Sheet Metal Working: Series of operations that involve cutting, bending and drawing sheet metal. Sheet metal (from 0.4mm or 1/64in to 6mm or 1/4in thickness); Plate (from 6mm upwards). Operations are usually performed as cold working.

Advantages of Sheet Metal:
- Relatively low cost.
- Good dimensional accuracy and good surface finish.
- High strength

Basic Types of Sheet Metal Operations

**Cutting:** It involves processes such as punching, shearing and blanking.
**Bending:** Deform the sheet around a straight axis.
**Drawing:** Deform the sheet into convex or concave shapes.

<table>
<thead>
<tr>
<th>TABLE 17-1 Classification of the Nonsqueezing Metalforming Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shearing</td>
</tr>
<tr>
<td>1. Simple shearing</td>
</tr>
<tr>
<td>2. Slitting</td>
</tr>
<tr>
<td>5. Fineblanking</td>
</tr>
<tr>
<td>10. Trimming</td>
</tr>
<tr>
<td>11. Cutoff</td>
</tr>
</tbody>
</table>
When subjected to a tensile force there are three deformations to be measured: the longitudinal strain, the strain in the width direction and the strain in the thickness direction. The material is anisotropic.
Shearing:
Shearing of sheet metal between two cutting edges:
(1) just before the punch contacts work
(2) punch begins to push into work, causing plastic deformation;
(3) punch compresses and penetrates into work causing a smooth cut surface;
(4) fracture is initiated at the opposing cutting edges which separates the sheet.

Forces in a Shearing Operation
L = Total length Sheared
 t = thickness

\[ \text{Force} = 0.7 \times \text{UTS} \times t \times L \]

Shearing: A cutting metal operation usually along a straight line, between two cutting edges.
Punching and Blanking are very similar. In punching the cut piece is scrap, while in blanking the cut piece is the desired product.
Conventionally sheared surface showing the distinct regions of deformation and fracture and (bottom) magnified view of the sheared edge. *(Courtesy of Feintool Equipment Corp., Cincinnati, OH.)*

**Percent Penetrations**

<table>
<thead>
<tr>
<th>Material</th>
<th>% Penetration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon Steel</td>
<td>30</td>
</tr>
<tr>
<td>Aluminum</td>
<td>60</td>
</tr>
<tr>
<td>10 C Steel Annealed</td>
<td>50</td>
</tr>
<tr>
<td>10 C Steel Cold Rolled</td>
<td>38</td>
</tr>
<tr>
<td>20 C Steel Annealed</td>
<td>40</td>
</tr>
<tr>
<td>20 C Steel Cold Rolled</td>
<td>28</td>
</tr>
<tr>
<td>30 C Steel Annealed</td>
<td>33</td>
</tr>
<tr>
<td>30 C Cold Rolled</td>
<td>22</td>
</tr>
</tbody>
</table>

Penetration = Roll over + Burnish

**Characteristics of a Die Cut edge**

- **Roll Over** – Flow of material around the punch and die. The larger the clearance the greater the roll over.
- **Burnish** – The rubbed or “cut” portion of the edge. The sharper the punch the wider the burnish.
- **Fracture** – The angled surface where the material separates from the parent material.
- **Burr** – The very sharp projection caused by a dull cutting on the punch or die.

Fineblanked surface of the same component as shown. *(Courtesy of Feintool Equipment Corp., Cincinnati, OH.)*
Die size determines blank size $D_b$; punch size determines hole size $D_h$; $c = \text{clearance}$

For a **round blank** of diameter $D_b$ is determined as:
- Blank punch diameter = $D_b - 2c$
- Blank die diameter = $D_b$

For a **round hole (piercing)** of diameter $D_h$ is determined as:
- Hole punch diameter = $D_h$
- Hole die diameter = $D_b + 2c$

**Clearance:** It is defined as the distance between the punch cutting edge and the die cutting edge. It depends on the hardness and thickness of the material. As the thickness increases, the clearance must increase. The clearance typical values ranges from 4% to 8% of the thickness of the material.

The recommended clearance is calculated by: $c = a \cdot t$
where $c=\text{clearance}$, $t=\text{thickness}$ and $a=\text{allowance}$

<table>
<thead>
<tr>
<th>Metal group</th>
<th>$a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>aluminum alloys (1100, 5052)</td>
<td>0.045</td>
</tr>
<tr>
<td>aluminum alloys (2024 and 6061); brass,</td>
<td>0.060</td>
</tr>
<tr>
<td>soft cold rolled steel, soft stainless steel</td>
<td></td>
</tr>
<tr>
<td>cold rolled steel, stainless steel, (hard &amp; half-hard)</td>
<td>0.075</td>
</tr>
</tbody>
</table>

**Angular Clearance:** Allows the blank or the slug to drop off easily. Typical values ranges from 0.25 degrees to 1.5 degrees
Forming Properties of Sheet Metal

Sheet metal, due to its manufacturing process is not an isotropic material. Anisotropy is caused by the thermal processing of the sheet. Two types, namely crystallographic anisotropy and mechanical fibering.

**Example:** Low carbon steel exhibits an upper and lower yield strength. As a result during deformation, it shows stretch strain bands (Lueder’s bands). These can be eliminated by a reduction of thickness of 0.5 to 1.5% by cold rolling.

Typical Range of Average Normal Anisotropy ($R_{avg}$) for various Sheet Metals

<table>
<thead>
<tr>
<th>Material</th>
<th>$R_{avg}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc</td>
<td>0.2</td>
</tr>
<tr>
<td>Hot rolled steel</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>Cold rolled rimmed steel</td>
<td>1.0-1.35</td>
</tr>
<tr>
<td>Cold rimmed aluminum–killed steel</td>
<td>1.35-1.8</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.6-0.8</td>
</tr>
<tr>
<td>Copper and Brass</td>
<td>0.8-1.0</td>
</tr>
<tr>
<td>Titanium</td>
<td>4-6</td>
</tr>
</tbody>
</table>
Example

Estimate the force required for punching a 25mm diameter hole through a 3.2mm thick annealed titanium alloy Ti-6Al-4V sheet at room temperature. Data: UTS = 1000MPa

\[ F = 0.7 \times UTS \times t \times L = 0.7 \times 1000 \, MPa \times 0.0032 \, m \times \pi \times 0.025 = 176 \, kN \]
Cutlery manufacturing:

Cutlery manufacture involves **blanking** the stainless steel or sterling silver to the proper shape. A series of **rolling operations** then gives the piece the correct thickness. After heat treatment and **trimming**, the piece has a pattern embossed on it in a **stamp**ing **operation**. Finally, the piece is buffed and polished.
**Blanking:** The metal inside a closed contour is the desired part.

**Punching:** The metal inside the contour is discarded.

**Notching:** Edges or corners of a material is punched.

**Trimming:** Cutting scrap or excess material for a fully or partially shaped part.

**Shaving:** Finishing operation of a previously cut edge by removing a minimum amount of material.
Progressive Stamping Dies

Common method to handle complex parts
Deep Drawing

Blanking

Deep Drawing

Re-drawing

Ironing

Doming

Necking

Seaming

Complex 3D shapes can be made out of sheet metal.

<table>
<thead>
<tr>
<th>Process</th>
<th>Process illustration</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Blanking</td>
<td><img src="image1" alt="Blanking Process Illustration" /></td>
<td><img src="image2" alt="Blanking Result" /></td>
</tr>
<tr>
<td>2. Deep drawing</td>
<td><img src="image3" alt="Deep Drawing Process Illustration" /></td>
<td><img src="image4" alt="Deep Drawing Result" /></td>
</tr>
<tr>
<td>3. Redrawing</td>
<td><img src="image5" alt="Redrawing Process Illustration" /></td>
<td><img src="image6" alt="Redrawing Result" /></td>
</tr>
<tr>
<td>4. Ironing</td>
<td><img src="image7" alt="Ironing Process Illustration" /></td>
<td><img src="image8" alt="Ironing Result" /></td>
</tr>
<tr>
<td>5. Doming</td>
<td><img src="image9" alt="Doming Process Illustration" /></td>
<td><img src="image10" alt="Doming Result" /></td>
</tr>
<tr>
<td>6. Necking</td>
<td><img src="image11" alt="Necking Process Illustration" /></td>
<td><img src="image12" alt="Necking Result" /></td>
</tr>
<tr>
<td>7. Seaming</td>
<td><img src="image13" alt="Seaming Process Illustration" /></td>
<td><img src="image14" alt="Seaming Result" /></td>
</tr>
</tbody>
</table>
Usually a cold working process. A punch forces a flat sheet metal into a deep die cavity. The die cavity is usually circular or rectangular. When the depth of the product is greater than its diameter, it is known as **Deep Drawing** and when the depth of the product is less than its diameter, it is known as **Shallow Drawing**. The sheet metal is supported on both sides by the blankholder, to avoid wrinkling.

*If the Hold-down pressure (blankholder force) is too high the sheet will tear and if it is too low it will wrinkle.*

**Draw beads may be used to control metal flow.**

![Diagram of deep drawing process](image-url)
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elongation</td>
<td>Determines the capability of the sheet metal to stretch without necking and failure; high strain-hardening exponent ( n ) and strain-rate sensitivity exponent ( m ) are desirable</td>
</tr>
<tr>
<td>Yield-point elongation</td>
<td>Typically observed with mild-steel sheets (also called Lüder’s bands or stretcher strains), flamelike depressions on the sheet surface, can be eliminated by temper rolling but sheet must be formed within a certain time after rolling</td>
</tr>
<tr>
<td>Anisotropy (planar)</td>
<td>Exhibits different behavior in different planar directions, present in cold-rolled sheets because of preferred orientation or mechanical fibering, causes earing in deep drawing, can be reduced or eliminated by annealing but at lowered strength</td>
</tr>
<tr>
<td>Anisotropy (normal)</td>
<td>Determines thinning behavior of sheet metals during stretching, important in deep drawing</td>
</tr>
<tr>
<td>Grain size</td>
<td>Determines surface roughness on stretched sheet metal, the coarser the grain—the rougher the appearance (orange peel), also affects material strength.</td>
</tr>
<tr>
<td>Residual stresses</td>
<td>Typically caused by nonuniform deformation during forming, results in part distortion when sectioned, can lead to stress-corrosion cracking, reduced or eliminated by stress relieving.</td>
</tr>
<tr>
<td>Springback</td>
<td>Due to elastic recovery of the plastically deformed sheet after unloading, causes distortion of part and loss of dimensional accuracy, can be controlled by techniques such as overbending and bottoming of the punch</td>
</tr>
<tr>
<td>Wrinkling</td>
<td>Caused by compressive stresses in the plane of the sheet, can be objectionable, depending on its extent, can be useful in imparting stiffness to parts by increasing their section modulus, can be controlled by proper tool and die design</td>
</tr>
<tr>
<td>Quality of sheared edges</td>
<td>Depends on process used; edges can be rough, not square, and contain cracks, residual stresses, and a work-hardened layer, which are all detrimental to the formability of the sheet; edge quality can be improved by fine blanking, reducing the clearance, shaving, and improvements in tool and die design and lubrication</td>
</tr>
<tr>
<td>Surface condition of sheet</td>
<td>Depends on sheet rolling practice; important in sheet forming as it can cause tearing and poor surface quality</td>
</tr>
</tbody>
</table>
FIGURE 7.51 Examples of (a) pure drawing and (b) pure stretching; the bead prevents the sheet metal from flowing freely into the die cavity. (c) Unsupported wall and possibility of wrinkling of a sheet in drawing. Source: After W.F. Hosford and R.M. Caddell.

FIGURE 7.53 Schematic illustration of the ironing process. Note that the cup wall is thinner than its bottom. All beverage cans without seams (known as two-piece cans) are ironed, generally in three steps, after being deep drawn into a cup. Cans with separate tops and bottoms are known as three-piece cans.
Estimation of the Blank Diameter

\[
\frac{\pi D_o^2}{4} = \frac{\pi}{4} d_1^2 + \pi d_1 h \Rightarrow D_o = \sqrt{d_1^2 + 4d_1h}
\]
**Formability Test:**

Deformation in sheet materials are carried out by either stretching and/or drawing. The ability of the sheet to withstand large degrees of stretching or drawing deformation (shape change) without failure is known as **formability**.

**Erichsen Test – Cupping Test**

A round punch is forced into a clamped sheet until a crack (sudden drop in force) appears.
Forming Limit Diagram (FLD)

Figure 7.63 (a) Forming-limit diagram (FLD) for various sheet metals. Note that the major strain is always positive. The region above the curves is the failure zone; hence, the state of strain in forming must be such that it falls below the curve for a particular material; \( R \) is the normal anisotropy. (b) Illustrations of the definition of positive and negative minor strains. If the area of the deformed circle is larger than the area of the original circle, the sheet is thinner than the original thickness because the volume remains constant during plastic deformation. Source: After S.S. Hecker and A.K. Ghosh.
A FLD shows what combinations of the major and minor strains produce failure in a sheet metal. To develop the FLD, the major and minor engineering strains are obtained. The curves represent the limits of drawing between failure and safe regions,
By measuring the ellipses on the deformed pattern, the largest and shortest directions of the ellipses are the **major strains** and **minor strain** respectively. Please note that the axes for these strains are $90^\circ$ apart. This can be carried out at many different **locations** in the work-piece.

If both **major and minor strains** are **positive**, the deformation are **stretching**, and the sheet metal will **decrease in thickness**.

If the **minor strain** is **negative**, this **contraction** may partially or whole **compensate any positive stretching in the major direction**. The **combination of tension and compression** is known as **drawing**, and the thickness may decrease, increase, or stay the same, depending on relative magnitude of the two strains.
Example:
A grid of 2.5mm circles is electroetched on a blank of AK sheet steel. After forming into a complex shape the circle in the region of critical strain is distorted into an ellipse with major diameter of 4.5mm and minor diameter of 2.0mm. Is the component close to failure??

Major strain \[ \varepsilon_1 = \frac{4.5 - 2.5}{2.5} \cdot 100 = 80\% \]

Minor strain \[ \varepsilon_2 = \frac{2.0 - 2.5}{2.5} \cdot 100 = -20\% \]

The coordinates indicate that the part is in imminent danger.
Major and minor strains in various regions of an automobile body.
Limit Drawing Ratio

It is defined as the ratio between the largest diameter of the blank that can be drawn into a specific punch diameter without failure:
The recommended drawing ratios are the following:
• for the first drawing: \(~2\)
• for the second drawing: \(1.2 \text{ – } 1.25\)
• for the third drawing: \(1.15 \text{ - } 1.18\)
• for further drawings: \(1.1 \text{ - } 1.12\)

Reduction:
The value of the reduction \((r)\) should be less than 0.5 for a cylinder.

Thickness to Diameter ratio
The thickness of the starting blank divided by the blank diameter. The recommended values for this ratio are greater than 1%. As the ratio decreases, the tendency for wrinkling increases.

The starting diameter of the blank must be of the right size for the final dimensions of the cup to be correct. Assume constant volume and neglect any thinning during the process.
Example: Determine if the following is feasible for manufacturing: A cylindrical cup with an inside diameter of 3.0in and height of 2.0in. Its starting blank size id 5.5in and its thickness 3/32in.

\[
DR = \frac{D_{\text{blank}}}{D_{\text{punch}}} = \frac{5.5}{3.0} = 1.833 < 2
\]

\[
r = \frac{D_{\text{blank}} - D_{\text{punch}}}{D_{\text{blank}}} = \frac{5.5 - 3.0}{5.5} = 0.4545 < 0.5
\]

\[
\frac{t_{\text{blank}}}{D_{\text{blank}}} = \frac{\left(\frac{3}{32}\right)}{5.5} = 0.017 > 0.01
\]

The drawing operation is feasible.
Anisotropy Ratio

There are two different types of anisotropy ratio, namely, normal and planar anisotropy ratio.

**Normal Anisotropy Ratio** \((R)\) : Measured in a tensile specimen, it is the ratio between the true strain in the width direction and the true strain in the thickness direction.

The tensile specimen must conform specific technical standards. The longitudinal direction of the tensile specimen can be parallel or to a certain angle with respect to the rolling direction of the sheet.

\[
R = \frac{\varepsilon_{\text{width}}}{\varepsilon_{\text{thickness}}}
\]

\[
R_{\text{average}} = \frac{R_0 + 2R_{45} + R_{90}}{4}
\]
Planar Anisotropy Ratio: It determines the variation of the true strain in the plane of the sheet (rolling plane).

\[ \Delta R = R_{45} - \frac{R_0 + R_{90}}{2} \]

The value of the normal anisotropy ratio determines the limiting drawing ratio and the value of the planar anisotropy ratio correlates with the material propensity to earing. High values of normal anisotropy combined with low values of planar anisotropy provides optimal drawability. The maximum value of the normal anisotropy also depends on the grain size of the material.

Table 16.4

<table>
<thead>
<tr>
<th>Typical Ranges of Average Normal Anisotropy, ( R_{\text{avg}} ), for Various Sheet Metals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zinc alloys</td>
</tr>
<tr>
<td>Hot-rolled steel</td>
</tr>
<tr>
<td>Cold-rolled, rimmed steel</td>
</tr>
<tr>
<td>Cold-rolled, aluminum-killed steel</td>
</tr>
<tr>
<td>Aluminum alloys</td>
</tr>
<tr>
<td>Copper and brass</td>
</tr>
<tr>
<td>Titanium alloys ((\alpha))</td>
</tr>
<tr>
<td>Stainless steels</td>
</tr>
<tr>
<td>High-strength, low-alloy steels</td>
</tr>
</tbody>
</table>

Note: If \( \Delta R = 0 \), no ears form. The height of ears increases as \( \Delta R \) increases.
The relationship between average normal anisotropy and the limiting drawing ratio for various sheet metals. Source: After M. Atkinson.

\[ \text{LDR} = \frac{\text{Maximum blank diameter}}{\text{Punch diameter}} = \frac{D_b}{D_p} \]

\[ \Delta R = \frac{R_{90} + R_{90} - 2R_{45}}{2} \]

\[ R = \frac{\varepsilon_w}{\varepsilon_t} \]
Example:

A special deep-drawing steel showed a 30% longitudinal elongation and 16% decrease in thickness when it is subjected to a tensile test. Estimate the limiting drawing ratio (LDR) for this steel.

\[
\frac{l - l_o}{l_o} = 0.3 \Rightarrow \frac{l}{l_o} = 1.3 \Rightarrow \ln(1.3) = 0.26236
\]

\[
\frac{w - w_o}{w_o} = -0.16 \Rightarrow \frac{w}{w_o} = 0.84 \Rightarrow \ln(0.84) = -0.1743
\]

\[
R = \frac{\ln\left(\frac{w_o}{w}\right)}{\ln\left(\frac{h_o}{h}\right)} = \frac{\ln\left(\frac{w_o}{w}\right)}{\ln\left(\frac{wl}{w_0l_o}\right)} = \frac{\ln\left(\frac{1}{0.84}\right)}{\ln(0.84 \cdot 1.3)} = 1.98
\]

From the graph the LDR~2.7
Drawing Force

\[ F_{\text{max}} = \pi D_p t (UTS) \left[ \left( \frac{D_b}{D_p} \right)^2 - 0.7 \right] \]

Wrinkling can be reduced if a blankholder is loaded by *maximum punch force*

The force increases with increasing blank diameter, thickness, strength and the ratio
**Bending**

Some sheet are bend along certain lines to produce a desired shape. Bending introduces plastic deformation to the part and it should remain in the desired shape (angle) after the load is released. Spring-back is the part of deformation (the elastic part) that recovers in the plastically deformed material once the load has been released.

When the load is released there is a decrease in the bending angle (Springback) due to the elastic recovery of the material.
Bend allowance: The amount of deformation of the neutral axis of the sheet depends on the bend radius and bend angle. The final dimension of the neutral axis (in the bending area) is used to calculate the blank length for the bend part. \( R \) is the bend radius, \( \alpha \) is the bend angle, \( t \) is the thickness and \( k \) is a constant.

In an ideal case, the neutral axis remains at the center of the section \( k=0.5 \). In practice, \( k \) ranges from 0.33 (for \( R<2t \)) to 0.5 (for \( R>2t \)).

\[
L_b = \alpha (R + kt) = \alpha_o \left( R_o + kt \right) = \alpha_f \left( R_f + kt \right)
\]
As the part is bended, the longitudinal dimension of the flat length is increased. The bend allowance is the amount of material that need to be added to the flange dimensions (leg parts) in order to develop a flat pattern. Example: suppose that flanges lengths of 2” and 3” with an inside radius of 0.250” at 90 degrees are required.

Then the flat dimensions are \((2"-(0.25+0.125))\) and \((3"-(0.25+0.125))\), i.e 1.625 and 2.625 respectively.

The length of the flat sheet (bend allowance) is \(1.625 + 2.625 + 0.457 = 4.707"\)

**Bend deduction:** It is the amount of material that has to be removed from the sum of the flanges to obtain a flat pattern.

\[
L_b = \alpha(R + kt) = \left(\pi \frac{90}{180}\right)(0.250 + 0.33 \times 0.125) = 0.457
\]
<table>
<thead>
<tr>
<th>Angle</th>
<th>8 Gauge</th>
<th>10 Gauge</th>
<th>12 Gauge</th>
<th>14 Gauge</th>
<th>16 Gauge</th>
<th>18 Gauge</th>
<th>20 Gauge</th>
<th>22 Gauge</th>
<th>24 Gauge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K factor</td>
<td>K factor</td>
<td>K factor</td>
<td>K factor</td>
<td>K factor</td>
<td>K factor</td>
<td>K factor</td>
<td>K factor</td>
<td>K factor</td>
</tr>
<tr>
<td>MT IR</td>
<td>MT IR</td>
<td>MT IR</td>
<td>MT IR</td>
<td>MT IR</td>
<td>MT IR</td>
<td>MT IR</td>
<td>MT IR</td>
<td>MT IR</td>
<td>MT IR</td>
</tr>
</tbody>
</table>
Springback

After releasing the pressure of the forming tool, the deformed workpiece experience a dimensional change (strain) due to the elastic recovery of the material.

Springback is found in all forming operations, but is more pronounced in bending. As the yield strength of the material increases or as the Modulus of elasticity decreases the springback deformation increases.

Overbending, i.e. bending to a smaller radius of curvature than the required can compensate for the springback of the material.

For aluminum alloys and austenitic steels the springback can be approximated by the equation

\[
\frac{R_o}{R_f} = 4 \left( \frac{R_o \sigma_{\text{yield}}}{Et} \right)^3 - 3 \frac{R_o \sigma_{\text{yield}}}{Et} + 1
\]

where \( R_o \) is the radius of curvature before releasing the load and \( R_f \) is the radius of curvature after releasing the load; \( t \) is the thickness, \( E \) is the Modulus of Elasticity and \( \sigma_{\text{yield}} \) is the yield stress.
Example

A 0.0359in thickness sheet (20-gage) is bent to a radius of 0.5in. Calculate the radius of the part after it is bent and the required bend angle to achieve a 90o bend after springback has occurred. Data: Yield Strength=40000psi; E=29x10^6psi

\[
\frac{R_o}{R_f} = 4\left(\frac{R_o \sigma_{\text{yield}}}{Et}\right)^3 - 3 \frac{R_o \sigma_{\text{yield}}}{Et} + 1
\]

\[
\frac{0.5}{R_f} = 4\left(\frac{0.5 \cdot 40000}{29 \cdot 10^6 \cdot 0.0359}\right)^3 - 3 \frac{0.5 \cdot 40000}{29 \cdot 10^6 \cdot 0.0359} + 1 = 0.942
\]

\[
R_f = 0.531in
\]

\[
L_b = \alpha_o \left( R_o + kt \right) = \alpha_f \left( R_f + kt \right)
\]

\[
\alpha_o \left(0.5 + \frac{0.0359}{2}\right) = 90 \cdot \left(0.531 + \frac{0.0359}{2}\right)
\]

\[
\Rightarrow \alpha_o = 95.4^o
\]
Bending Force

The bending load can be calculated from the following equation:

\[ F_b = \frac{K \cdot L \cdot UTS \cdot t^2}{W} \]

Where \( UTS \) is the ultimate tensile strength of the material (psi);
\( L \) is the length of the bent part (in), \( t \) is the thickness (in);
\( W \) is the width between the contact points (in) or 8\( t \) for V-bends
\( K \) is 1.3 for die opening of 8\( t \), 1.20 for die opening of 16\( t \), 0.67 for U-bending, 0.33 for a wiping die
Example:

Estimate the force required for a 90 degrees bending of a St 50 steel of thickness of 2mm in a V die. The die opening can be taken as eight times the thickness. The length of the part is 1m.

Die Opening $W=8\times2=16\text{mm}$

$UTS=500\text{MPa}$

$$F_b = \frac{K \cdot L \cdot UTS \cdot t^2}{W} = \frac{1.33 \times 1 \times 500 \times (0.002)^2}{0.016} = 166.25\text{kN}$$
**Minimum Bend Radius:**

On the inside of neutral plane, the metal is compressed, while on the outside of the neutral plane is stretched. The outer layers under tension should not be excessively stretched as there is the possibility of rupture. The amount of stretching depends on the sheet thickness and the bend radius. There is a minimum bend radius that depends on the material properties. Minimum bend radius 0.5t for soft materials, 3t for spring steels and 1t for the others.

---

**TABLE 7.2 Minimum bend radii for various materials at room temperature.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Material Condition</th>
<th>Soft</th>
<th>Hard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum alloys</td>
<td></td>
<td>0</td>
<td>6t</td>
</tr>
<tr>
<td>Beryllium copper</td>
<td></td>
<td>0</td>
<td>4t</td>
</tr>
<tr>
<td>Brass, low leaded</td>
<td></td>
<td>0</td>
<td>2t</td>
</tr>
<tr>
<td>Magnesium</td>
<td></td>
<td>5t</td>
<td>13t</td>
</tr>
<tr>
<td>Steels</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Austenitic stainless</td>
<td></td>
<td>0.5t</td>
<td>6t</td>
</tr>
<tr>
<td>Low carbon, low alloy, and HSLA</td>
<td></td>
<td>0.5t</td>
<td>4t</td>
</tr>
<tr>
<td>Titanium</td>
<td></td>
<td>0.7t</td>
<td>3t</td>
</tr>
<tr>
<td>Titanium alloys</td>
<td></td>
<td>2.6t</td>
<td>4t</td>
</tr>
</tbody>
</table>
Example:
A sheet material is to be bended according to the dimensions given in the figure. Determine the following: (a) starting blank size and (b) the bending force necessary if a V-die will be used with a die opening dimension of $W=1.0''$. Data: $E=30000\text{ksi}$; Yield Strength=$40000\text{psi}$ and a tensile strength=$65000\text{psi}$.

Length $L = 1.75'$, and the length of the part is: $1.5 +1.00 + BA$.
$R/t = 0.187/0.125 = 1.5 < 2.0$, so $K_{ba} = 0.33$
For an included angle $A' = 120^\circ$, then $A = 60^\circ$

\[
L_b = \alpha(R + kt) = \left(\pi \frac{60}{180}\right)(0.187 + 0.33 \times 0.125) = 0.239''
\]

Length $= 1.5 +1.0 + 0.239 = 2.739''$

**Force:**
\[
F = \frac{(K_{bf}T_sL_t^2)}{W} = 1.33 \times (65,000)(1.75)(0.125)^2/1.0 = 2,364 \text{ lb}
\]

\[
F_b = \frac{K \cdot L \cdot UTS \cdot t^2}{W} = \frac{1.33 \times 1.75 \times 65000 \times (0.125)^2}{1} = 2364\text{lb}
\]
Bending and Forming Tubes

FIGURE 7.28 Methods of bending tubes. Using internal mandrels, or filling tubes with particulate materials such as sand, prevents the tubes from collapsing during bending. Solid rods and structural shapes are also bent by these techniques.

FIGURE 7.29 A method of forming a tube with sharp angles, using an axial compressive force. Compressive stresses are beneficial in forming operations because they delay fracture. Note that the tube is supported internally with rubber or fluid to avoid collapsing during forming. Source: After J.L. Remmerswaal and A. Verkaik.
Stretch-Forming

The form die is pressed into the work with force $F_{\text{die}}$, causing it to be stretched and bent over the form. $F = \text{stretching force}$.

It is used extensively in the aircraft industry to produce parts of large radius of curvature. The materials used are very ductile.
Spinning

Ideal for

- Lower production volumes
- Large parts
- Inexpensive tooling
(a) Schematic illustration of the shear-spinning process for making conical parts. The mandrel can be shaped so that curvilinear parts can be spun. (b) and (c) Schematic illustrations of the tube-spinning process.
**Roll Bending**
Large metal sheets and plates are formed into curved sections using rolls.

**Roll Forming**
Continuous bending process in which opposing rolls produce long sections of formed shapes from coil or strip stock.
High Energy Rate Forming

Explosive Forming

Short time – High Energy forming processes. It includes explosive forming, electrohydraulic forming and electromagnetic forming.

Use of explosive charge to form sheet (or plate) metal into a die cavity.

Explosive charge causes a shock wave whose energy is transmitted to force part into cavity.

Applications: large parts, typical of aerospace industry.
Electromagnetic Forming

Sheet metal is deformed by mechanical force of an electromagnetic field induced in the work-piece by an energized coil.

Presently the most widely used HERF process

Applications: tubular parts

A pinched aluminum can, produced from a pulsed magnetic field created by rapidly discharging 2 kilojoules from a high voltage capacitor bank into a 3-turn coil of heavy gauge wire. Source: Bert Hickman, Stoneridge Engineering.
Hydroforming

Hydroforming uses water at high pressure to force the piece into a specific shape.