Sheet Metal Forming

2.810

D. Cooper

- “Sheet Metal Forming” Ch. 16 Kalpakjian
- “Design for Sheetmetal Working”, Ch. 9 Boothroyd, Dewhurst and Knight
Examples - sheet metal formed
Sheet metal stamping/drawing – car industry

- **90 million** cars and commercial vehicles produced worldwide in 2014

[Diagram showing the stamping process with labels for metal sheet, female die, male die (punch/post), blank holder (ring) on cushion, and compressible cushion.]
Stamping Auto body panels

- 3 to 5 dies each
- Prototype dies ~ $50,000
- Production dies ~ $0.75-1 mil.

- Forming dies
- Trimming station
- Flanging station
Objectives

By the end of today you should be able to...

...**describe** different forming processes, when they might be used, and **compare** their production rates, costs and environmental impacts

...**calculate** forming forces, **predict** part defects (tearing, wrinkling, dimensional inaccuracy), and **propose** solutions

...**explain** current developments: opportunities and challenges
LMP Shop

Brake press

Finger brake

Diagram showing punch steel, die steel, and V-die.
### Technology – a brief review

#### Material drawn into shape
- **Conventional drawing/stamping** – expensive tooling, no net thinning, quick
- **Hydro-forming** – cheap tooling, no net thinning, slow, high formability

#### Material stretched into shape
- **Stretch forming** – very cheap tooling, net thinning, slow, low formability
- **Super-plastic forming** – cheap tooling, net thinning, expensive sheet metal, slow, very high formability

<table>
<thead>
<tr>
<th>Technology</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional drawing/stamping</td>
<td>20-1000pts/hr</td>
</tr>
<tr>
<td>Hydro-forming</td>
<td>7-13cycles/hr</td>
</tr>
<tr>
<td>Stretch forming</td>
<td>3-8pts/hr</td>
</tr>
<tr>
<td>Super-plastic forming</td>
<td>0.3-4pts/hr</td>
</tr>
</tbody>
</table>
Drawing – expensive tooling, no net thinning, quick

Deep-drawing

Shallow-drawing (stamping)
Deep-drawing

Blank holder helps prevent wrinkling and reduces springback

Blank holder not necessary if blank diameter / blank thickness is less than 25-40. Smaller values for deeper forming.
Blank holder force: forming window

![Graph showing the relationship between depth of draw and blankholder force. The graph illustrates the window for forming, with a region marked for wrinkling and tearing.]

- Depth of draw
- Blankholder force
- Wrinkling
- Tearing
- Window for forming
Deep Drawing of drinks cans

Hosford and Duncan (can making): http://www.chymist.com/Aluminum%20can.pdf

FIGURE 16.31 The metal-forming processes involved in manufacturing a two-piece aluminum beverage can.
Hydro-forming – cheap tooling, no net thinning, slow(ish), high formability

Low volume batches
Hydro-forming – cheap tooling, no net thinning, slow(ish), high formability

Low volume batches
Hydro-forming – cheap tooling, no net thinning, slow, high formability

Small flexforming tool made by additive manufacturing
**Stretch forming** – very cheap tooling, net thinning, slow, low formability, sheet metal up to 15mx9m

* source: http://www.cyrilbath.com/sheet_process.html

Low volume batches
Higher aspect ratio, deeper parts
Super-plastic forming – cheap tooling, net thinning, slow, expensive sheet metal, very high formability

Low volume batches, 0.5-0.75 melting temp
Forming forces and part geometry
Tensile test – the Stress-strain diagram

\[ \sigma_y = Y \]

UTS
True stress & strain

\[ \varepsilon_{tr} = \ln(1 + \varepsilon_{en}) \]

\[ \sigma_{tr} = \sigma_{en}(1 + \varepsilon_{en}) \]

True stress can be expressed using a power law (Hollomon equation):

\[ \sigma_{tr} = K\varepsilon_{tr}^n \]

\[ \sigma_y = Y \]
Power-Law Expression (Hollomon equation)

\[ \sigma_{tr} = K \varepsilon_{tr}^n \]

Can be re-written:

\[ \log(\sigma_{tr}) = n \log(\varepsilon_{tr}) + \log K \]
Power-Law Expression (Hollomon equation)

\[ \sigma_{tr} = K \varepsilon_{tr}^n \]

Can be re-written: \[ \log(\sigma_{tr}) = n \log(\varepsilon_{tr}) + \log K \]
<table>
<thead>
<tr>
<th>Material</th>
<th>K (MPa)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1100-O</td>
<td>180</td>
<td>0.20</td>
</tr>
<tr>
<td>2024-T4</td>
<td>690</td>
<td>0.16</td>
</tr>
<tr>
<td>5052-O</td>
<td>202</td>
<td>0.13</td>
</tr>
<tr>
<td>6061-O</td>
<td>205</td>
<td>0.20</td>
</tr>
<tr>
<td>6061-T6</td>
<td>410</td>
<td>0.05</td>
</tr>
<tr>
<td>7075-O</td>
<td>400</td>
<td>0.17</td>
</tr>
<tr>
<td>Brass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70-30, annealed</td>
<td>900</td>
<td>0.49</td>
</tr>
<tr>
<td>85-15, cold rolled</td>
<td>580</td>
<td>0.34</td>
</tr>
<tr>
<td>Cobalt-based alloy, heat treated</td>
<td>2070</td>
<td>0.50</td>
</tr>
<tr>
<td>Copper, annealed</td>
<td>315</td>
<td>0.54</td>
</tr>
<tr>
<td>Steel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low-C, annealed</td>
<td>530</td>
<td>0.26</td>
</tr>
<tr>
<td>1020, annealed</td>
<td>745</td>
<td>0.20</td>
</tr>
<tr>
<td>4135, annealed</td>
<td>1015</td>
<td>0.17</td>
</tr>
<tr>
<td>4135, cold rolled</td>
<td>1100</td>
<td>0.14</td>
</tr>
<tr>
<td>4340, annealed</td>
<td>640</td>
<td>0.15</td>
</tr>
<tr>
<td>304 stainless, annealed</td>
<td>1275</td>
<td>0.45</td>
</tr>
<tr>
<td>410 stainless, annealed</td>
<td>960</td>
<td>0.10</td>
</tr>
<tr>
<td>Titanium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti-6Al-4V, annealed, 20°C</td>
<td>1400</td>
<td>0.015</td>
</tr>
<tr>
<td>Ti-6Al-4V, annealed, 200°C</td>
<td>1040</td>
<td>0.026</td>
</tr>
<tr>
<td>Ti-6Al-4V, annealed, 600°C</td>
<td>650</td>
<td>0.064</td>
</tr>
<tr>
<td>Ti-6Al-4V, annealed, 800°C</td>
<td>350</td>
<td>0.146</td>
</tr>
</tbody>
</table>
Tensile instability - necking

\[ \sigma = k \varepsilon^n \]

- True: \( d\varepsilon = \frac{dl}{l} \)
- Nominal: \( \sigma = \frac{F}{A_0}, \varepsilon = \frac{l-l_0}{l_0} \)

Neck forms at \( \varepsilon^* \)

Tensile instability (1-D)
\[
F = \sigma A; \text{ so } dF = \sigma dA + Ad\sigma = 0 \text{ at max load}
\]

\[
\frac{d\sigma}{\sigma} = -\frac{dA}{A} = d\varepsilon
\]

\[
\frac{d\sigma}{d\varepsilon} = \sigma
\]

With \( \sigma = k \varepsilon^n \):
\[
\frac{d\sigma}{d\varepsilon} = n k \varepsilon^{n-1} = \sigma = k \varepsilon^n
\]

\[ \Rightarrow \quad \varepsilon^* = n \]
Useful assumptions

Only interested in plastic effects:

**Perfectly plastic material**

At Y, material deforms (‘flows’) in compression and fails in tension.

Interested in elastic and plastic effects:

**Elastic-perfectly plastic material**
3D Problems

In 1-D, \[ \sigma = K \varepsilon^n \] assuming perfectly plastic, yielding at: \[ \sigma = Y \]

In 3-D, \[ \sigma_{\text{eff}} = K \varepsilon_{\text{eff}}^n \] assuming perfectly plastic, yielding at: \[ \sigma_{\text{eff}} = Y \]

For any general stress state we can find a set of principal axes. The stress tensor for these axes contains no off-diagonal (shear) terms – only three principal stresses along the three axes.

Mohr’s circle allows rotation of axes in two dimensions about one principal axis.
### 3D Yield Criteria

<table>
<thead>
<tr>
<th><strong>Tresca:</strong> Yielding occurs at a maximum shear stress</th>
<th><strong>Von Mises:</strong> Yielding at maximum distortion strain energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective stress (in principal directions):</td>
<td>Effective stress (in principal directions):</td>
</tr>
<tr>
<td>( \sigma_{eff} = \left[ \sigma_i - \sigma_j \right]_{\text{max, } i \neq j} )</td>
<td>( \sigma_{eff} = \sqrt{\frac{1}{2} \left[ \left( \sigma_2 - \sigma_3 \right)^2 + \left( \sigma_3 - \sigma_1 \right)^2 \right]} ) + ( \left( \sigma_1 - \sigma_2 \right)^2 )</td>
</tr>
<tr>
<td>Yield criterion:</td>
<td>Yield criterion:</td>
</tr>
<tr>
<td>( \sigma_{eff} = Y )</td>
<td>( \sigma_{eff} = Y )</td>
</tr>
<tr>
<td>( \tau_{\text{max}} = k = \frac{Y}{2} )</td>
<td>( Y = \sqrt{3k} )</td>
</tr>
<tr>
<td>Effective strain:</td>
<td>Effective strain:</td>
</tr>
<tr>
<td>( \varepsilon_{eff} = \left( \varepsilon_i \right)_{\text{max}} )</td>
<td>( \varepsilon_{eff} = \sqrt{\left( \frac{2}{3} \right) \times \left( \varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2 \right)} )</td>
</tr>
</tbody>
</table>
Shearing

\[ F = 0.7 \ T \ L \ (UTS) \]

- **F** = Shear Force
- **T** = Sheet Thickness
- **L** = Total length Sheared
- **UTS** = Ultimate Tensile Strength of material

Shear press - LMP Shop

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Side Note: For a general state of stress use “effective stress”

2-6 EFFECTIVE STRESS

With either yield criterion, it is useful to define an effective stress denoted as \( \bar{\sigma} \) which is a function of the applied stresses. If the magnitude of \( \bar{\sigma} \) reaches a critical value, then the applied stress state will cause yielding; in essence, it has reached an effective level. For the von Mises criterion,

\[
\bar{\sigma} = \frac{1}{\sqrt{2}} \left[ (\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \right]^{1/2}
\] (2-16)

while for the Tresca criterion,

\[
\bar{\sigma} = \sigma_1 - \sigma_3 \quad \text{where} \quad \sigma_1 > \sigma_2 > \sigma_3
\] (2-17)

Yielding occurs when \( \sigma_{\text{effective}} = Y \)

Material taken from *Metal Forming*, by Hosford and Caddell
Origin of effective strain

2-7 EFFECTIVE STRAIN

Effective strain is defined such that the incremental work per unit volume is

\[ dw = \bar{\sigma} \overline{d\varepsilon} = \sigma_1 d\varepsilon_1 + \sigma_2 d\varepsilon_2 + \sigma_3 d\varepsilon_3 \]  (2-18)

For the von Mises criterion, the effective strain is given by

\[ d\overline{\varepsilon} = \frac{\sqrt{2}}{3} [(d\varepsilon_1 - d\varepsilon_2)^2 + (d\varepsilon_2 - d\varepsilon_3)^2 + (d\varepsilon_3 - d\varepsilon_1)^2]^{1/2} \]  (2-19)

which may be expressed in a simpler form as

\[ d\overline{\varepsilon} = \left[ \frac{2}{3} (d\varepsilon_1^2 + d\varepsilon_2^2 + d\varepsilon_3^2) \right]^{1/2} \]  (2-20)

If the straining is proportional (with a constant ratio of \( d\varepsilon_1 : d\varepsilon_2 : d\varepsilon_3 \)), the total effective strain may be expressed in terms of the total strains as

\[ \overline{\varepsilon} = \left[ \frac{2}{3} (\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2) \right]^{1/2} \]  (2-21)

If the strain path is not constant, \( \overline{\varepsilon} \) must be found from a path integral of \( d\overline{\varepsilon} \). In

\[ \overline{\sigma} = K \overline{\varepsilon}^n \]

Material taken from *Metal Forming*, by Hosford and Caddell
3D Yield Effective stress

Tresca predicts ‘flow’ for lower stresses than von Mises

\[ \sigma_3 = 0 \]
Forming Limit Diagrams

Figure 15-8  Strips of varying width are stretched to obtain different $\varepsilon_2/\varepsilon_1$ ratios.

Excluded: $\varepsilon_1$ must be $> \varepsilon_2$. 
Tensile test

\[ \varepsilon_1 = -2 \varepsilon_2 \]

\[ \varepsilon_1 = n = \text{necking} \]

Major Strain

Minor Strain

balanced biaxial tension
Pure Shear
\[ \varepsilon_1 = -\varepsilon_2 \]
Stretch forming: **Forming force**

\[ F = \frac{Y_S + UTS}{2} \times A \]

- **F** = stretch forming force (lbs)
- **Y_S** = material yield strength (psi)
- **UTS** = ultimate tensile strength of the material (psi)
- **A** = Cross-sectional area of the workpiece (in²)

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Forces needed to bend sheet metal
Bending

\[ \Delta L = (L - L_0) = (\rho + y)\theta - \rho \theta = y \theta \]

\[ \varepsilon = \frac{\Delta L}{L_0} = \frac{y \theta}{\rho \theta} = \frac{y}{\rho} \]

\[ \varepsilon_{\max} = \frac{h/2}{R + h/2} = \frac{1}{2R/R + 1} \]

Figure Coordinate system for analysis of bending.
Stress distribution through the thickness of the part

Elastic

Elastic-plastic

Fully plastic

Fully Plastic Moment, $M = Y (b \, h/2) \, h/2 = Ybh^2/4$
Balance external and internal moments

\[ \sigma h - Y \]

Fully plastic

\[ Ybh^2/4 = FL/4 = M_{\text{max}} \]

\[ F = bh^2Y/L \]
Bending Force Requirement

\[ F = \frac{LT^2}{W} (UTS) \]

- \( T \) = Sheet Thickness
- \( W \) = Width of Die Opening
- \( L \) = Total length of bend (into the page)
- \( UTS \) = Ultimate Tensile Strength of material

Note: the notation used in the text (L, W) differs from that used in the previous development (b, L).
LMP Shop

Brake press

Finger brake

[Images of brake press and finger brake]

[Diagram of punch steel and die steel with labels: Punch steel, Die steel, Sheet metal, V-die]
What shape have we created?
Steel versus aluminum...

Strength ($\sigma_y$) versus Stiffness ($E$)

- Mild steel (33,000 psi) & Al. 5052$_{H32}$ (33,000 psi)
- Al. 5052$_{H32}$ (10.6E6 psi)
Steel versus aluminum…

Strength ($\sigma_y$) versus Stiffness ($E$)

Mild steel (33,000psi) & Al. 5052$_{H32}$ (33,000psi)

Mild steel (30E6psi) Low spring back

Al. 5052$_{H32}$ (10.6E6psi) High spring back
Steel versus aluminum...

Strength ($\sigma_y$) versus Stiffness ($E$)

- Mild steel (33,000psi) & Al. 5052$_{H32}$ (33,000psi)
- Al. 2024$_{T3}$ (50,000psi)
- Mild steel (30E6psi)
- Al. 2024$_{T3}$ & 5052$_{H32}$ (10.6E6psi)
- Low spring back
- High spring back

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Steel versus aluminum...

**Strength ($\sigma_y$) versus Stiffness ($E$)**

- **Al. $2024_{T3}$ (50,000psi)**
  - High spring back

- **Mild steel (33,000psi) & Al. $5052_{H32}$ (33,000psi)**
  - Low spring back

- **Mild steel (30E6psi)**
  - Low spring back

- **Al. $2024_{T3}$ & $5052_{H32}$ (10.6E6psi)**
  - High spring back
<table>
<thead>
<tr>
<th>Material</th>
<th>Yield Strength, Y (psi)</th>
<th>Modulus, E (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al 2024 (T3)</td>
<td>50000</td>
<td>10600000</td>
</tr>
<tr>
<td>Al EC (99.0 %)</td>
<td>14000</td>
<td>10000000</td>
</tr>
<tr>
<td>Mild Steel</td>
<td>33000</td>
<td>30000000</td>
</tr>
<tr>
<td>Titanium</td>
<td>80000</td>
<td>15000000</td>
</tr>
</tbody>
</table>

The graph compares the stress-strain behavior of different materials: Ti (Tin), Mild steel, and Al EC (Aluminum EC). The plot shows the stress (σ) on the y-axis and the strain (ε) on the x-axis.
<table>
<thead>
<tr>
<th></th>
<th>Al 2024 (T3)</th>
<th>Al EC (99.0%)</th>
<th>Mild Steel</th>
<th>Titanium</th>
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<td>Yield Strength, $Y$ (psi)</td>
<td>50000</td>
<td>14000</td>
<td>33000</td>
<td>80000</td>
</tr>
<tr>
<td>Modulus, $E$ (psi)</td>
<td>106000000</td>
<td>100000000</td>
<td>300000000</td>
<td>150000000</td>
</tr>
</tbody>
</table>

- $\sigma$: Stress
- $\varepsilon$: Strain
- Ti: Titanium
- Mild steel
- Al EC: Aluminum EC
Springback note R in the figure below is mislabeled, should go to the centerline of the sheet.

Springback: \[ \frac{R_i}{R_f} = 4 \left( \frac{R_i Y}{ET} \right)^3 - 3 \left( \frac{R_i Y}{ET} \right) + 1 \]
1. Assume plane sections remain plane:
   \[ e_y = -\frac{y}{r} \]  

2. Assume elastic-plastic behavior for material
   \[ \sigma = E e \quad \text{for} \quad e < e_{\psi} \]
   \[ \sigma = \sigma_Y \quad \text{for} \quad e \geq e_{\psi} \]
Bending Moment – Curvature

\[ M = \frac{1}{r} EI \]

\[ Y \]

Loading

Unloading

\[ M_Y \]

\[ 1/r_Y \]

\[ 1/R_1 \]

\[ 1/R_0 \]

\[ 1/r \]
3. We want to construct the following Bending Moment “M” vs. curvature “1/ρ” curve

Springback is measured as

\[ \frac{1}{R_0} - \frac{1}{R_1} \]

Permanent set is

\[ \frac{1}{R_1} \]

\[ M = \frac{M_Y}{(1/\rho)_Y} \left( \frac{1}{\rho} - \frac{1}{R_1} \right) \]
4. Stress distribution through the thickness of the beam

- Elastic
- Elastic-plastic
- Fully plastic
5. \( M = \int_A \sigma y \, dA \)

Elastic region

\[
M = \int \sigma y \, dA = - E \int \frac{y^2}{\rho} \, dA = - \frac{EI}{\rho} \tag{3}
\]

At the onset of plastic behavior

\[
\sigma = - \frac{y}{\rho} E = - \frac{h}{2\rho} E = -Y \tag{4}
\]

This occurs at

\[
1/\rho = 2Y / hE = 1/\rho_Y \tag{5}
\]

Substitution into eqn (3) gives us the moment at on-set of yield, \( M_Y \)

\[
M_Y = - \frac{EI}{\rho_Y} = E I \frac{2Y}{hE} = 2IY/h \tag{6}
\]

After this point, the \( M \) vs \( 1/r \) curve starts to “bend over.” Note from \( M=0 \) to \( M=M_Y \) the curve is linear.
In the elastic – plastic region

\[ M = \int \sigma ybdy = 2 \int_{y_Y}^{h/2} Ybydy + 2 \int_{0}^{y_Y} \frac{y}{Y} Ybydy \]

\[ = 2Yb \left[ \frac{y^2}{2} \bigg|_{y_Y}^{h/2} + \frac{Y}{y_Y} b \left( \frac{y^3}{3} \right) \bigg|_{0}^{y_Y} \right] \]

\[ = Yb \left( \frac{h^2}{4} - y_Y^2 \right) + \frac{2}{3} Yb \left( Yb - y_Y^2 \right) \]

\[ M = \frac{bh^2}{4} Y \left[ 1 - \frac{1}{3} \left( \frac{y_Y}{h/2} \right)^2 \right] \quad (7) \]

Note at \( y_Y = h/2 \), you get on-set at yield, \( M = M_Y \)
And at \( y_Y = 0 \), you get fully plastic moment, \( M = 3/2 \ M_Y \)
To write this in terms of \( M \) vs \( 1/\rho \) rather than \( M \) vs \( y_Y \), note that the yield curvature \((1/\rho)_Y\) can be written as (see eqn (1))

\[
\frac{1}{\rho_Y} = \frac{\varepsilon_Y}{h/2}
\]

(8)

Where \( \varepsilon_Y \) is the strain at yield. Also since the strain at \( y_Y \) is \(-\varepsilon_Y\), we can write

\[
\frac{1}{\rho} = \frac{\varepsilon_Y}{y_Y}
\]

(9)

Combining (8) and (9) gives

\[
\frac{y_Y}{h/2} = \frac{(1/\rho)_Y}{1/\rho}
\]

(10)
Substitution into (7) gives the result we seek:

\[ M = \frac{3}{2} M_Y \left[ 1 - \frac{1}{3} \left( \frac{1}{\rho} \right)_Y \right]^2 \]  

(11)

Elastic unloading curve

\[ M = \frac{M_Y}{(1/\rho)_Y} \left[ \frac{1}{\rho} - \frac{1}{R_1} \right] \]  

(12)
Now, eqn’s (11) and (12) intersect at $1/\rho = 1/R_0$

Hence,

$$\frac{M_Y}{(1/\rho)_Y} \left[ \frac{1}{R_0} - \frac{1}{R_1} \right] = \frac{3}{2} M_Y \left[ 1 - \frac{1}{3} \left( \frac{(1/\rho)_Y}{1/R_0} \right)^2 \right]$$

Rewriting and using $(1/\rho)_Y = 2Y/hE$ (from a few slides back), we get

$$\left[ \frac{1}{R_0} - \frac{1}{R_1} \right] = 3 \frac{Y}{hE} - 4R_0^2 \left( \frac{Y}{hE} \right)^3$$

(13)
\[ \frac{1}{R_0} - \frac{1}{R_1} = 3 \frac{Y}{hE} - 4R^2 \left( \frac{Y}{hE} \right)^3 \]
Methods to reduce springback

• Smaller Y/E
• Larger thickness
• Over-bending
• Stretch forming
• “coining” or bottoming the punch
Pure Bending

Bending & Stretching

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Stress diagrams showing tension and compression in pure bending. The diagrams illustrate the neutral axis and the change in cross-sectional areas due to bending and stretching.

Fully plastic state is indicated with σ and h.
Stretch forming: can we achieve a strain of 0.035 at A?

Sheet thickness 1mm, \( \mu = 0.1 \)

Material: \( \sigma = 520\varepsilon^{0.18} \text{MPa} \)
Can we achieve a strain of 0.035 at A?

Sheet thickness 1mm, μ=0.1
Material: \( \sigma = 520 \varepsilon^{0.18} \text{MPa} \)

\[ F_A = 0.001 \times 520 \times (0.035)^{0.18} = 284 \text{kN/m} \]

\[ F_B = F_A \times \exp(0.1 \times 0.25) = 292 \text{kN/m} \]

\[ F_C = F_B \times \exp(0.1 \times 1.05) = 323 \text{kN/m} \]

Max allowable force
\[ = 0.001 \times 520 \times (0.18)^{0.18} = 381 \text{kN/m} \]
Friction and the capstan equation

Typical stamping lubricants:
- Oil-based lubricants
- Aqueous lubricants
- Soaps and greases
- Solid films

\[ T_{load} = T_{hold} \times \exp(\mu \theta) \]
Research opportunities and challenges: reducing cost and environmental impacts
Energy & cost: Stamping alum car hoods

- Final part = 5.4kgs
- Total number of parts made = 400
- Die material: cast and machined zinc alloy

Energy. 2.3GJ/pt. Stamping alum. car hoods. 5.4kgO/P. (400pts)

Cost. 136USD/pt


Sheet metal scrapped in factory = 44%

Excludes equipment depreciation and labor during forming
60 Ton Discrete Die Press (LMP - Hardt)
The Shape Control Concept
Stretch Forming with Reconfigurable Tool @ Northrop Grumman
Flexible Forming at Ford
Conventional Spinning

Flexible Spinning

Greater accuracy required

Too slow?
Thank you

Resourceful Manufacturing & Design Group

http://remade.engin.umich.edu