Sheet-metal forming

Subjects of interest

- Introduction/objectives
- Deformation geometry
- Forming equipments
- Shearing and blanking
- Bending
- Stretch forming
- Deep drawing
- Forming limit criteria
- Defects in formed parts
Objectives

- Methods of sheet metal processes such as stretching, shearing, blanking, bending, deep drawing, redrawing are introduced.
- Variables in sheet forming process will be discussed together with formability and test methods.
- Defects occurring during the forming process will be emphasised. The solutions to such defect problems will also be given.
Sheet metal forming is a process that materials undergo permanent deformation by cold forming to produce a variety of complex three dimensional shapes.

The process is carried out in the plane of sheet by tensile forces with high ratio of surface area to thickness.

Friction conditions at the tool-metal interface are very important and controlled by press conditions, lubrication, tool material and surface condition, and strip surface condition.

High rate of production and formability is determined by its mechanical properties.
**Classification of sheet metal parts** (based on contour)

1) Singly curved parts
2) Contoured flanged parts, i.e., parts with stretch flanges and shrink flanges.
3) Curved sections.
4) Deep-recessed parts, i.e., cups and boxes with either vertical or sloping walls.
5) Shallow-recessed parts, i.e., dish-shaped, beaded, embossed and corrugated parts.
Classification of sheet metal forming (based on operations)

- Blanking
- Stretching
- Deep drawing
- Coining
- Stamping
- Ironing
- Folding
- Bending
- Roll forming of sheet
- Wiping down a flange
Stress state in deformation processes

- The **geometry** of the workpiece can be essentially **three dimensional** (i.e., rod or bar stock) or **two dimensional** (i.e., thin sheets).

- The **state of stress** is described by **three principal stresses**, which act along axes perpendicular to **principal planes**.

- The principal stresses are by convention called $\sigma_1$, $\sigma_2$, and $\sigma_3$ where $\sigma_1 > \sigma_2 > \sigma_3$

**Principal stresses on an element in a three-dimensional stress state**

- Hydrostatic stress state is when $\sigma_1 = \sigma_2 = \sigma_3$
Shear stresses provide driving force for plastic deformation.

Hydrostatic stresses cannot contribute to shape change but involve in failure processes.

- **Shear stresses**
- **Hydrostatic stresses**

Tensile

- crack growth or void formation

Compressive

- hinder crack, close void.
• In **sheet deformation processes** (i.e., sheet metal forming, vacuum forming, blow moulding), the workpiece is subjected to two dimensional **biaxial stresses**. (also depending on geometry)

• In **bulk deformation processes** (i.e. forging, rolling and extrusion), the workpiece is subjected to **triaxial stresses**, which are normally **compressive**.
Deformation geometry

**Plane stress**

- **Principal stresses** $\sigma_1$ and $\sigma_2$ are set up together with their associated strain in the $x$-$y$ plane.

- The sheet is free to contact (*not constrained*) in the $\sigma_3$ ($z$) direction. There is strain in this direction but no stress, thus $\sigma_3 = 0$, resulting in *biaxial stress system*.

- Since the stress are effectively confined to one plane, this stress system is known as *plane stress*. 
**Plane strain**

- Deformation (strain) often occurs in only two dimensions (parallel to $\sigma_1$ and $\sigma_2$).

- $\sigma_3$ is finite, preventing deformation (strain) in the $z$ direction (constrained), which is known as **plane strain**.

**Example:** the extrusion of a thin sheet where material in the centre is constrained in the $z$ direction.
Forming equipments

Forming equipments include

1) **Forming presses**
2) **Dies**
3) **Tools**
Forming machines

• Using mechanical or hydraulic presses.

1) **Mechanical presses**
   - energy stored in a flywheel is transferred to the movable slide on the down stroke of the press.
   - quick - acting, short stroke.

2) **Hydraulic presses**
   - slower - acting, longer stroke.
Actions of presses

(according to number of slides, which can be operated independently of each other.)

1) **Single - action press**
   - one slide
   - vertical direction

2) **Double - action press**
   - two slides
   - the second action is used to operate the hold-down, which prevents wrinkling in deep drawing.

3) **Triple - action press**
   - two actions above the die, one action below the die.
Example:

Press brake – single action

• A single action press with a very long narrow bed.
• Used to form long, straight bends in pieces such as channels and corrugated sheets.
Basic tools used with a metalworking press are the **punch** and the **die**.

- **Punch** → A *convex tool* for making holes by shearing, or making surface or displacing metal with a hammer.
- **Die** → A *concave die*, which is the female part as opposed to punch which is the male part.

**Die materials:**
- High alloy steels heat treated for the punches and dies.
**Compound dies**

- **Several operations** can be performed on the same piece in **one stroke** of the press.
- **Combined processes** and create a complex product in one shot.
- Used in metal stamping processes of thin sheets.

**Transfer dies**

- Transfer dies are also called **compounding type dies**.
- The part is **moved from station to station** within the press for each operation.
A die set is composed of

1) **Punch holder** which holds punch plate connected with blanking and piecing punches for cutting the metal sheet.

2) **Die block** consists of die holder and die plate which was designed to give the desired shape of the product.

3) **Pilot** is used to align metal sheet at the correct position before blanking at each step.

4) **Striper plate** used for a) alignment of punch and die blocks b) navigate the punch into the die using harden striper inserts and c) remove the cut piece from the punch.
Forming method

There are a great variety of sheet metal forming methods, mainly using shear and tensile forces in the operation.

• Progressive forming
• Rubber hydroforming
• Bending and contouring
• Spinning processes
• Explosive forming
• Shearing and blanking
• Stretch forming
• Deep drawing
**Progressive forming**

- **Punches** and **dies** are designed so that **successive stages** in the forming of the part are carried out in the same die on each stroke of the press.

- Progressive dies are also known as multi-stage dies.

**Example:** progressive blanking and piercing of flat washer.

- The strip is fed from left to right.
- The **first punch** is to make the **hole** of the washer.
- The washer is then **blanked** from the strip.
- The punch A is piercing the hole for the next washer.
Metal sheet used in blanking process

- **Optimise the material usage.**
- **Determining factors are 1) volume of production**
  **2) the complexity of the shape**
Rubber hydroforming

- Using a pad of **rubber** or **polyurethane** as a die.
- A **metal blank** is placed over the **form block**, which is fastened to the bed of a single-action hydraulic press.
- During forming the **rubber** (placed in the retainer box on the upper platen of the press) transmits a nearly uniform hydrostatic pressure against the sheet.
- **Pressure** ~ 10 MPa, and where higher local pressure can be obtained by using auxiliary tooling.
Hydroforming

- Used for sheet forming of aluminium alloys and reinforced thermoplastics.

Stamp hydroforming machine setup with a fluid supplied from one side of the draw blank.

A drawing of hydroforming setup with fluid supplied from to both sides of the materials.
(a) **Three-roll bender:** sometimes does not provide uniform deformation in thin-gauge sheet due to the midpoint of the span → **localisation of the strain.** Often need the forth roll.

(b) **Wiper-type bender:** The contour is formed by successive hammer blows on the sheet, which is clamped at one end against the form block. **Wiper rolls** must be pressed against the block with a uniform pressure supplied by a hydraulic cylinder.

(c) **Wrap forming:** The sheet is compressed against a form block, and at the same time a longitudinal stress is applied to prevent buckling and wrinkling. **Ex:** coiling of a spring around a mandrel.
Bending and contouring machines

Pipe bending machine

www.rollfab.com.au

www.macri.it

www.lathes.co.uk

www.diydata.com

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Spinning processes

• Deep parts of circular symmetry such as tank heads, television cones.

Materials: aluminium and alloys, high strength - low alloy steels, copper, brass and alloys, stainless steel,

• The metal blank is clamped against a form block, which is rotated at high speed.
• The blank is progressively formed against the block, by a manual tool or by means of small-diameter work rolls.

Note: (a) no change in thickness but diameter,
(b) diameter equals to blank diameter but thickness stays the same.
**Explosive forming**

- Produce *large parts* with a relatively low production lot size.
- The sheet metal blank is placed over a die cavity and an *explosive charge* is detonated in medium (water) at an appropriate *standoff distance* from the blank at a very high velocity.
- The shockwave propagating from the explosion serves as a ‘*friction-less punch*’
Shearing and blanking

Shearing: The separation of metal by the movement of two blades operated based on shearing forces.

- A narrow strip of metal is severely plastically deformed to the point where it fractures at the surfaces in contact with the blades.
- The fracture then propagates inward to provide complete separation.

**Clearance**

- **Proper** → clean fracture surface.
- **Insufficient** → ragged fracture surface.
- **Excessive** → greater distortion, greater energy required to separate metal.

**Thickness**

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Clearance</th>
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Maximum punch force

• No friction condition.
• The force required to shear a metal sheet ~ length cut, sheet thickness, shearing strength.
• The maximum punch force to produce shearing is given by

\[ P_{\text{max}} \approx 0.7 \sigma_u hL \]

where \( \sigma_u \) = the ultimate tensile strength
\( h \) = sheet thickness
\( L \) = total length of the sheared edge

The shearing force by making the edges of the cutting tool at an inclined angle
**Blanking**: The shearing of close contours, when the metal inside the contour is the desired part.

**Punching or piercing**: The shearing of the material when the metal inside the contour is discarded.

**Notching**: The punch removes material from the edge or corner of a strip or blank or part.
**Parting**: The simultaneous cutting along at least two lines which balance each other from the standpoint of side thrust on the parting tool.

**Slitting**: Cutting or shearing along single lines to cut strips from a sheet or to cut along lines of a given length or contour in a sheet or workpiece.

**Trimming**: Operation of cutting scrap off a partially or fully shaped part to an established trim line.
**Shaving**: A secondary shearing or cutting operation in which the surface of a previously cut edge is finished or smoothed by removing a minimal amount of stock.

**Ironing**: A continuous thinning process and often accompanies deep drawing, i.e., thinning of the wall of a cylindrical cup by passing it through an ironing die.

**Fine blanking**: Very smooth and square edges are produced in small parts such as gears, cams, and levers.
Bending

- A process by which a straight length is transformed into a curved length.
- produce channels, drums, tanks.
Bending

The *bend radius* $R$ = the radius of curvature on the concave, or inside surface of the bend.

Fibres on the outer surface are *strained* more than fibres on the inner surface are *contracted*. Fibres at the mid thickness is *stretched*.

Decrease in thickness (radius direction) at the bend to preserve the constancy of volume.

$R$ ↓ thickness on bending
**Condition:**
- No change in thickness
- The neutral axis will remain at the centre fibre.
- Circumferential stretch on the top surface $e_a = \text{shrink on the bottom surface, } e_b$

\[ e_a = -e_b = \frac{1}{(2R/h) + 1} \]  \[ ...\text{Eq. 1} \]

**The minimum bend radius**
- For a given bending operation, the *smallest bend radius* can be made without *cracking* on the outer tensile surface.
- Normally expressed in multiples of sheet thickness.

**Example:** a *3T bend radius* means the metal can be bend without cracking though a radius equal to three times the sheet thickness $T$.  

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Effect of b/h ratio on ductility

- Stress state is biaxial \((\sigma_2/\sigma_1 \text{ ratio})\)
- Width / thickness \(b/h\) ratio

Cracks occur near the centre of the sheet

Effect of b/h on biaxiality and bend ductility
**Springback**

*Dimensional change* of the formed part after releasing the pressure of the forming tool due to the changes in strain produced by *elastic recovery*.

*Springback* is encountered in all forming operations, but most easily occurs in bending.
For aluminium alloys and austenitic stainless steels in a number of cold-rolled tempers, approximate springback in bending can be expressed by

\[
\frac{R_o}{R_f} = 4\left(\frac{R_o\sigma}{Eh}\right)^3 - 3\frac{R_o\sigma}{Eh} + 1
\]  

...Eq.2

Where \( R_o \) = the radius of curvature before release of load

\( R_f \) = the radius of curvature after release of lead

and \( R_o < R_f \)

Solutions: compensating the springback by bending to a smaller radius of curvature than is desired (overbending). By trial-and-error.

The force \( P_b \) required to bend a length \( L \) about a radius \( R \) may be estimated from

\[
P_b = \frac{\sigma_o L h^2}{2(R + h/2)} \tan \frac{\alpha}{2}
\]

...Eq.3
**Tube bending**

- **Bending** of tube and structural material for industry, architecture, medical, refinery.

- Heat induction and hot slap bending require the *heating* of pipe, tube or structural shapes.

- **Heat Induction bending** is typically a higher cost bending process and is primarily used in large diameter material.
Stretch forming

• Forming by using *tensile forces* to stretch the material over a tool or form block.

• used most extensively in the *aircraft industry* to produce parts of large radius of curvature. (normally for uniform cross section).

• required materials with *appreciable ductility*.

• *Springback* is largely eliminated because the stress gradient is relatively uniform.
Stretch forming equipment

- Using a hydraulic driven ram (normally vertical).
- Sheet is gripped by two jaws at its edges.
- Form block is slowly raised by the ram to deform sheet above its yield point.
- The sheet is strained plastically to the required final shape.

**Examples:** large thin panel, most complex automotive stamping involve a stretching component.
**Diffuse necking** (a limit to forming)

In biaxial tension, the necking which occurs in uniaxial tension is inhibited if $\sigma_2/\sigma_1 > 1/2$, and the materials then develops **diffuse necking**. (not visible)

The **limit of uniform deformation** in strip loading occurs at a strain equals to the **strain-hardening exponent** $n$.

\[ \varepsilon_u = n \]

**Localised necking**

- Plastic instability of a thin sheet will occur in the form of a narrow **localised neck** followed by fracture of the sheet.
- Normal strain along $X_2$ must be zero.

\[ \varepsilon_u = 2n \]
Deep drawing

The metalworking process used for shaping flat sheets into cup-shaped articles.

Examples: bathtubs, shell cases, automobile panels.

Pressing the metal blank of appropriate size into a shaped die with a punch.
• It is best done with *double-action press*.
• Using a *blank holder* or a *holddown ring*.

- **Complex interaction** between metal and die depending on geometry.
- No precise *mathematical description* can be used to represent the processes in simple terms.
A cup is subjected to three different types of deformation.

- Metal in the punch region is thinned down → biaxial tensile stress.
- Metal in the cup wall is subjected to a circumference strain, or hoop and a radial tensile strain.
- Metal at the flange is bent and straightened as well as subjected to a tensile stress at the same time.

As the metal being drawn,
- Change in radius
- Increase in cup wall

Thickness profile of drawn cup
Clearance between the punch and the die > 10-20% thickness.

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**Redrawing**

- Use successive drawing operations by reducing a cup or drawn part to a **smaller diameter** and **increased height** – known as **redrawing**.

**Examples:** slender cups such as cartridge case and closed-end tubes.

1) **Direct or regular redrawing:**
   - smaller diameter is produced by means of a **hold-down ring**. The metal must be bent at the punch and unbent at the die radii see Fig (a). **Tapered die** allows lower punch load, Fig (b).

2) **Reverse or indirect redrawing:**
   - the cup is turned inside out → the outside surface becomes the inside surface, Fig (c). Better control of **wrinkling** and no **geometrical limitations** to the use of a hold-down ring.
**Punch force vs. punch stroke**

\[ \text{Punch force} = F_{\text{deformation}} + F_{\text{frictional}} + (F_{\text{ironing}}) \]

- \( F_{\text{deformation}} \) - varies with length of travel
- \( F_{\text{frictional}} \) - mainly from hold down pressure
- \( F_{\text{ironing}} \) - after the cup has reached the maximum thickness.
**Drawability** (deep drawing)

**Drawability** is a ratio of the initial blank diameter \(D_o\) to the diameter of the cup drawn from the blank ~ punch diameter \(D_p\)

**Limiting draw ratio (LDR)**

\[
LDR \approx \left( \frac{D_o}{D_p} \right)_{\text{max}} \approx e^\eta
\]

...Eq. 4

Where \(\eta\) is an efficiency term accounting for frictional losses.

Normally the **average maximum reduction** in deep drawing is \(~50\%\).
Practical considerations affecting drawability

- **Die radius** – should be about \( 10 \times \text{sheet thickness} \).
- **Punch radius** – a sharp radius leads to local thinning and tearing. Clearance between punch and die should be about 20-40% > sheet thickness.
- **Hold-down pressure** – about 2% of average \( \sigma_o \) and \( \sigma_u \).
- **Lubrication of die side** - to reduce friction in drawing.
- **Material properties** - low yield stress, high work hardening rates, high values of strain ratio of width to thickness \( R \).

Since the forming load is carried by the side wall of the cup, failure therefore occurs at the thinnest part.

In practice the materials always fails either at (a) **the shoulder of the die** and (b) **the shoulder of the punch**.
**Practical considerations for round and rectangular shells**

- **Different pressures** (tension, compression, friction, bending) force the material into shape, perhaps with multiple successive operations.

**Round shell**
- **Different flow patterns** at sides and corners.
- Corners require similar flow as round shells while sides need simple bending.
- The **corner radii** control the maximum draw depth.
- Centre to center distance of corners ≥ 6 x corner radius
  - Bottom radius ≥ corner radius

**Rectangular shell**

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www.drawform.com
To improve drawability

- To avoid failures in the thin parts (at the punch or flange), metal in that part need to be strengthened, or weaken the metal in other parts (to correct the weakest link).

- If sufficient friction is generated between punch and workpiece, more of the **forming load is carried by the thicker parts**.

- Concerning about **crystallographic texture** (slip system), degree of anisotropy or strain ratio $R$.

The dependence of limiting draw ratio on $R$ and work hardening rate, $n$
The **plastic strain ratio** $R$ measures the **normal anisotropy**, which denotes high resistance to thinning in the thickness direction.

$$R = \frac{\ln(w_o / w)}{\ln(h_o / h)}$$

...Eq.5

Where $w_o$ and $w$ are the initial and final width,

$h_o$ and $h$ are the initial and final thickness.

But it is difficult to measure thickness on thin sheets, therefore we have

$$R = \frac{\ln(w_o / w)}{\ln(wL / w_o L_o)}$$

...Eq.6
Example: A tension test on a special deep-drawing steel showed a 30% elongation in length and a 16% decrease in width. What limiting draw ratio would be expected for the steel?

\[
\frac{L - L_o}{L_o} = 0.30 \\
\frac{w - w_o}{w_o} = -0.16 \\
\]

\[
\frac{L}{L_o} = 1.30 \\
\frac{w}{w_o} = 1 - 0.16 = 0.84 \\
\]

\[
R = \frac{\ln(w_o / w)}{\ln((w / w_o)(L / L_o))} = \frac{\ln(1/0.84)}{\ln(0.84 \times 1.30)} = \frac{\ln 1.190}{\ln 1.092} = 1.98 \\
\]

From Fig. 20-16 Dieter page 673, the limiting draw ratio \( \sim 2.7 \)
Forming limit criteria

- **Tensile test** only provides ductility, work hardening, but it is in a uniaxial tension with frictionless, which cannot truly represent material behaviours obtained from unequal biaxial stretching occurring in sheet metal forming.

- **Sheet metal formability tests** are designed to measure the ductility of a materials under condition similar to those found in sheet metal forming.
Erichsen cupping test

- Simple and easy.
- Symmetrical and equal biaxial stretching.
- Allow effects of tool-workpiece interaction and lubrication on formability to be studied.
- The sheet metal specimen is hydraulically punched with a 20 mm diameter steel ball at a constant load of 1000 kg.
- The distance $d$ is measured in millimetres and known as Erichsen number.

Results of cupping test on steel sheets.
The forming limit diagram

- The sheet is marked with a close packed array of circles using chemical etching or photo printing techniques.
- The blank is then stretched over a punch, resulting in stretching of circles into ellipses.
- The major and minor axes of an ellipse represent the two principal strain directions in the stamping.
- The percentage changes in these strains are compared in the diagram.
- Comparison is done in a given thickness of the sheet.

Grid analysis (a) before (b) after deformation of sheet.

Forming limit diagram
Example: A grid of 2.5 mm circles is electroetched on a blank of sheet steel. After forming into a complex shape the circle in the region of critical strain is distorted into and ellipse with major diameter 4.5 mm and minor diameter 2.0 mm. How close is the part to failing in this critical region?

Major strain

\[ e_1 = \frac{4.5 - 2.5}{2.5} \times 100 = 80\% \]

Minor strain

\[ e_2 = \frac{2.0 - 2.5}{2.5} \times 100 = -20\% \]

The coordinates indicate that the part is in imminent danger of failure.
Defects in formed parts

- Edge conditions for blanking.
- Local necking or thinning or buckling and wrinkling in regions of compressive stress.
- Springback tolerance problems.
- Cracks near the punch region in deep drawing → minimised by increasing punch radius, lowering punch load.

www.bgprecision.com

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• **Radial cracks** in the flanges and edge of the cup due to not sufficient ductility to withstand large circumferential shrinking.

• **Wrinkling** of the flanges or the edges of the cup resulting from buckling of the sheet (due to circumferential compressive stresses) → **solved by** using **sufficient hold-down pressure** to suppress the buckling.

• **Surface blemishes** due to large surface area. **EX: orange peeling** especially in large grain sized metals because each grain tends to deform independently → use finer grained metals.

• **Mechanical fibering** has little effect on formability.

• **Crystallographic fibering** or preferred orientation may have a large effect. **Ex:** when bend line is parallel to the rolling direction, or earing in deep drawn cup due to anisotropic properties.

*Earing in drawn can*

aluminium.matter.org.uk
• **Stretcher strains** or ‘worms’ (flamelike patterns of depressions). Associated with yield point elongation.

• The metal in the **stretcher strains** has been strained an amount \( B \), while the remaining received essentially zero strain.

• The elongation of the part is given by some intermediate strain \( A \).

• The number of **stretcher strains** increase during deformation. The strain will increase until the when the entire part is covered it has a strain equal to \( B \).

**Solution:** give the steel sheet a small cold reduction (usually 0.5-2% reduction in thickness). **Ex:** temper-rolling, skin-rolling to eliminate yield point.
References
