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
- 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

\[
\sigma = \sigma_{ij} = \begin{bmatrix}
T^{(e_1)} \\
T^{(e_2)} \\
T^{(e_3)}
\end{bmatrix} = \begin{bmatrix}
\sigma_{11} & \sigma_{12} & \sigma_{13} \\
\sigma_{21} & \sigma_{22} & \sigma_{23} \\
\sigma_{31} & \sigma_{32} & \sigma_{33}
\end{bmatrix} \equiv \begin{bmatrix}
\sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\
\sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\
\sigma_{zx} & \sigma_{zy} & \sigma_{zz}
\end{bmatrix} \equiv \begin{bmatrix}
\sigma_x & \tau_{xy} & \tau_{xz} \\
\tau_{yx} & \sigma_y & \tau_{yz} \\
\tau_{zx} & \tau_{zy} & \sigma_z
\end{bmatrix},
\]

• Principal stresses

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

\[
I_1 = \sigma_{11} + \sigma_{22} + \sigma_{33} = \sigma_{kk}
\]

\[
I_2 = \begin{vmatrix}
\sigma_{22} & \sigma_{23} \\
\sigma_{32} & \sigma_{33}
\end{vmatrix} + \begin{vmatrix}
\sigma_{11} & \sigma_{13} \\
\sigma_{31} & \sigma_{33}
\end{vmatrix} + \begin{vmatrix}
\sigma_{11} & \sigma_{12} \\
\sigma_{21} & \sigma_{22}
\end{vmatrix}
\]

\[
= \sigma_{11}\sigma_{22} + \sigma_{22}\sigma_{33} + \sigma_{11}\sigma_{33} - \sigma_{12}^2 - \sigma_{23}^2 - \sigma_{31}^2
\]

\[
= \frac{1}{2} (\sigma_{ii}\sigma_{jj} - \sigma_{ij}\sigma_{ji})
\]

\[
I_3 = \text{det}(\sigma_{ij})
\]

\[
= \sigma_{11}\sigma_{22}\sigma_{33} + 2\sigma_{12}\sigma_{23}\sigma_{31} - \sigma_{12}^2\sigma_{33} - \sigma_{23}^2\sigma_{11} - \sigma_{31}^2\sigma_{22}
\]
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

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

  - In principal stress terms:

\[ \tau_{\text{max}} = \frac{1}{2} \left| \sigma_{\text{max}} - \sigma_{\text{min}} \right| \quad \text{Tresca yield criterion (1864)} \]
Hydrostatic and distortional stress

\[ \sigma_{ij} = s_{ij} + \pi \delta_{ij} \]

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

\[ \pi = \frac{\sigma_{kk}}{3} = \frac{\sigma_{11} + \sigma_{22} + \sigma_{33}}{3} = \frac{1}{3} I_1. \]

**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

\[
J_1 = s_{kk} = 0,
\]

\[
J_2 = \frac{1}{2} s_{ij} s_{ji} \\
= \frac{1}{2} (s_1^2 + s_2^2 + s_3^2) \\
= \frac{1}{6} \left[ (\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2 \right] + \sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2 \\
= \frac{1}{6} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right] \\
= \frac{1}{3} I_1^2 - I_2,
\]

\[
J_3 = \det(s_{ij}) \\
= \frac{1}{3} s_{ij} s_{jk} s_{ki} \\
= s_1 s_2 s_3 \\
= \frac{2}{27} I_1^3 - \frac{1}{3} I_1 I_2 + I_3.
\]

- Von Mises stress

\[
\sigma_{VM} = \sqrt{\frac{1}{2} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]} = \sqrt{3} J_2
\]

- Octahedral stress:

\[
\tau_{oct} = \frac{1}{3} \sqrt{\left( \sigma_1 - \sigma_2 \right)^2 + \left( \sigma_2 - \sigma_3 \right)^2 + \left( \sigma_3 - \sigma_1 \right)^2} = \sqrt{\frac{2}{3} J_2}
\]
Huber-Mises-Hencky yield criterion

- Yielding starts when $J_2$ reaches a critical value

<table>
<thead>
<tr>
<th>Condition</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>$2\sigma_y^2 = (\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2 + 6(\sigma_{12}^2 + \sigma_{23}^2 + \sigma_{31}^2)$</td>
</tr>
<tr>
<td>Principal stress</td>
<td>$2\sigma_y^2 = (\sigma_I - \sigma_{II})^2 + (\sigma_{II} - \sigma_{III})^2 + (\sigma_{III} - \sigma_I)^2$</td>
</tr>
<tr>
<td>Plane stress general</td>
<td>$\sigma_y^2 = \sigma_{11}^2 - \sigma_{11}\sigma_{22} + \sigma_{22}^2 + 3\sigma_{12}^2$</td>
</tr>
<tr>
<td>Plane stress principal</td>
<td>$\sigma_y^2 = \sigma_I^2 - \sigma_I\sigma_{II} + \sigma_{II}^2$</td>
</tr>
<tr>
<td>Pure shear</td>
<td>$\sigma_y = \sqrt{3}\left</td>
</tr>
<tr>
<td>Uniaxial</td>
<td>$\sigma_y = \sigma_1$</td>
</tr>
</tbody>
</table>
Graphic representation

Von Mises
Tresca

Spherical pressure vessel

Torsion test

Compression test

Tensile test

Spherical bathosphere
Uniaxial loading

- **σ**: Stress
- **σ_u**: Ultimate stress
- **σ_t**: Fracture stress
- **σ_y**: Yield stress
- **σ_pl**: Proportionality limit

- Elastic region
- Yielding
- Strain hardening
- Necking
- Elastic behavior
- Plastic behavior
- Proportionality limit
- Ultimate stress
- Fracture stress
- Yield stress
- Proportionality limit

[Diagram of stress-strain curve with labels for various stress and strain stages.]
2 Forming processes
Shaping processes
Stretch forming – deep drawing
Defects in deep drawing
Parameters influencing formability

- Material Properties
  - Mechanical properties: \(\varepsilon_0, E, R_{0.2}, n, r, m\)
  - Metallurgical properties
  - Texture, size, shape, density of the voids
  - Chemical properties
  - Chemical composition

- Process parameters
  - Stress state
  - Strain rate
  - Temperature
  - Part configuration
  - Lubrication

- Strain bounding criteria
  - Tearing
  - Strain localization
  - Wrinkling
  - Roughness
  - Springback

Formability
Example
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

- 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

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

$r$ = $\frac{\varepsilon_w}{\varepsilon_t}$ = True strain in width direction / True strain in thickness direction
Directional dependence of $r$
Coefficient of normal anisotropy

\[ r_m = \frac{r_{0^\circ} + 2r_{45^\circ} + r_{90^\circ}}{4} \]

- Depends on strain

![Diagram showing the coefficient of anisotropy](image)

![Graph showing the longitudinal strain](image)
Planar anisotropy

• Variation of normal anisotropy

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

• Responsible for earing
Biaxial anisotropy coefficient

- Barlat
  - Flatwise compression

\[ r_b = \frac{\varepsilon_{TD}}{\varepsilon_{RD}} \]

- Pöhland
  - Biaxial tension
Consequences of anisotropy

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

- Yield criterion for anisotropic materials: Hill1948

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

\[
2F = \frac{1}{Y^2} + \frac{1}{Z^2} - \frac{1}{X^2} \quad 2L = \frac{1}{R^2}
\]

\[
2G = \frac{1}{X^2} + \frac{1}{Z^2} - \frac{1}{Y^2} \quad 2M = \frac{1}{S^2}
\]

\[
2H = \frac{1}{X^2} + \frac{1}{Y^2} - \frac{1}{Z^2} \quad 2N = \frac{1}{T^2}
\]
Hill 1990

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

\( \sigma_b \): yield stress in biaxial tension
\( \tau \): yield stress in pure shear

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

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

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

- New criteria for the complex steel alloys for automotive

| Author, year         | $\sigma_0$ | $\sigma_{30}$ | $\sigma_{45}$ | $\sigma_{75}$ | $\sigma_{90}$ | $\sigma_b$ | $r_0$ | $r_{30}$ | $r_{45}$ | $r_{75}$ | $r_{90}$ | $r_b$ | 3D | A1 | A2 |
|----------------------|------------|---------------|---------------|---------------|---------------|-----------|-------|--------|--------|--------|--------|------|----|----|
| Hill’s family        |            |               |               |               |               |           |       |        |        |        |        |      |    |    |
| Hill 1948            | x          |               |               |               |               |           |       |        |        |        |        |      |    |    |
| Hill 1979            | x          |               |               |               |               |           |       |        |        |        |        |      |    |    |
| Hill 1990            | x          | x             |               |               |               |           |       |        |        |        |        |      |    |    |
| Hill 1993            | x          |               |               |               |               |           |       |        |        |        |        |      |    |    |
| Lin, Ding 1996       | x          |               |               |               |               |           |       |        |        |        |        |      |    |    |
| Hu 2005              | x          | x             |               |               |               |           |       |        |        |        |        |      |    |    |
| Leacock 2006         | x          | x             | x             |               |               |           |       |        |        |        |        |      |    |    |
| Hershey’s family     |            |               |               |               |               |           |       |        |        |        |        |      |    |    |
| Hosford 1979         | x          |               |               |               |               |           |       |        |        |        |        |      |    |    |
| Barlat 1989          | x          |               |               |               |               |           |       |        |        |        |        |      |    |    |
| Barlat 1991          | x          | x             |               |               |               |           |       |        |        |        |        |      |    |    |
| Karafillis Boyce 1993| x          | x             | x             |               |               |           |       |        |        |        |        |      |    |    |
| Barlat 1997          | x          |               |               |               |               |           |       |        |        |        |        |      |    |    |
| BBC 2000             | x          |               |               |               |               |           |       |        |        |        |        |      |    |    |
| Barlat 2000          | x          |               |               |               |               |           |       |        |        |        |        |      |    |    |
| Bron, Besson 2003    | x          |               |               |               |               |           |       |        |        |        |        |      |    |    |
| Barlat 2004          | x          |               |               |               |               |           |       |        |        |        |        |      |    |    |
| BBC 2005             | x          |               |               |               |               |           |       |        |        |        |        |      |    |    |
| Drucker’s family     |            |               |               |               |               |           |       |        |        |        |        |      |    |    |
| Cazacu–Barlat 2001   | x          | x             | x             | x             | x             | x         | x     | x      | x      |        |        |      |    |    |
| Cazacu–Barlat 2003   | x          | x             | x             | x             | x             | x         | x     | x      | x      |        |        |      |    |    |
| C-P – B 2006         | x          | x             | x             | x             | x             | x         | x     | x      | x      |        |        |      |    |    |
| Polynomial criteria  |            |               |               |               |               |           |       |        |        |        |        |      |    |    |
| Comsa 2006           | x          | x             | x             | x             | x             | x         | x     | x      | x      |        |        |      |    |    |
| Soare 2007 (Poly 4)  | x          | x             | x             | x             | x             | x         | x     | x      | x      |        |        |      |    |    |
Experimental correlation

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
Deep drawing methods

- Swift test
  - Limit drawing ratio

\[ \text{LDR} = \frac{D_{\text{max}}}{d} \]
Forming limit strain diagram
Nakazima test

- Forming test with varying boundary conditions
Determination of deformability limits: Hecker method

- Deformation of a printed circular grid
  - Largest strain $\varepsilon_1$
    - Always positive
  - Smallest strain $\varepsilon_2$
    - Positive or negative
Forming limit curve

\[ \varepsilon_1 + \varepsilon_2 + \varepsilon_3 = 0 \]

- Plane tension: \( \varepsilon_3 = -\varepsilon_1 \)
- Uniaxial tension: \( \varepsilon_3 < 0 \)
- Shear: \( \varepsilon_2 = -\varepsilon_1, \varepsilon_3 = 0 \)
- Plane strain compression: \( \varepsilon_3 = -\varepsilon_2 \)

r important
n important
Influencing parameters
Other parameters

- Temperature
- Strain rate
- Punch curvature
- Pressure
- Dimensions of the grid
- …
Alternative measurement method: Digital Image Correlation
Introduction – Digital Image Correlation

Deformation matrix

\[
\begin{bmatrix}
\mu(x, y, s) \\
\nu(x, y, s)
\end{bmatrix} = \begin{bmatrix} x \\ y \end{bmatrix} + \begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} + \begin{bmatrix} \frac{\partial^2 u}{\partial x^2} & \frac{\partial^2 u}{\partial x \partial y} & \frac{\partial^2 u}{\partial y^2} \\ \frac{\partial^2 v}{\partial x^2} & \frac{\partial^2 v}{\partial x \partial y} & \frac{\partial^2 v}{\partial y^2} \end{bmatrix} \begin{bmatrix} \Delta x \Delta y + \frac{(\Delta x)^2}{2} \\ \frac{(\Delta y)^2}{2} \end{bmatrix}
\]

Correlation coefficient

\[
\begin{align*}
\rho_{CC} &= \frac{\sum_y \sum_x f(x, y) g[\mu(x, y, s), \nu(x, y, s)]}{\sqrt{\left[\sum_y \sum_x f^2(x, y)\right] \left[\sum_y \sum_x g^2[\mu(x, y, s), \nu(x, y, s)]\right]}} \\
\rho_{SSD} &= 1 - \frac{\sum_y \sum_x [f(x, y) - g[\mu(x, y, s), \nu(x, y, s)]]^2}{\sum_y \sum_x f^2(x, y)}
\end{align*}
\]
DIC in forming - Challenges

- **Strain** $> 100\%$ is not exceptional $\rightarrow$ when judging strain, choice of strain definition is important
- **Strain rate** $\rightarrow 0,01/s$ up to $10/s$
- **Speckle technique** on sheet (low surface energy)
  - Custom paint
  - Spray/Print
- **Forming temperature** $100-300^\circ C$
- **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

Asymmetric thinning due to sag

Stress relaxation

Final thickness distribution

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

Sheet temperature during forming
Use of DIC to determine FLC

Test type 4

Forming limit curve (FLC)
ISO 12004
Example: steel
Effect of history and crystallographic texture on anisotropy
Steel production

1 - Production of Molten Steel

- Limestone
- Sinter Plant - Sinter
- Iron Ore
- Coke Ovens - Coke
- Coke
- Recycled Steel - Scrap
- Offcuts from various processes & scrap
- Blast Furnace - Molten Iron
- Basic Oxygen Vessel
- Electric Arc Furnace
- Molten Steel

Secondary Steelmaking
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
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)

- Thickness gauge: Am or X-ray type
- Shear
- Cleaning
- Entry Looper
- Annealing Furnace
- Delivery Looper
- Trimmer
- Skinpass Mill
- Width gauge (with Hole detector)
- Surface Inspection
- Tension Reels
Annealing differences

<table>
<thead>
<tr>
<th>batch</th>
<th>CAPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slow heating: 30 hours</td>
<td>Rapid heating: 90 s</td>
</tr>
<tr>
<td>Slow cooling: 25 hours</td>
<td>Fast cooling: 10 min</td>
</tr>
<tr>
<td>Coarse grain</td>
<td>Finer grain</td>
</tr>
<tr>
<td></td>
<td>Stronger</td>
</tr>
<tr>
<td>Higher ductility</td>
<td></td>
</tr>
<tr>
<td>High r: 1.6-2.1</td>
<td>Low r 1.0-1.4</td>
</tr>
</tbody>
</table>
• 1% deformation after annealing
Surface topography

• Importance of the surface topography
  o Forming process
    • Lubrication characteristics
  o Paint quality
    • Adhesion
    • gloss

• Determined by the skin pass
High strength steels

Hyper deep drawing

High strength and ultra high strength

Cold rolled and coated
- Deep drawing steel
- Structural steel
- HSLA steel
- IF HSS
- Bake hardening steel
- Rephosphorised steel
- Isotropic steel
- Dual phase steel
- TRIP steel

Formability

Strength

Conventional steel
IF HSS

• Vacuum degassed
  o Removal of C, N, O
  o Reduced dent resistance

• 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 $\Rightarrow$ increased strength
- Expensive
TRIP >> TWIP

[Graph showing tension vs stretch for TRIP and TWIP steels]
Consequences
Steel versus aluminium
## Al alloys used in automotive

### Table 3.10  Automotive aluminium alloys in current use

<table>
<thead>
<tr>
<th>Alloy AA DIN</th>
<th>AA6016 AlMg0.4Si1.2</th>
<th>AA6111 AlMg0.7Si0.9Cu0.7</th>
<th>AA6009 AlMg0.5Si0.8CuMn</th>
<th>AA5251 AlMg2Mn0.3</th>
<th>AA5754 AlMg3</th>
<th>AA5182 AlMg5Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temper</td>
<td>T4</td>
<td>T4</td>
<td>T4</td>
<td>H22 (Grade 3)</td>
<td>O / H111</td>
<td>O / H111</td>
</tr>
<tr>
<td>UTS (MPa)</td>
<td>210</td>
<td>290</td>
<td>250</td>
<td>190</td>
<td>215</td>
<td>270</td>
</tr>
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<td>0.2 proof stress (MPa)</td>
<td>105</td>
<td>160</td>
<td>130</td>
<td>120</td>
<td>110</td>
<td>140</td>
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<td>Elongation A80 (%)</td>
<td>26</td>
<td>25</td>
<td>24</td>
<td>18</td>
<td>23</td>
<td>24</td>
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<tr>
<td>r (mean value)</td>
<td>0.61</td>
<td>0.55</td>
<td>0.64</td>
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<td>0.70</td>
<td>0.80</td>
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<tr>
<td>n 5% (mean value)</td>
<td>0.30</td>
<td>0.28</td>
<td>0.29</td>
<td></td>
<td>0.35</td>
<td>0.33</td>
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<tr>
<td>Advantages</td>
<td>Formability, no stretcher-strain marks, balanced properties</td>
<td>No stretcher-strain marks, improved bake-hardening response</td>
<td>No stretcher-strain marks, mechanical strength</td>
<td>Corrosion resistance, cost</td>
<td>Good formability</td>
<td>Very good formability</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Limited bake-hardening response at Rover paint temperature</td>
<td>Corrosion concerns, limited formability</td>
<td>Limited hemming and forming properties</td>
<td></td>
<td></td>
<td>Possible stretcher-strain marks (Lüders lines) after deep drawing</td>
</tr>
<tr>
<td>Alloy type</td>
<td>BAKE HARDENING</td>
<td></td>
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<td>Typical use</td>
<td>SKIN PANELS</td>
<td></td>
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<td></td>
<td>NON-BAKE HARDENING</td>
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## Comparison 5xxx and 6xxx

<table>
<thead>
<tr>
<th></th>
<th>5xxx</th>
<th>6xxx</th>
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<tbody>
<tr>
<td>Formability</td>
<td>+++</td>
<td>++</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>+++</td>
<td>++</td>
</tr>
<tr>
<td>Heat resistance &gt; 65°C</td>
<td>Not good for &gt; % Mg</td>
<td>+++</td>
</tr>
<tr>
<td>Crash performance</td>
<td>+++</td>
<td>+++</td>
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<tr>
<td>Surface quality</td>
<td>Stretcher strain markings</td>
<td>+++</td>
</tr>
<tr>
<td>Strength</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Effect heat treatment on strength</td>
<td>decrease</td>
<td>increase</td>
</tr>
</tbody>
</table>
Deformability: tensile stress-strain curve

- **UTS**: Ultimate Tensile Strength
- **YS**: Yield Strength
- **Modulus**
  - **Aluminium**: 70 MPa (10 Msi)
  - **Steel**: 210 MPa (30 Msi)
- **Post-uniform elongation**
  - **Aluminium**: 4%
  - **Steel**: 19%
- **Work-hardening coefficient**
  - **Aluminium**: 0.23
  - **Steel**: 0.23
- **Uniform elongation**
  - **Aluminium**: 21%
  - **Steel**: 24%
- **Strain rate hardening**
  - **Aluminium**: -0.002
  - **Steel**: 0.013
Deformability: forming limit diagram

![Graph showing forming limit diagram for Steel and 6111-T4 Aluminium]
Спасибо