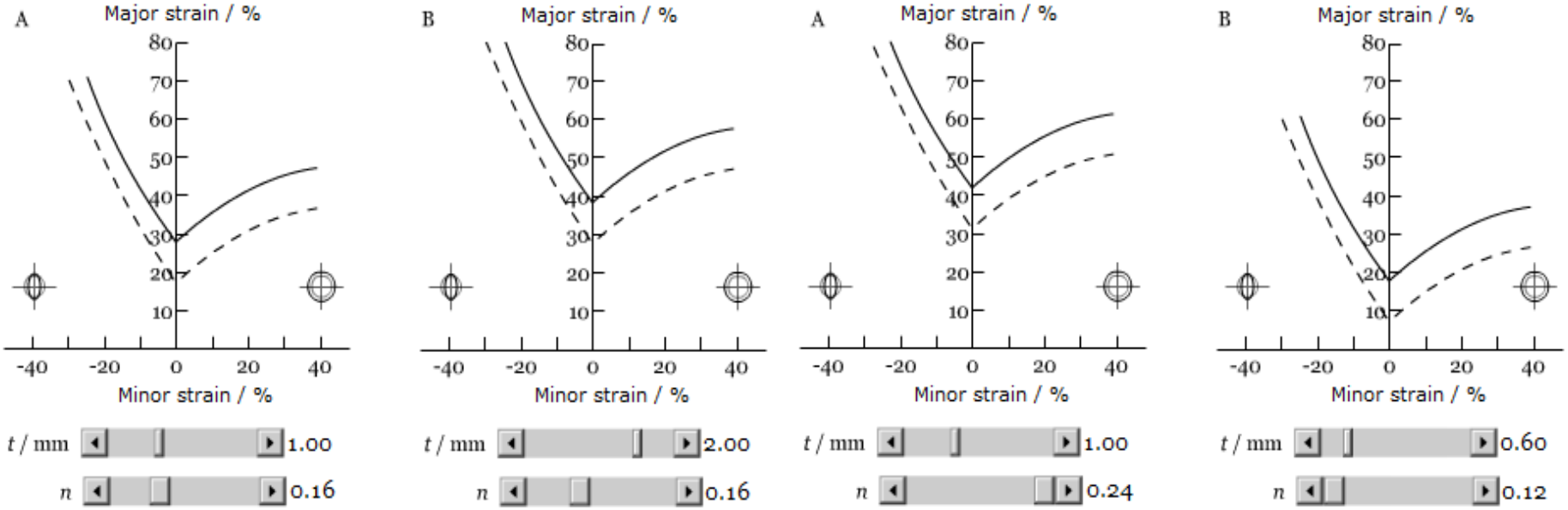



Major strain / %
80
70
60
50
40
30
20
10
-40
-20
0
20
40
Minor strain / %

Forming limit curve

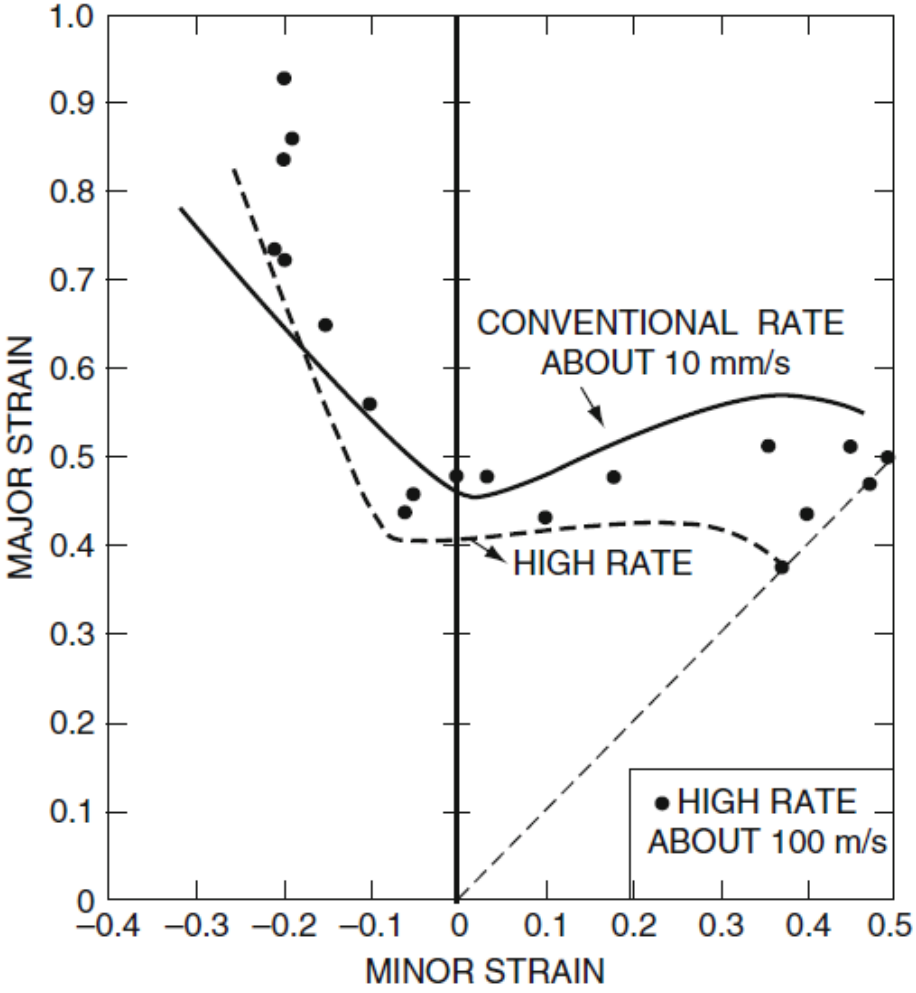


Influencing parameters



Other parameters

- Temperature
- Strain rate
- Punch curvature
- Pressure
- Dimensions of the grid
- …



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Alternative measurement method:
Digital Image Correlation

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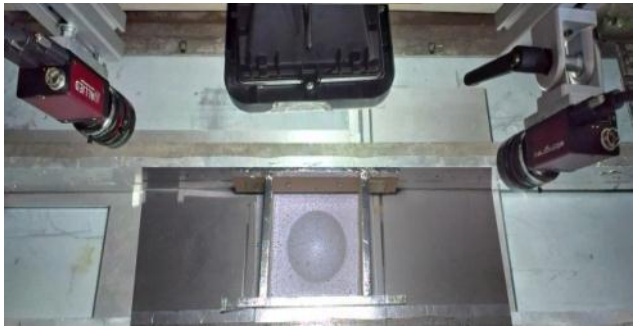
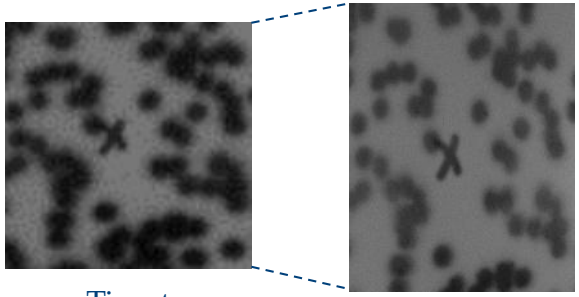
Introduction – Digital Image Correlation





Time t
Undeformed

Time t'
Deformed

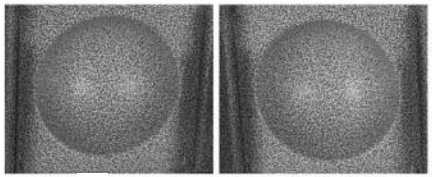


Image acquisition

Deformation matrix

$$\begin{bmatrix}\mu(x,y,\mathbf{s})\\ \nu(x,y,\mathbf{s})\end{bmatrix} = \underbrace{\begin{bmatrix}x\\ y\end{bmatrix} + \begin{bmatrix}u\\ v\end{bmatrix}}_{\text{RIGID}} + \underbrace{\begin{bmatrix}\frac{\partial u}{\partial x} & \frac{\partial u}{\partial y}\\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y}\end{bmatrix}\begin{bmatrix}\Delta x\\ \Delta y\end{bmatrix}}_{\text{AFFINE}} + \underbrace{\begin{bmatrix}\frac{\partial^2 u}{\partial x \partial y}\\ \frac{\partial^2 v}{\partial x \partial y}\end{bmatrix}\Delta x \Delta y}_{\text{IRREGULAR}} + \underbrace{\begin{bmatrix}\frac{\partial^2 u}{\partial x^2} & \frac{\partial^2 u}{\partial y^2}\\ \frac{\partial^2 v}{\partial x^2} & \frac{\partial^2 v}{\partial y^2}\end{bmatrix}\begin{bmatrix}(\Delta x)^2\\ (\Delta y)^2\end{bmatrix}}_{\text{QUADRATIC}}$$

Correlation coefficient

$$r_{CC} = \frac{\sum_y \sum_x f(x,y) g[\mu(x,y,\mathbf{s}),\nu(x,y,\mathbf{s})]}{\sqrt{\left[\sum_y \sum_x f^2(x,y)\right]\left[\sum_y \sum_x g^2[\mu(x,y,\mathbf{s}),\nu(x,y,\mathbf{s})]\right]}},$$

$$r_{SSD} = 1 - \frac{\sum_y \sum_x [f(x,y) - g[\mu(x,y,\mathbf{s}),\nu(x,y,\mathbf{s})]]^2}{\sum_y \sum_x f^2(x,y)},$$

B. Van Mieghem et al. Digital image correlation for on-line wall thickness measurements in thick gauge thermoforming. *Key Engineering Materials (2013)*

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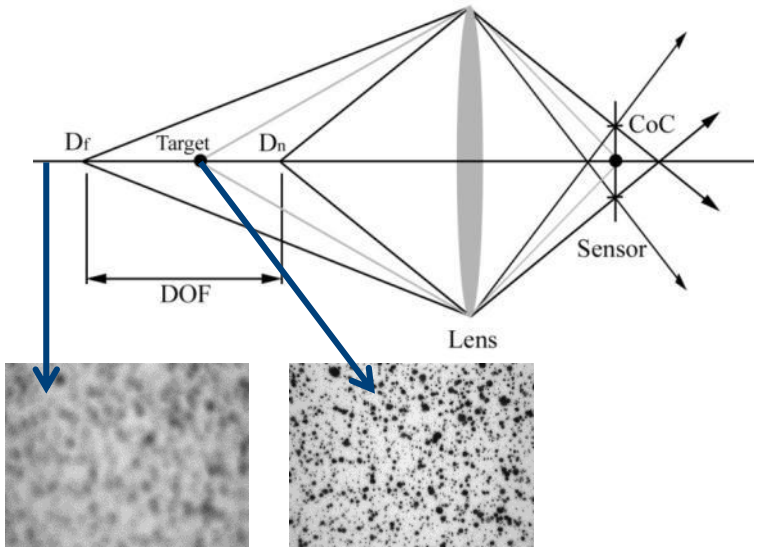
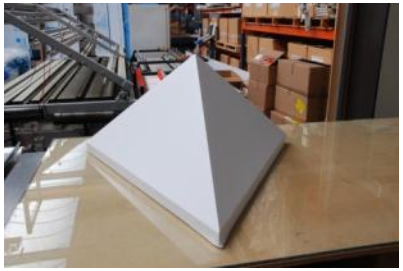
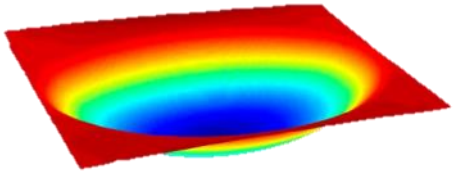
DIC in forming - Challenges

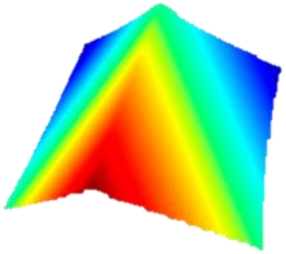
- **Strain** > 100% is not exceptional → when judging strain, choice of strain definition is important
- **Strain rate** → 0,01/s up to 10/s
- **Speckle technique** on sheet (low surface energy)
  - Custom paint
  - Spray/Print
- Forming **temperature** 100-300°C
- **Big displacements** in 3D
  - Field of View
  - Depth of Field
  - Lighting

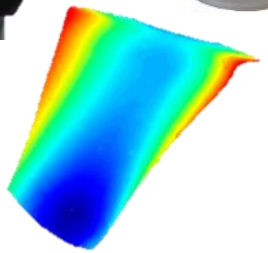


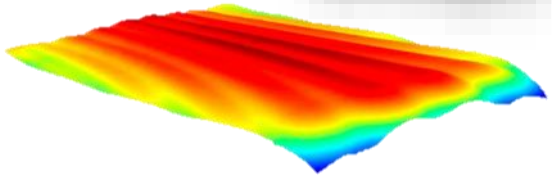
DIC in thermoforming



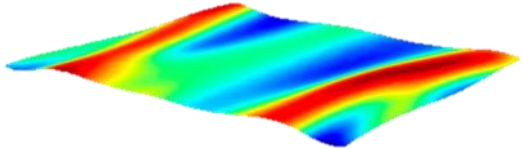




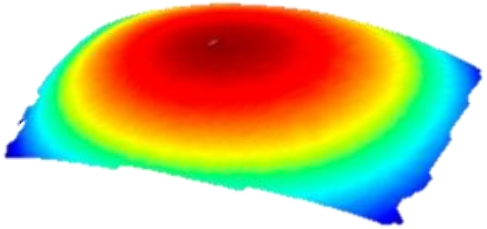


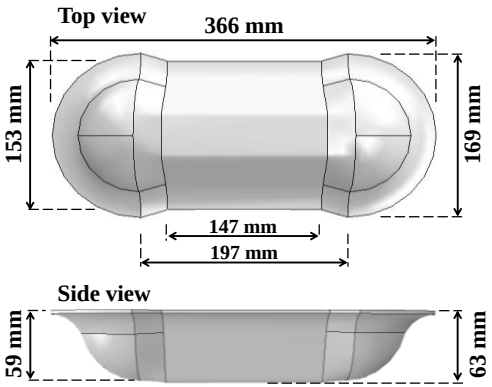


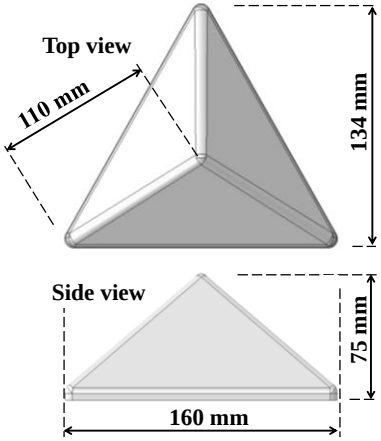
Stress relaxation

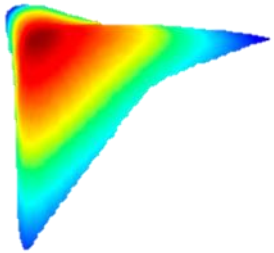


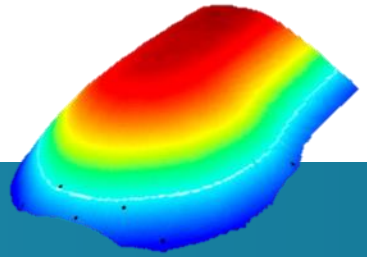
Bubble inflation



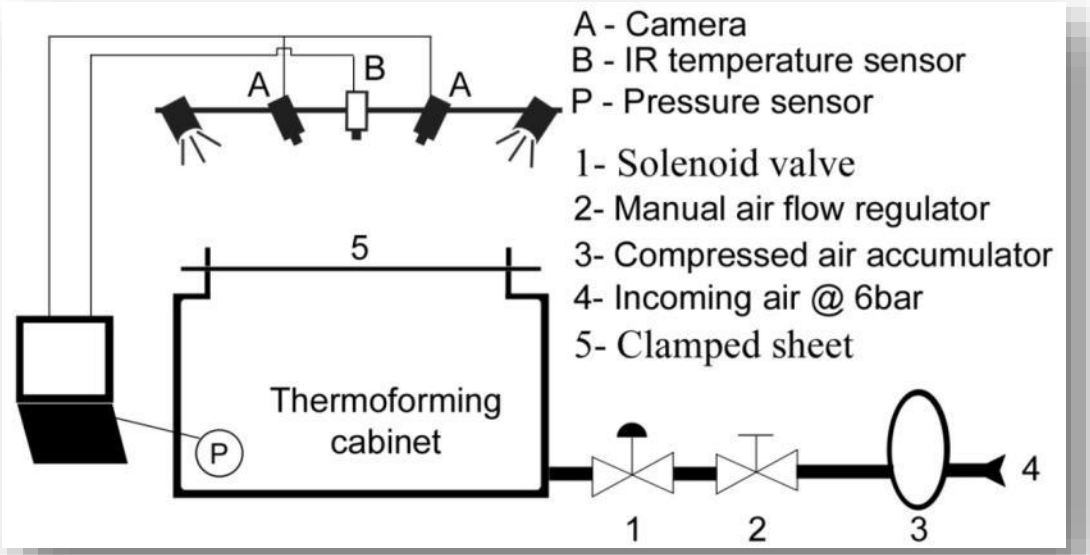








DIC in thermoforming - Applications

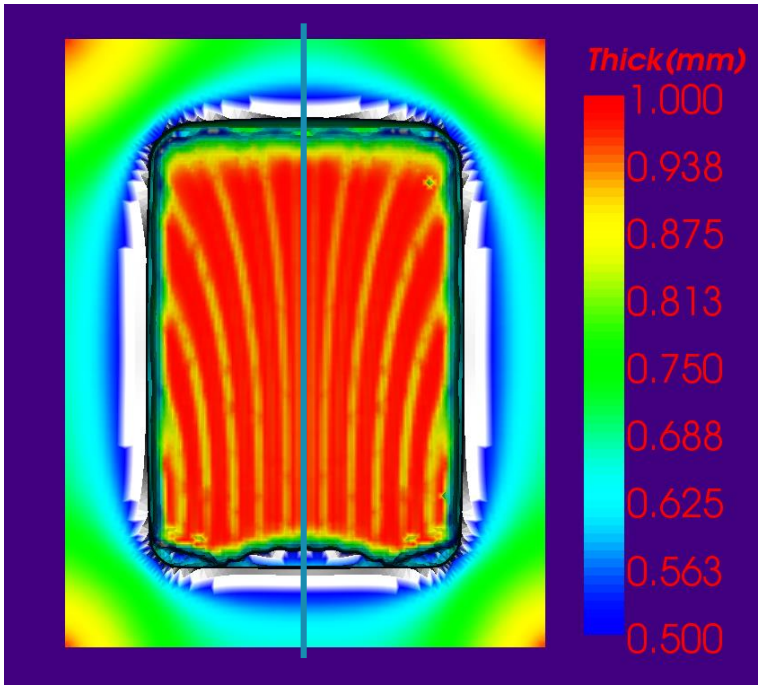


- Full field in-situ thickness maps
- Influence of extrusion anisotropy
- Simulation optimisation
- Process optimisation
- ...

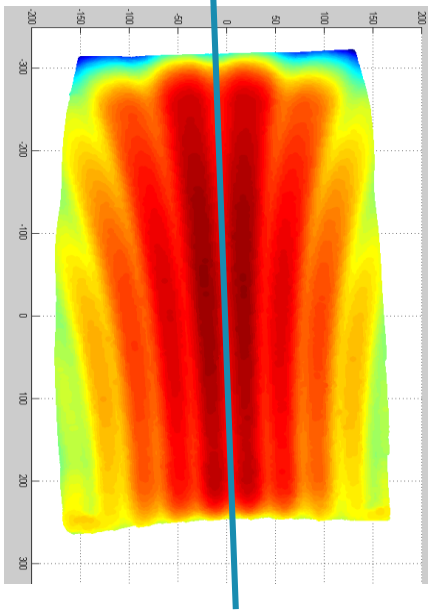
Applications – Full field thickness maps

- Symmetric products are not always symmetric in thickness

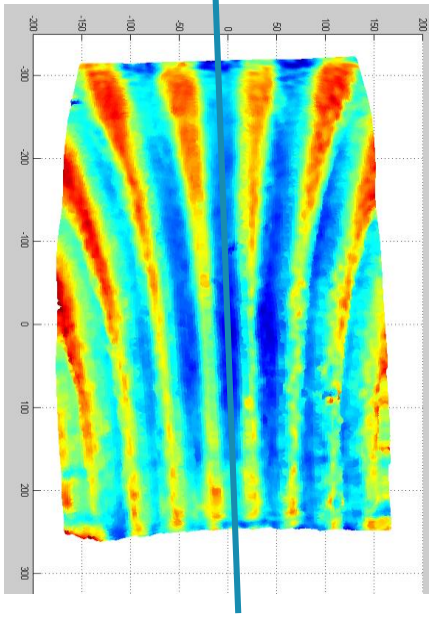
Simulation
Thickness symmetry



DIC
Shape
symmetry

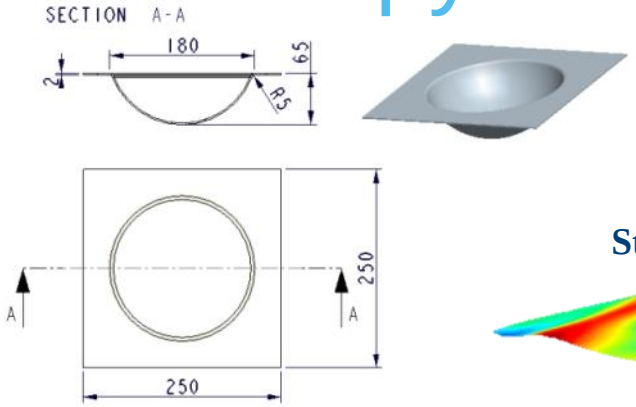


DIC
Thickness
asymmetry

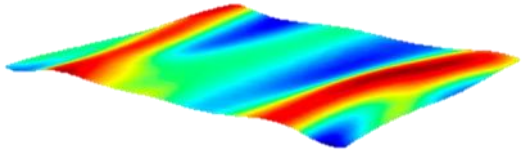


- Find cause by measuring in-situ during the process

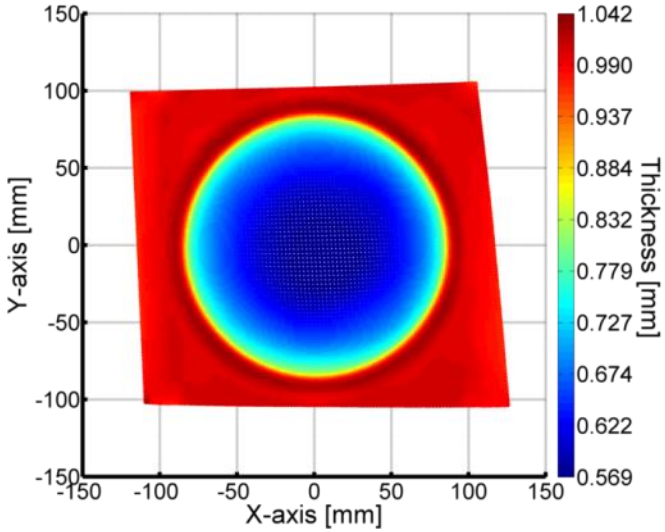
Applications – Influence of extrusion anisotropy



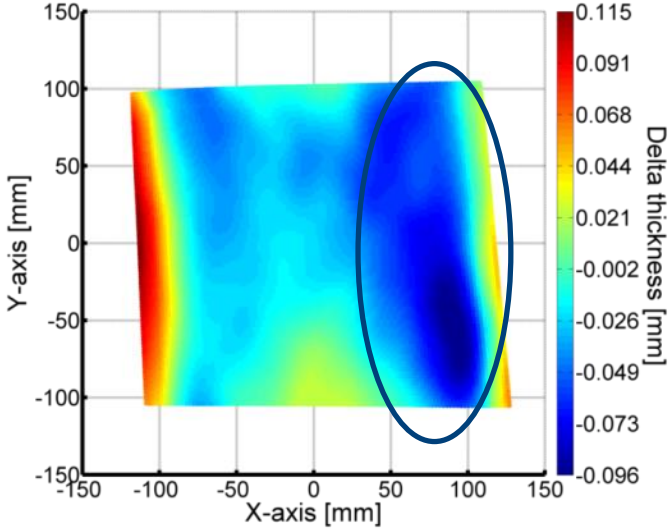
Stress relaxation

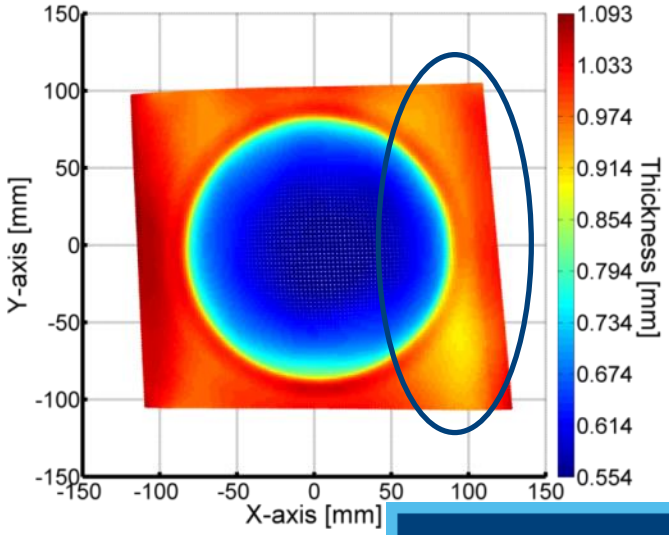


Final thickness distribution



Asymmetric thinning due to sag

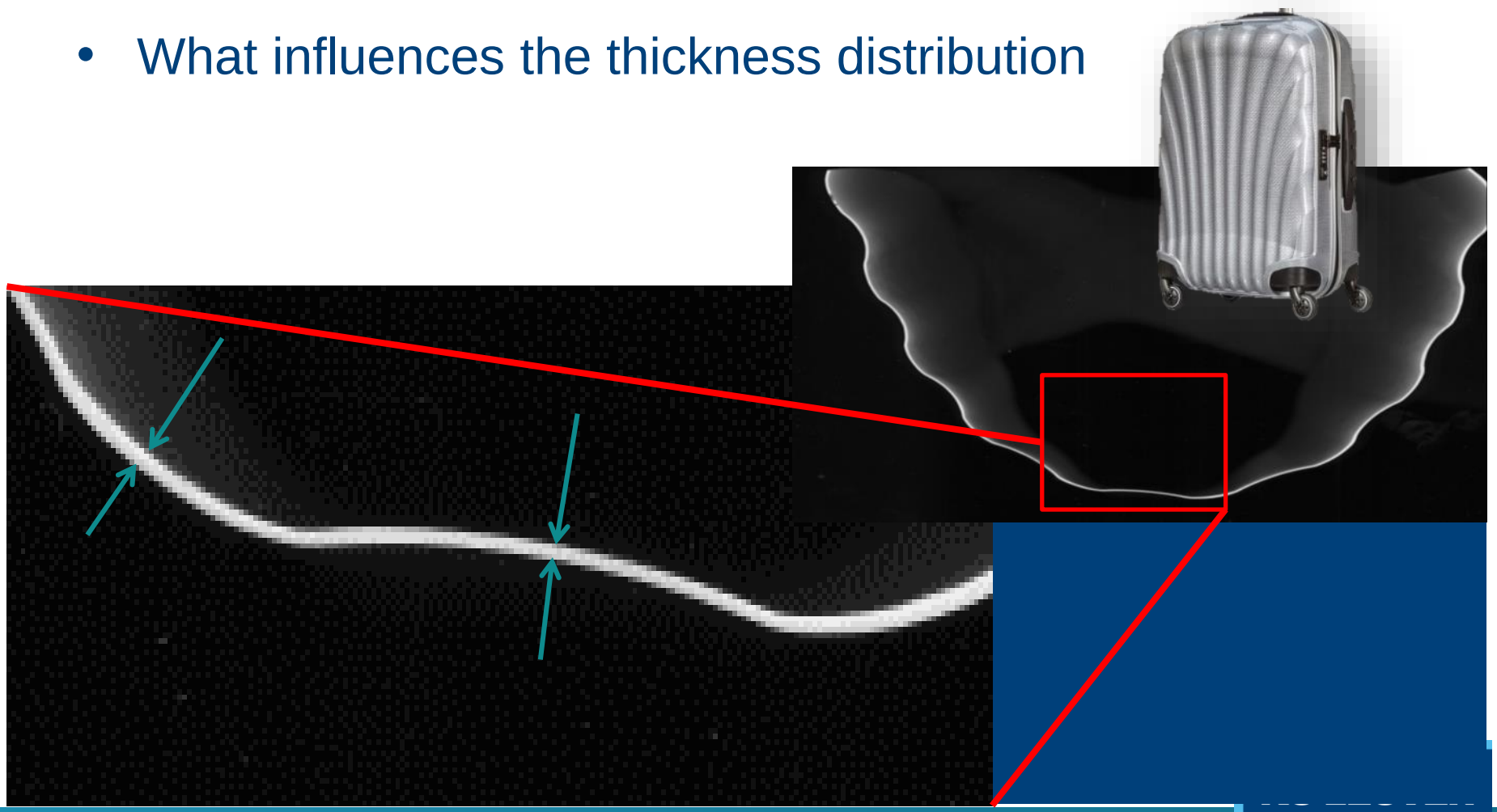




B. Van Mieghem et al. Impact assessment of extrusion anisotropy on quality of thermoformed products. *Composites Week @ Leuven and TEXCOMP-11 Conference* (2013)

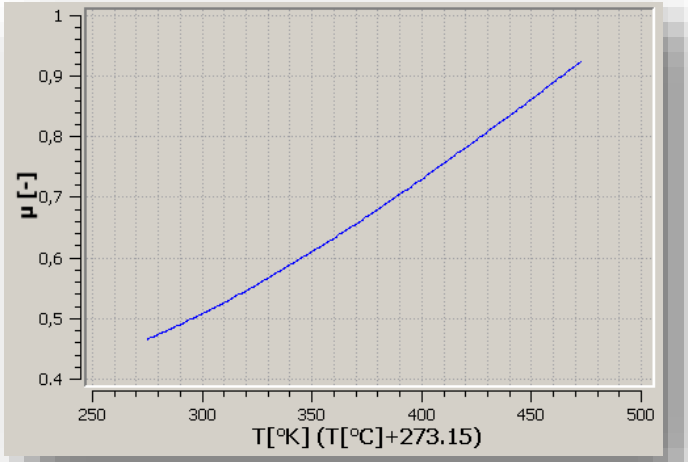
Applications – Simulation optimisation

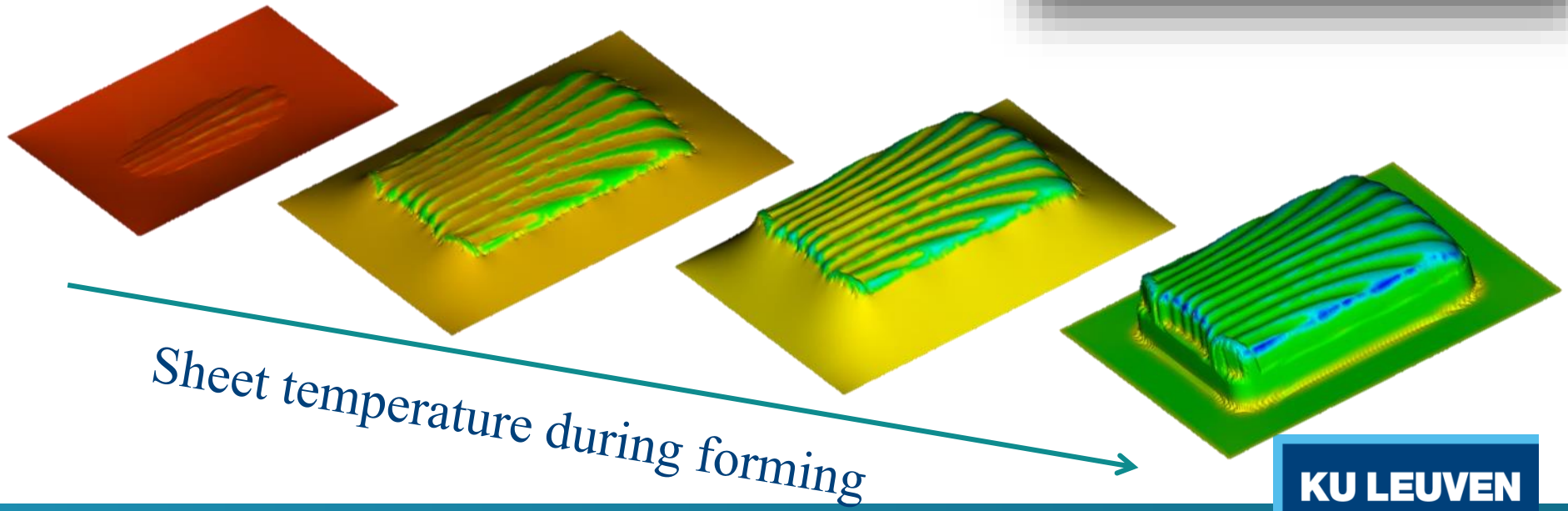
- Cross sectional thickness measurement
- What influences the thickness distribution



Applications – Simulation optimisation

- Sheet mould contact
  - Temperature dependent friction
  - Heat transfer coefficient air/sheet
  - Heat transfer coefficient mould





Use of DIC to determine FLC

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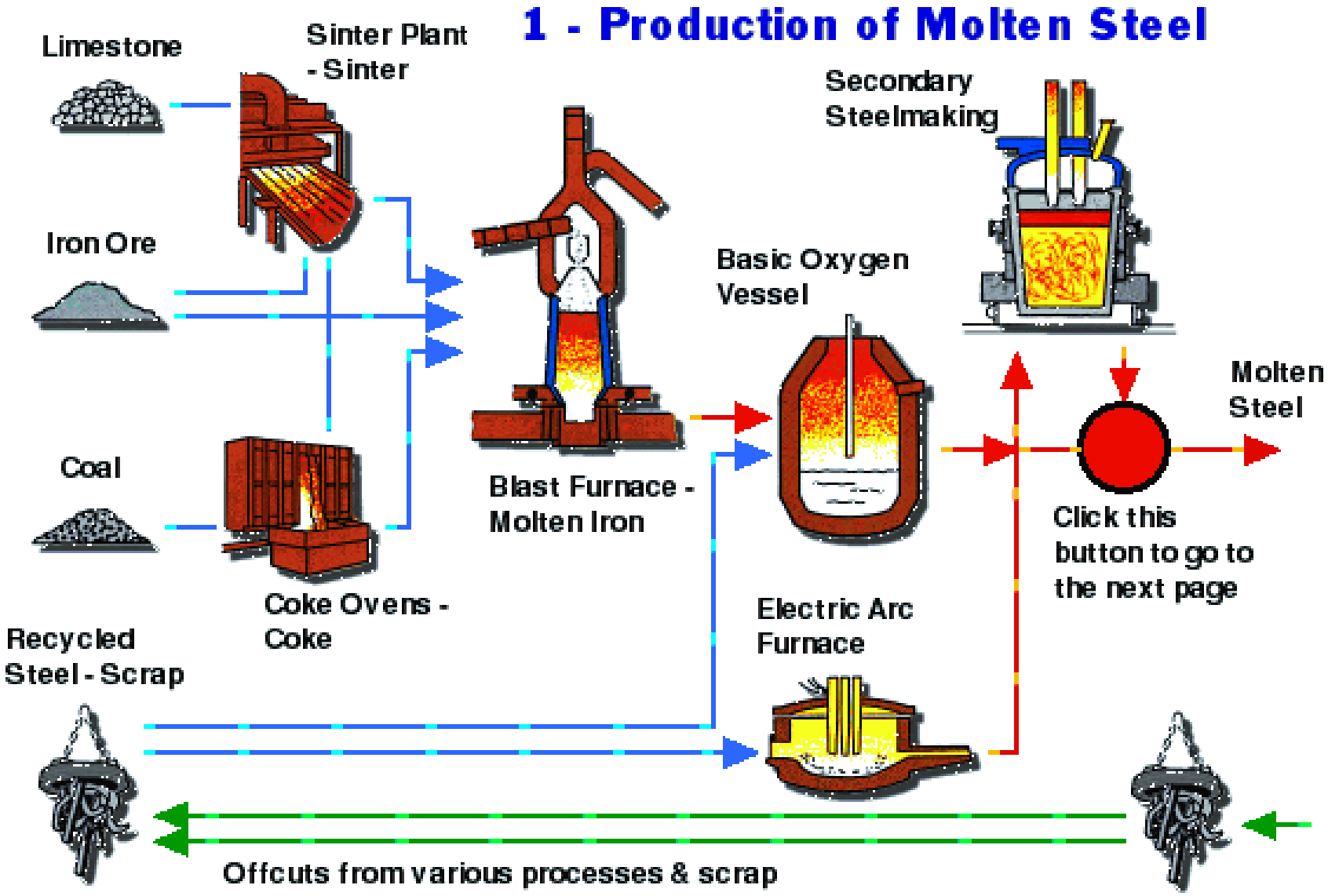
Example: steel
Effect of history and crystallographic texture on anisotropy

Steel production

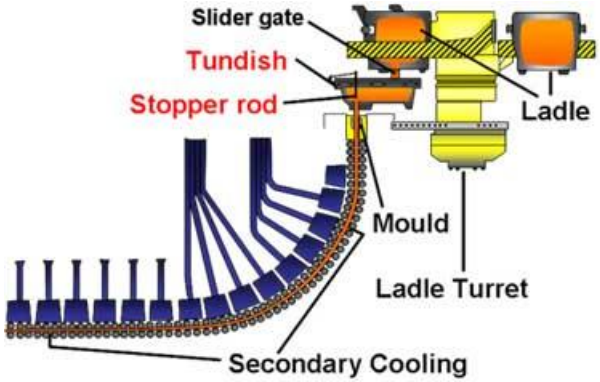


Steel production 2

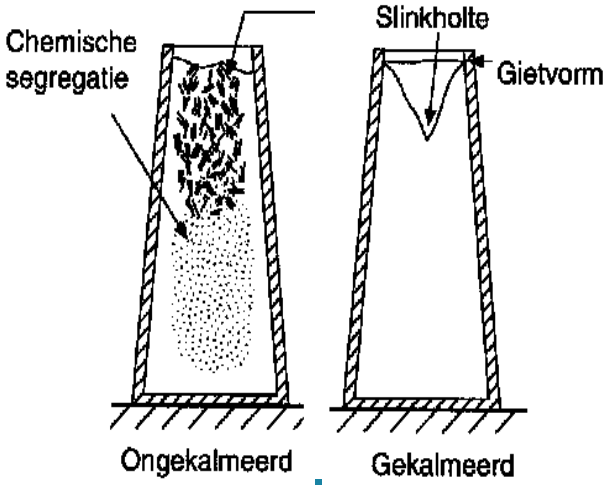
- Improvements for automotive:
  - AK (Al-killed)
    - Binding of Al with N: improved ageing resistance
    - Pancake grains
  - Vacuum degassing:
    - Removal of all inclusions
      - Low level of impurities
      - Addition of Ti and Nb
        - Binds C and N
    - IF-steel (interstitial free)
      - Ultradeep drawable steel
        - Improved r-factor
      - Complete ferritic matrix
        - C content very low C < 0.0002%

Production of steel slabs

- Continuous casting

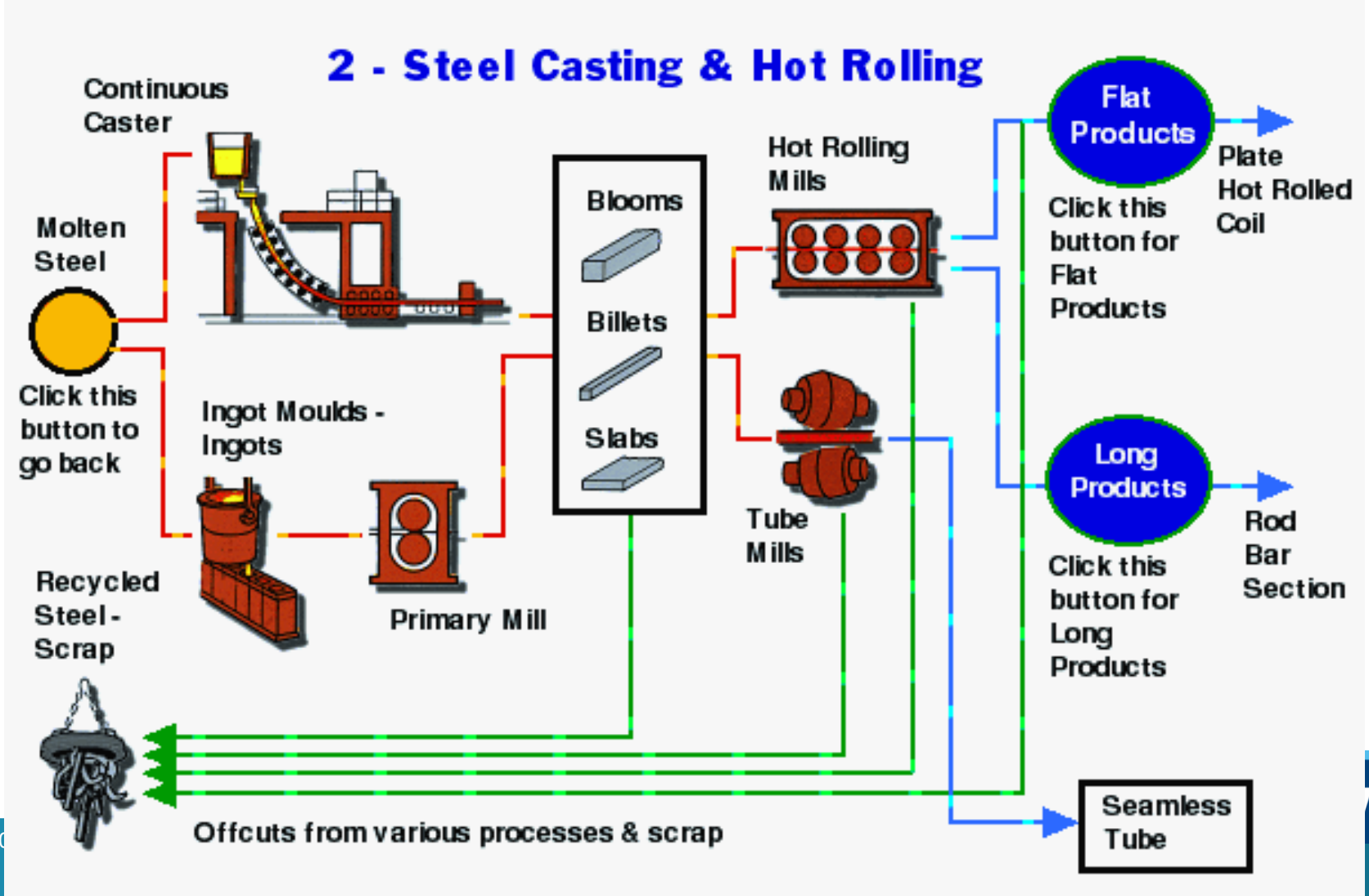


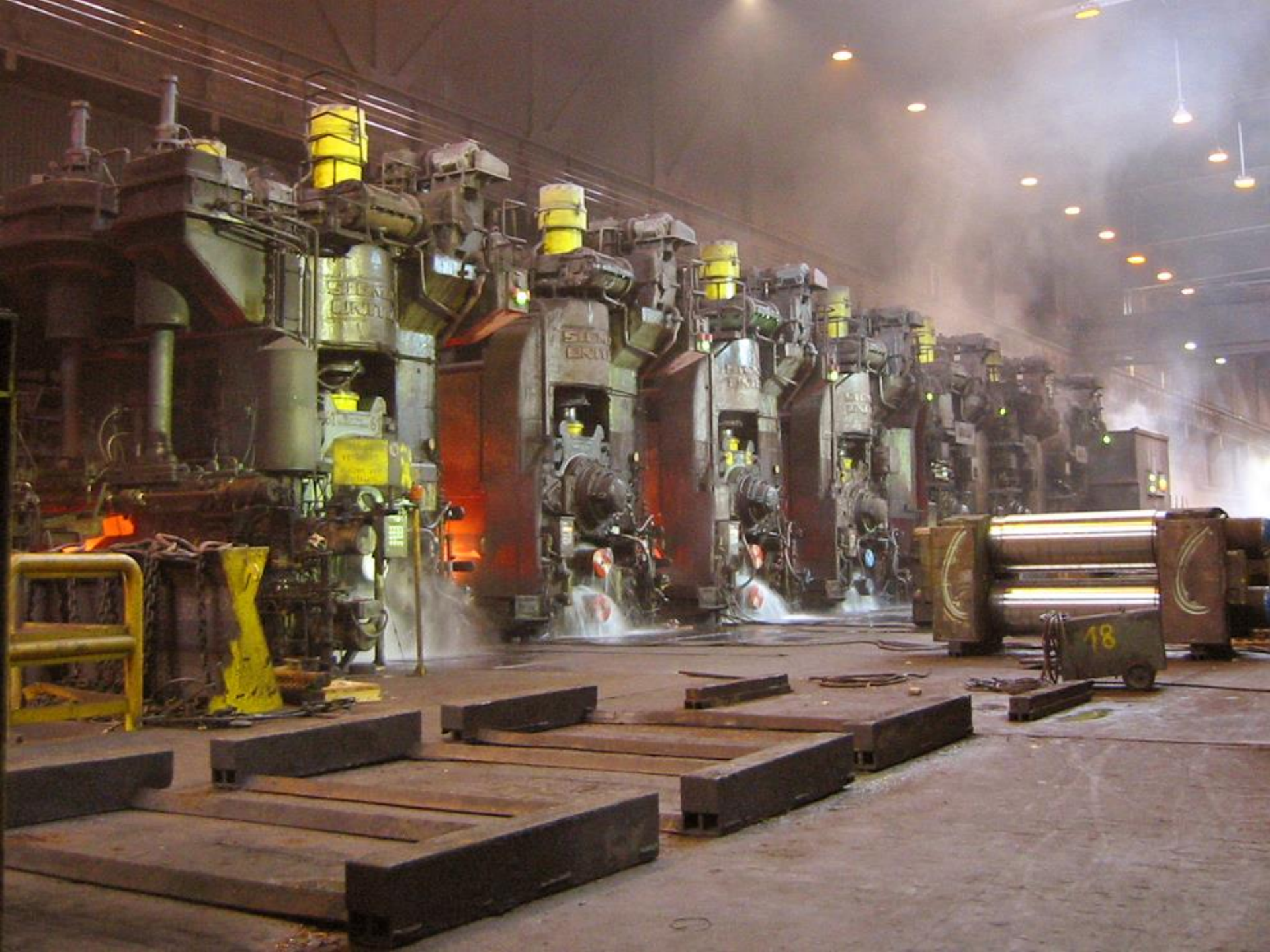
- Ingots



Sheet steel manufacturing

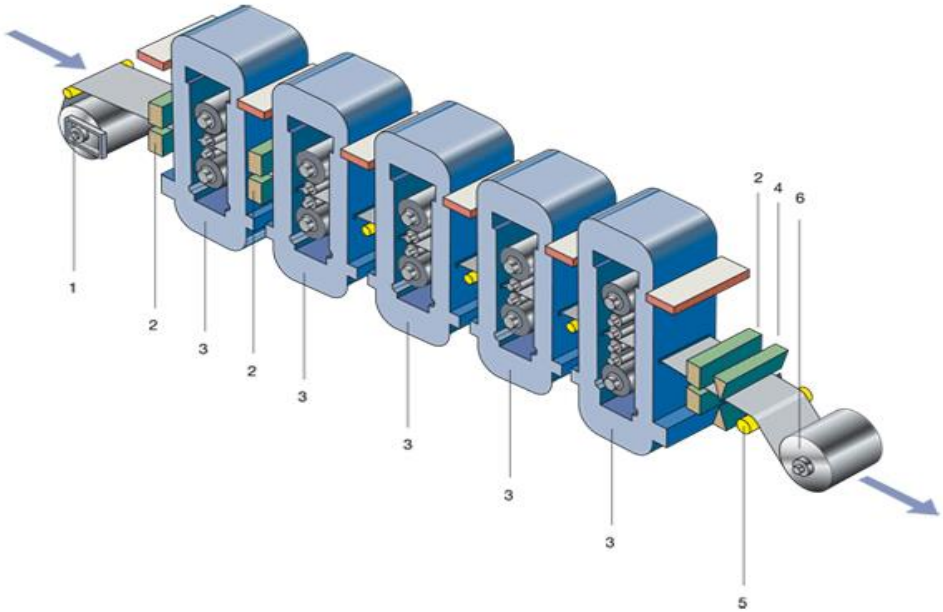
- Hot rolling to thickness of 3mm-1.6mm at 900-1200°C

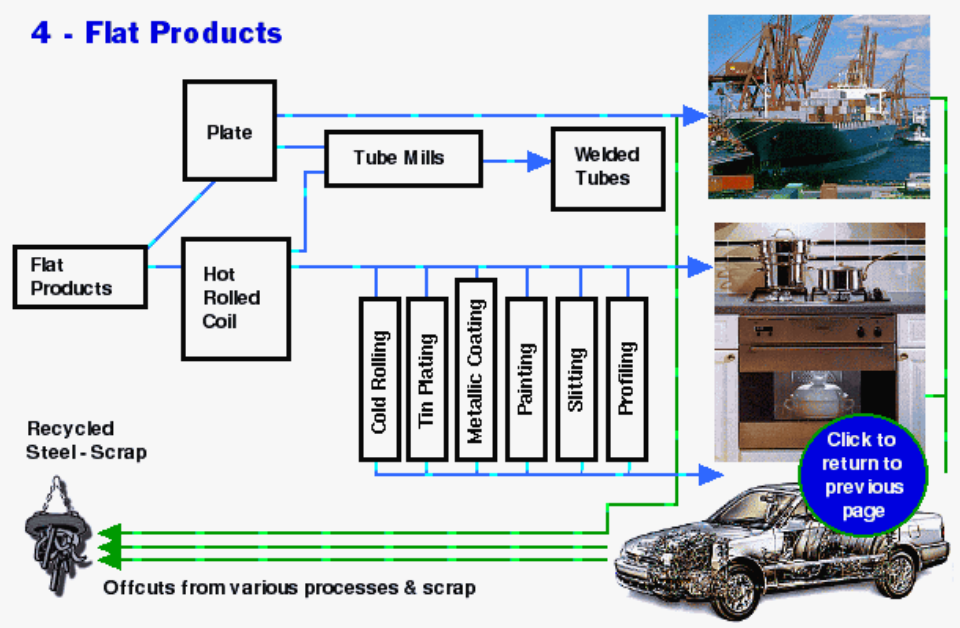



18

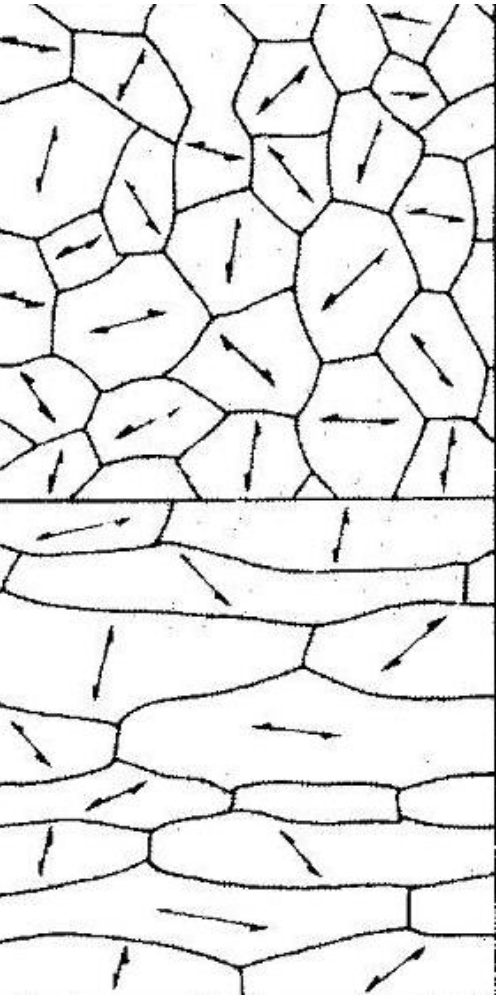
Sheet steel manufacturing

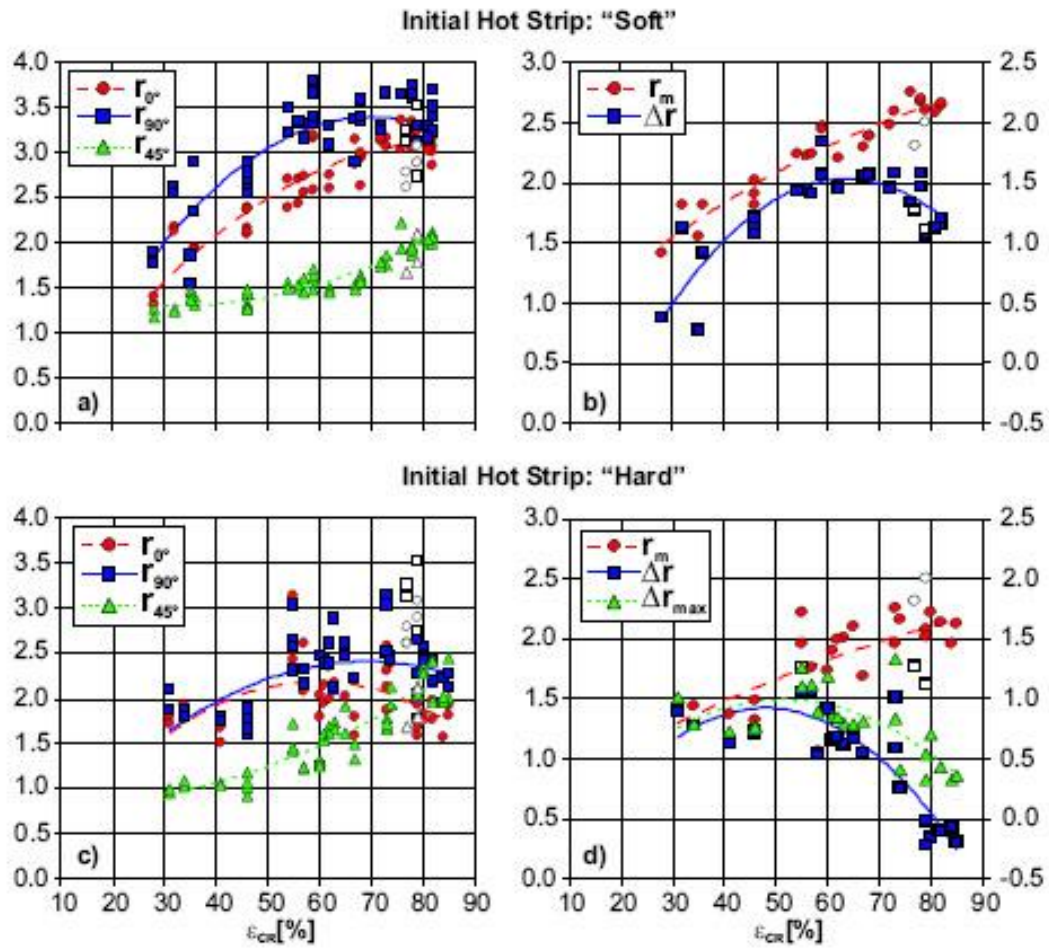
- Pickling with hydrochloric acid
  - Removal of oxide skin
- Cold rolling to 0.5mm





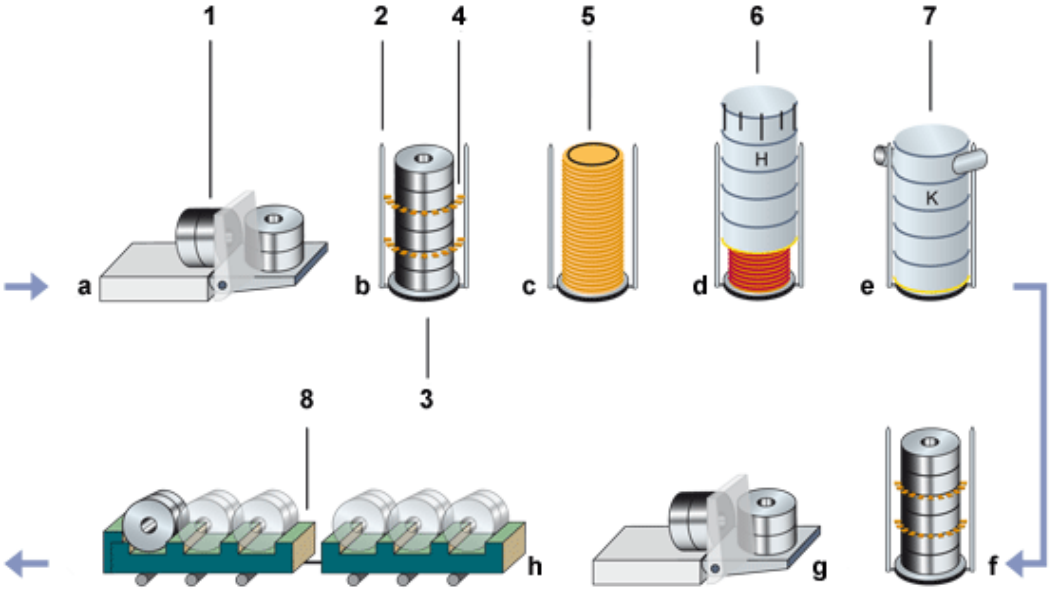
Effect of cold work on anisotropy



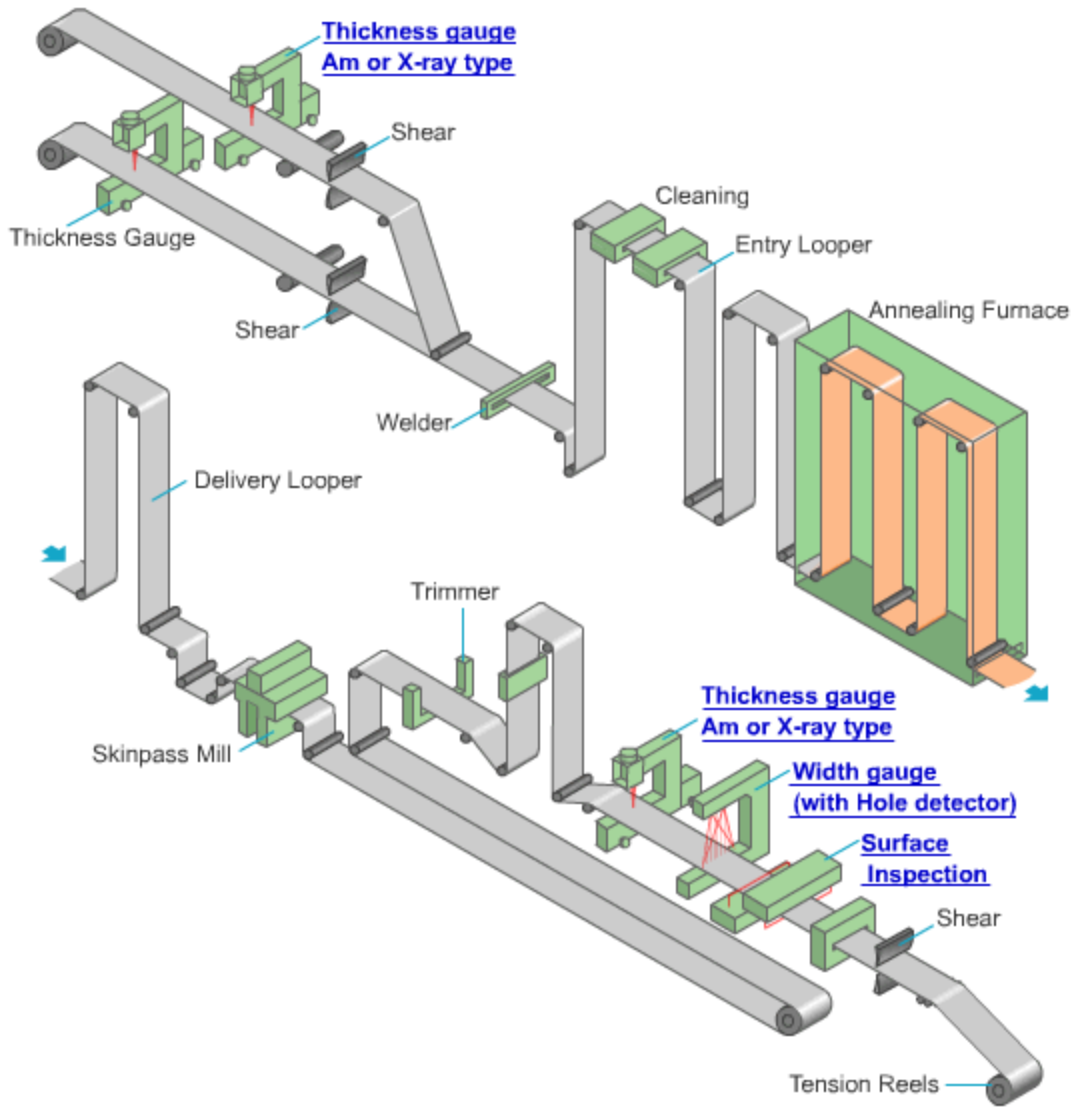


Annealing

- batch



Continuous Annealing (CAPL)

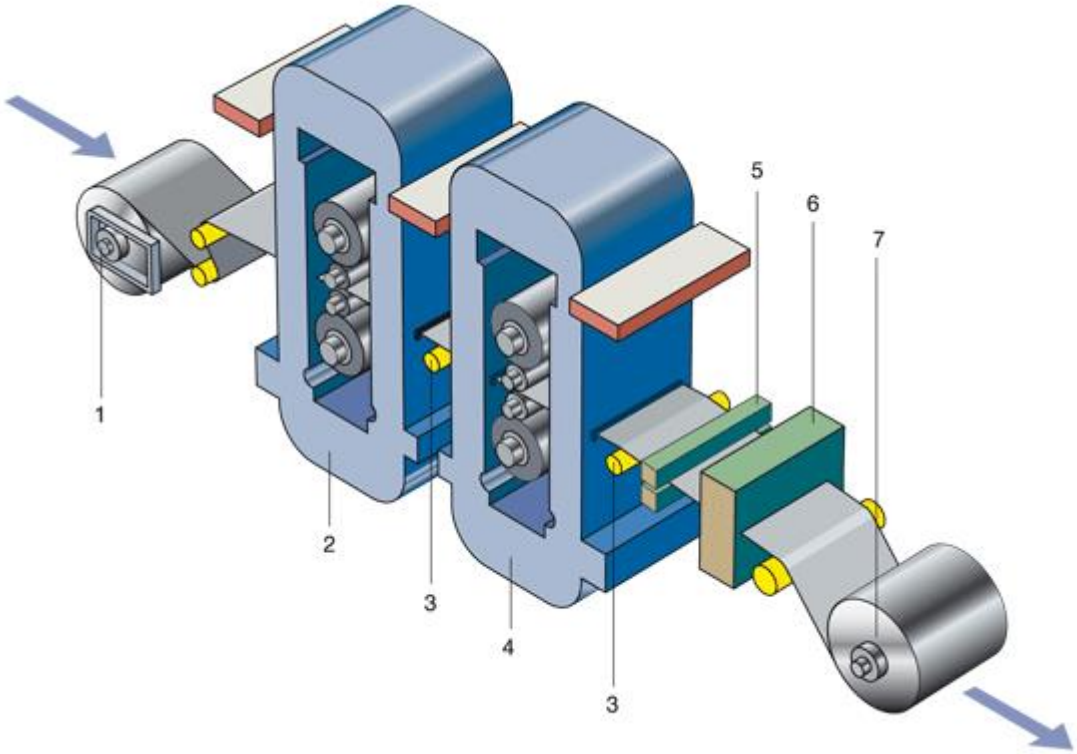


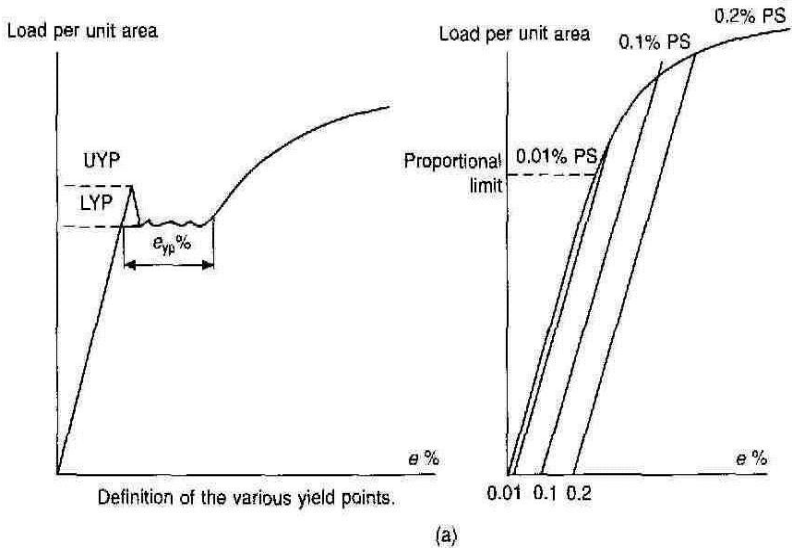
Annealing differences

batch	CAPL
Slow heating: 30 hours	Rapid heating: 90 s
Slow cooling: 25 hours	Fast cooling: 10 min
Coarse grain	Finer grain
	Stronger
Higher ductility	
High r: 1.6-2.1	Low r 1.0-1.4

skin pass

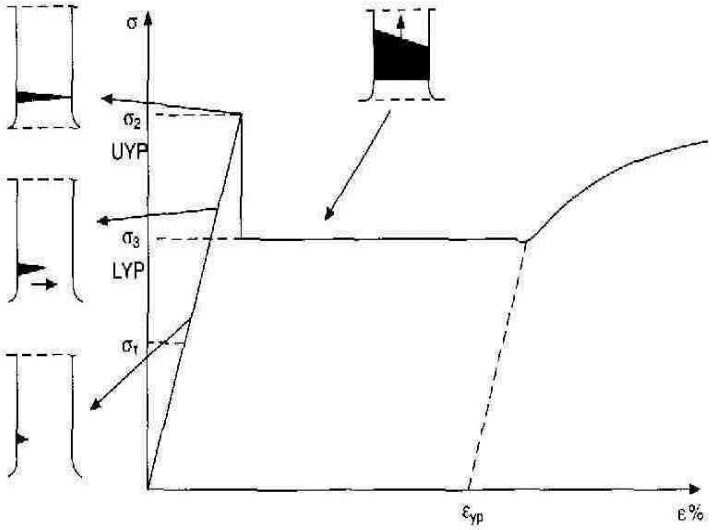
- 1% deformation after annealing



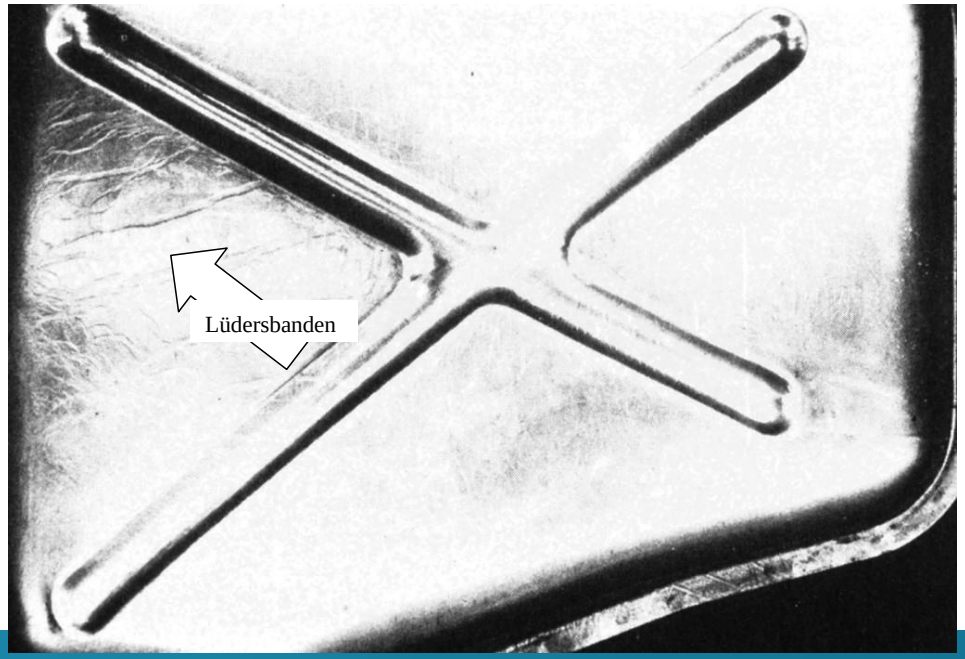


Definition of the various yield points.

(a)



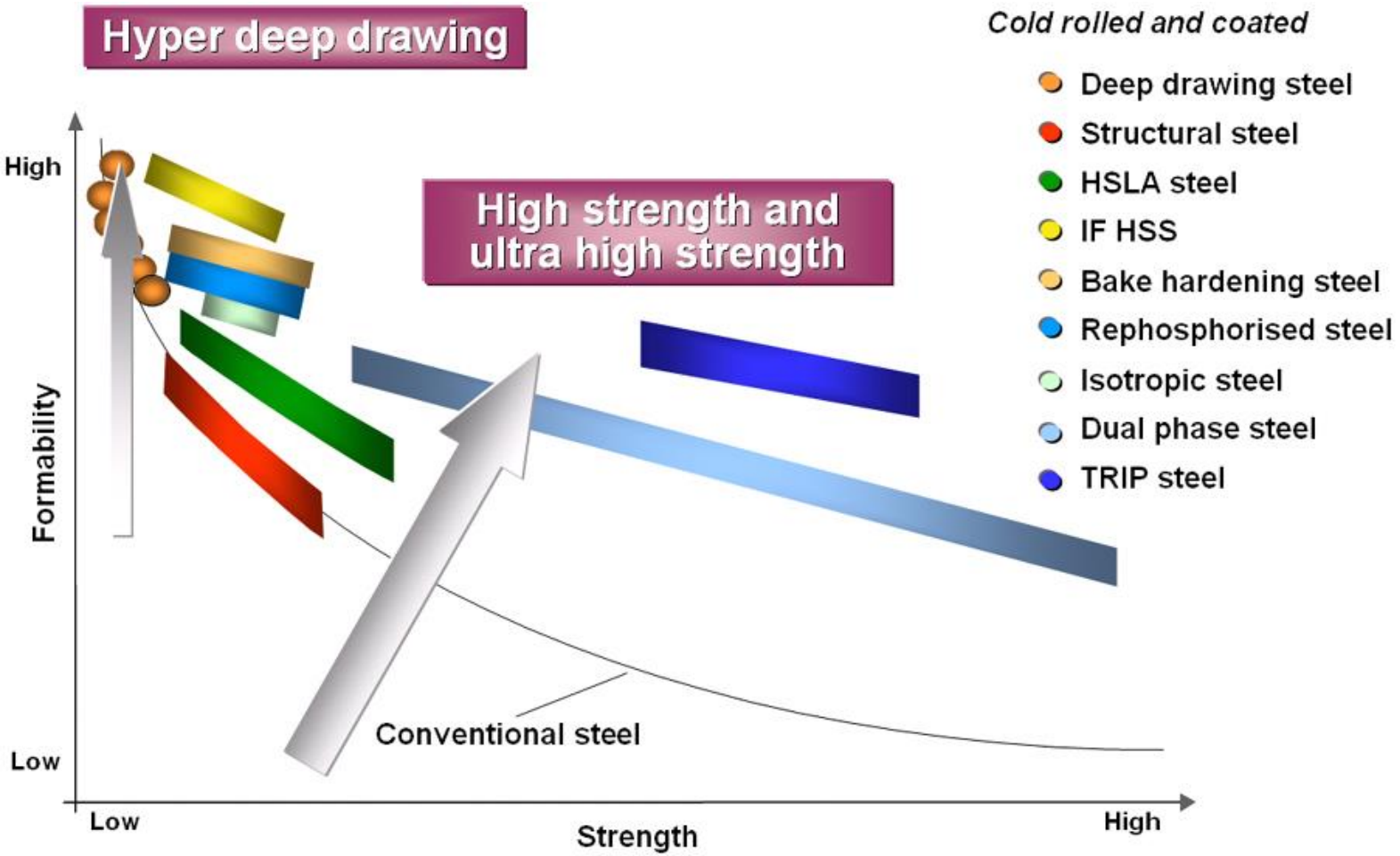
(b)



Surface topography

- Importance of the surface topography
  - Forming process
    - Lubrication characteristics
  - Paint quality
    - Adhesion
    - gloss
- Determined by the skin pass

High strength steels



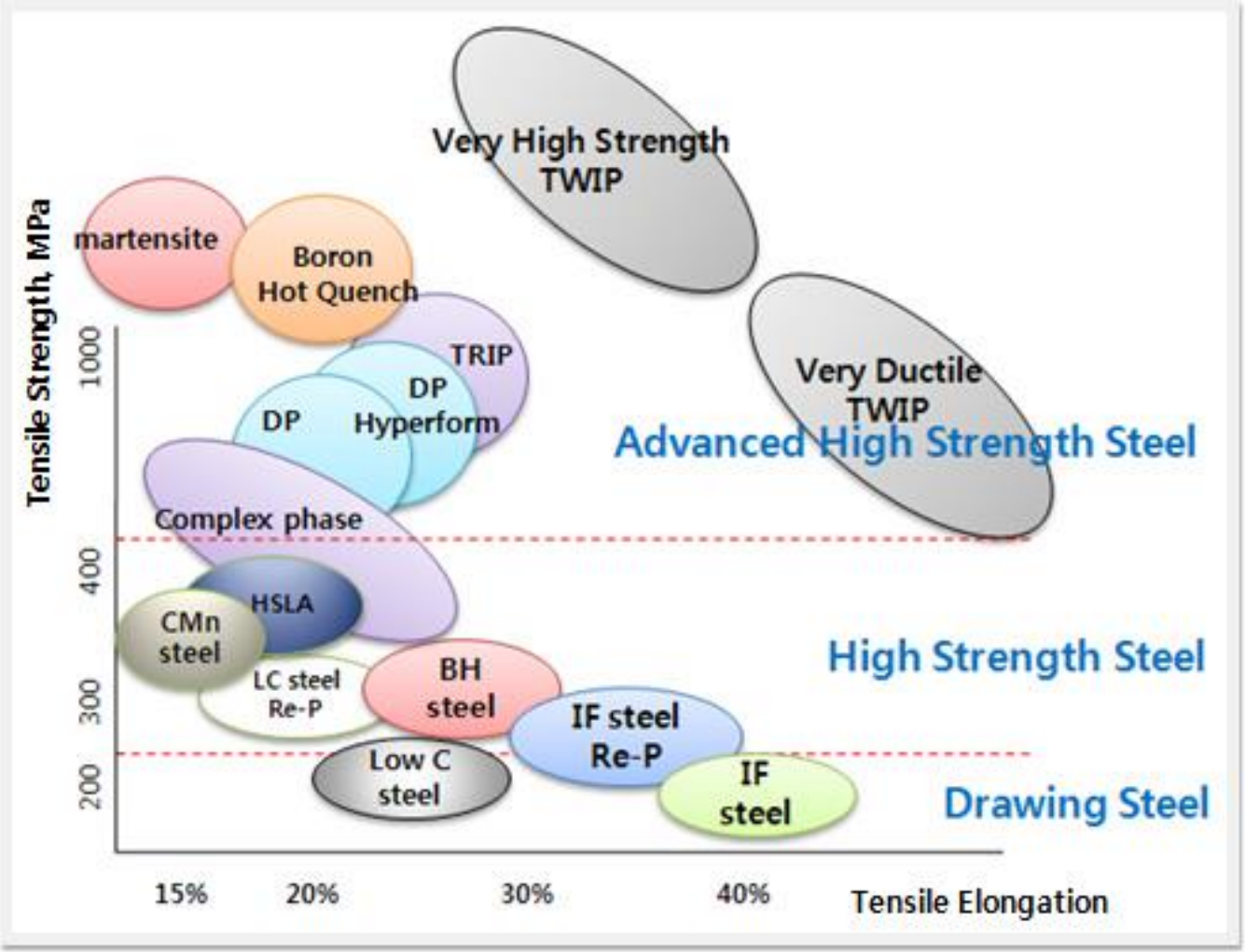
IF HSS

- Vacuum degassed
  - Removal of C, N, O
  - Reduced dent resistence

- Complete ferritic
- Alloyed with Mn, Si, P

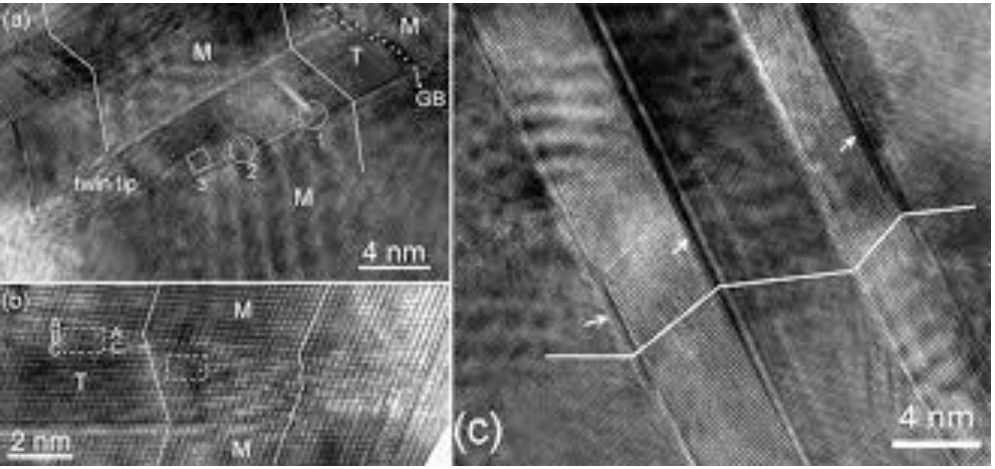
- Further strengthening via bake hardening

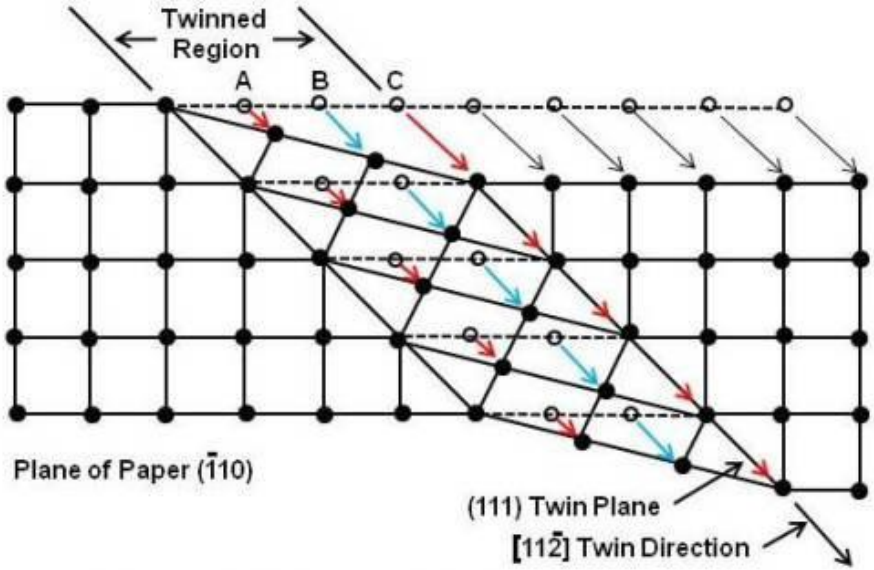
Second generation AHSS



TWIP

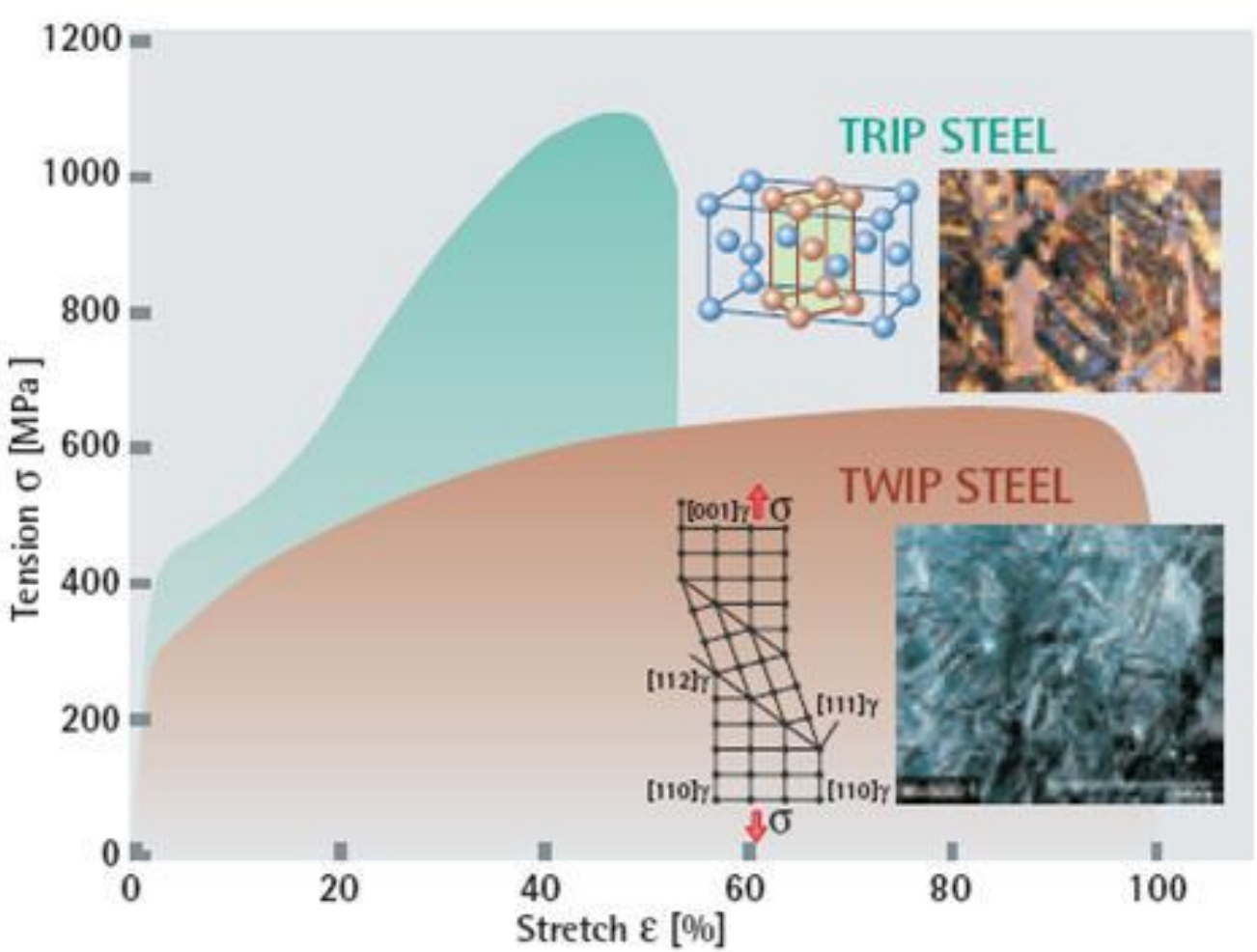
- TWIP: twinning induced plasticity
- High Mn (17-24%)
- Fully austenitic at room temperature
- Cold forming causes twinning
  - Fine sized austenite grains ➔ increased strength
- Expensive



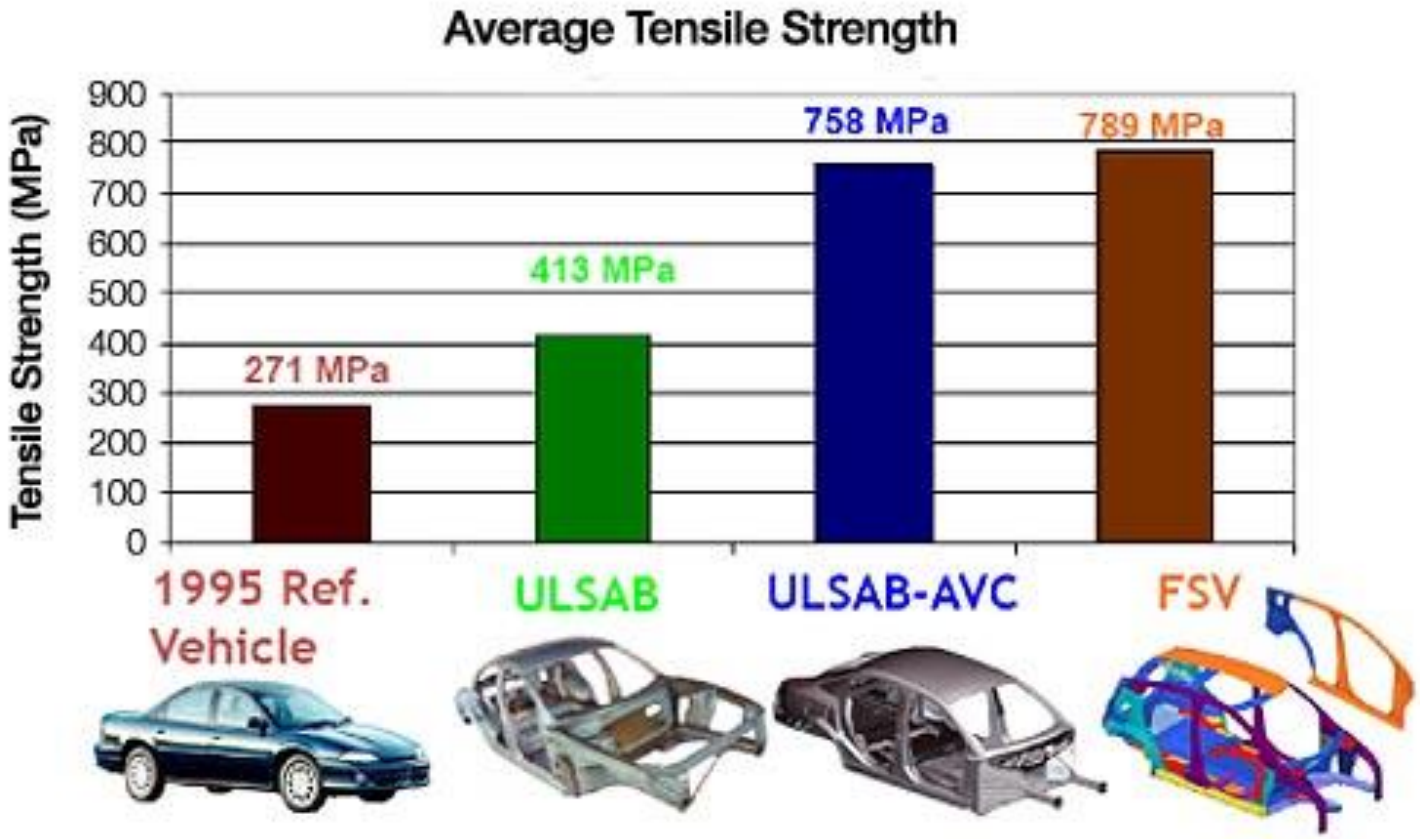


Schematic Diagram of Twinning in an f.c.c. Lattice

TRIP > < TWIP


TRIP STEEL
TWIP STEEL
Tension σ [MPa]
Stretch ε [%]
0
200
400
600
800
1000
1200
0
20
40
60
80
100
[001]γ
σ
[112]γ
[111]γ
[110]γ
[110]γ
σ

Consequences



Steel versus aluminium

Al alloys used in automotive

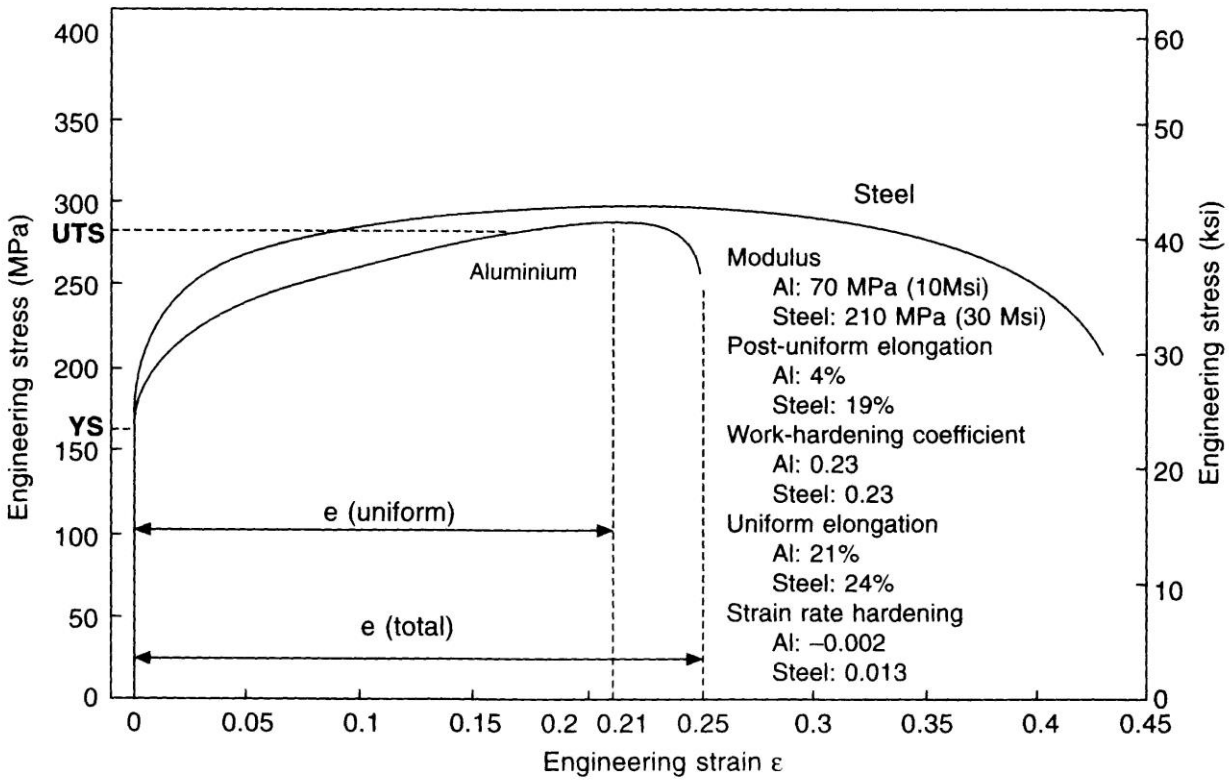
Table 3.10 Automotive aluminium alloys in current use

Alloy AA DIN	AA6016 AlMg0.4Si1.2	AA6111 AlMg0.7Si0.9Cu0.7	AA6009 AlMg0.5Si0.8CuMn	AA5251 AlMg2Mn0.3	AA5754 AlMg3	AA5182 AlMg5Mn
Temper	T4	T4	T4	H22 (Grade 3)	O / H111	O / H111
UTS (MPa)	210	290	250	190	215	270
0.2 proof stress (MPa)	105	160	130	120	110	140
Elongation A80 (%)	26	25	24	18	23	24
r (mean value)	0.61	0.55	0.64		0.70	0.80
n 5% (mean value)	0.30	0.28	0.29		0.35	0.33
Advantages	Formability, no stretcher-strain marks, balanced properties	No stretcher-strain marks, improved bake-hardening response	No stretcher-strain marks, mechanical strength	Corrosion resistance, cost	Good formability	Very good formability
Disadvantages	Limited bake-hardening response at Rover paint temperature	Corrosion concerns, limited formability	Limited hemming and forming properties	Possible stretcher-strain marks (Lüders lines) after deep drawing		
Alloy type		BAKE HARDENING			NON-BAKE HARDENING	
Typical use	SKIN PANELS			INNER PANELS		

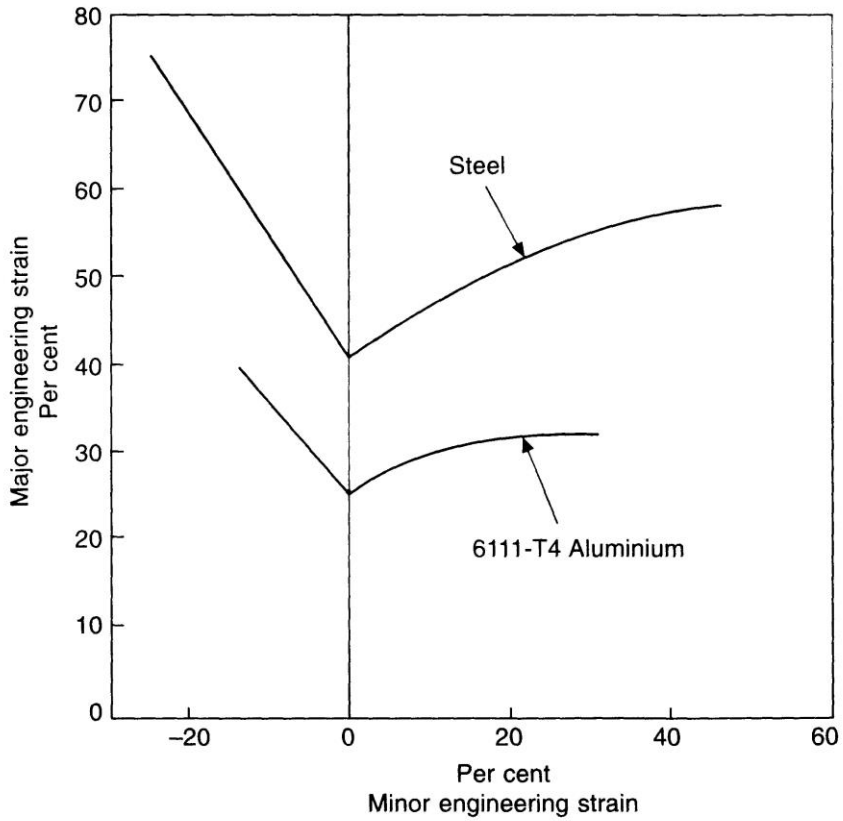
Comparison 5xxx and 6xxx

	5xxx	6xxx
Formability	+++	++
Corrosion resistance	+++	++
Heat resistance > 65°C	Not good for > % Mg	+++
Crash performance	+++	+++
Surface quality	Stretcher strain markings	+++
Strength	+	+++
Effect heat treatment on strength	decrease	increase

Deformability: tensile stress-strain curve



Deformability: forming limit diagram



Спасибо

KU LEUVEN