Forging and Sheet Metal Forming

Automotive Production Engineer

by

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Forging and Sheet Metal Forming

Outline

Part I: Forging of Metals (การคัดขึ้นรูป)

• Introduction to metal forming
• Hot and cold working
• Deformation geometry
• Classification of forging processes
• Die design and die materials
• Metal flow in forging
• Force in metal forging
• Forging defects
Forging and Sheet Metal Forming

Outline

Part II: Sheet metal forming (การขึ้นรูปโลหะ)

- Introduction to sheet metal forming
- Sheet metal parts
- Classification of sheet metal forming
- Forming limit criteria
- Defects in formed parts
Introduction to metal forming

ANATOMY OF AN AUTOMOBILE

- rearview mirror
- window frame
- seat
- windshield wiper
- steering wheel
- windshield washer
- air filter
- battery
- distributor
- radiator
- alternator
- oil filter
- disk brake
- body side moulding
- trunk
- tail light
- spare wheel
- wheel
- transmission
- muffler
- line shaft

www.infovisual.info
There are a wide range of different metal parts involved in an automobile production.
Introduction to metal forming

Metal processing

- Casting
  - Gravity die casting
  - Pressure die casting
  - Centrifugal casting
  - Injection moulding
  - Rotational moulding
  - i.e.

- Cutting
  - Electrochemical machining
  - Electrical discharge machining
  - Single/multiple point cutting
  - Grinding
  - i.e.

- Forming
  - Sheet metal forming
  - Forging
  - Rolling
  - Extrusion
  - Wire drawing
  - i.e.

- Joining
  - Fusion welding (arc, laser, electron beam)
  - Solid state welding (friction)
  - Mechanical joining
  - i.e.
Classification of metal forming by subgroups

- **Compressive forming**
  - Rolling
  - Open die forming
  - Closed die forming
  - Indenting
  - Pushing through a die

- **Combined tensile and compressive forming**
  - Pulling through a die
  - Deep drawing
  - Flange forming
  - Spinning
  - Upset bulging

- **Tensile forming**
  - Stretching
  - Expanding
  - Recessing

- **Forming by bending**
  - Bending with linear tool motion
  - Bending with rotary tool motion

- **Forming by shearing**
  - Joggling
  - Twisting
  - Blanking
  - Coining

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Introduction to metal forming

Forgings

Forged wheels

Forged aluminium pistons and connecting rods

Hot forming product
Introduction to metal forming

Net shape and metal powder forming products

Sintered metal parts
Metal injection moulding parts
Net shape metal powder parts

Powder metal forming parts
Introduction to metal forming

Metal Sheet forming products

Electromagnetic forming of automotive parts

Pre-Form Geometry

www.mse.eng.ohio-state.edu

Electromagnetically Formed

Steel Reference Panel

Stamped plates

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Introduction to metal forming

Forging machine

Specialized stretch form machines up to 1600 tons

www.ducommunaero.com

www.macri.it
Hot and cold working

**Working processes**

- The methods used to *mechanically shape metals* into other product forms.

**Hot working** (*0.6-0.8T_m*)
- Primary process
- Recrystallisation

**Cold working** (*< 0.3T_m*)
- Secondary process
- No recrystallisation
Annealing mechanisms in cold worked metals

- Mechanical properties change due to temperature after cold working
Annealing mechanisms in cold worked metals

- Recovery (~0.3T_m)
- Recrystallisation (~0.5T_m)
- Grain growth

Properties:
- Ductility
- Strength
- Hardness

Temperature:
- Cold worked and recovered
- New grains
Effects of grain size and strain on recrystallisation temperature

Schematic of recrystallisation diagram

Smaller grains → Better strength/properties
Effects of grain size and strain on recrystallisation temperature

Flow stress of aluminium as a function of strain at different temperature

Flow curves of Cu Zn28
Advantages and disadvantages of hot and cold working

**Hot working**

**Advantages**
- Low flow stress + high ductility
- Pore sealed up
- Smaller grains
- Softer metals

**Disadvantages**
- Surface oxidation
- Poor dimensional control
- Hot shortness
- Difficult handling

**Cold working**

**Advantages**
- Stronger
- Good surface finish
- Good dimensional control
- Easy handling

**Disadvantages**
- High deformation
- Reduced ductility
- Expensive equipment

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Deformation geometry

**Effect of principal stresses in metal working**

- **Biaxial-plane stress condition**
  - Two principal stresses, $\sigma_1$ and $\sigma_2$.
  - *EX*: Sheet metal forming

- **Triaxial-plane strain condition**
  - Three principal stresses, $\sigma_1$, $\sigma_2$ and $\sigma_3$, where $\sigma_1 > \sigma_2 > \sigma_3$.
  - *EX*: Forging, rolling extrusion
Part I: Forging of metals

- **Forging** is the working of metal into a useful shape by hammering or pressing.
- **Primitive blacksmith**
- Parts ranging in size of *a bolt to a turbine rotor*.
- Most carried out **hot**, although certain metals may be **cold-forged**.

www.eindiabusiness.com

www.prime-metals.com
Classification of forging processes

**By equipment**

1) Forging hammer or drop hammer
2) Press forging

**By process**

1) Open - die forging
2) Closed - die forging
Forging machines

Table 3.3

<table>
<thead>
<tr>
<th>Machine type</th>
<th>Load rating, $F$/kN</th>
<th>Available energy per blow, $W$/kJ</th>
<th>Ratio $W:F$/$m \times 10^{-3}$</th>
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</thead>
<tbody>
<tr>
<td>drop hammer</td>
<td>12 250</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>friction screw press</td>
<td>12 250</td>
<td>8.0</td>
<td>6.4</td>
</tr>
<tr>
<td>crank press</td>
<td>12 250</td>
<td>20</td>
<td>16</td>
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<tr>
<td>hydraulic press</td>
<td>12 250</td>
<td>250</td>
<td>200</td>
</tr>
</tbody>
</table>
Forging machines

- The energy supplied by the blow is equal to the potential energy due to the weight of the ram and the height of the fall.

\[ \text{Potential energy} = mgh \]

- Mass production (60-150 blow / min)
- Dies are subject to impact loading
Forging machines

- Continuous forming at slower rate
- Deeper penetration
- Expensive equipment

- Heat loss from workpiece (long contact)
- Die life
Closed and open die forging

Open-die forging

Closed-die forging

Impression-die forging
Open-die forging

- Flat dies
- Simple shape
- Large objects.
- Pre-forming
Close-die forging (Impression forging)

- Workpiece is formed under high pressure in a closed cavity.
- Small components
- Precision forging
- Expensive die
Forging load

Typical curve of forging load vs. stroke for closed-die forging.

Flash is the excess metal, which squirts out of the cavity as a thick ribbon of metal.
The **flash** serves two purposes:
- Acts as a ‘**safety value**’ for excess metal.
- Builds up **high pressure** to ensure that the metal fills all recesses of the die cavity.

**Remark:** It is necessary to achieve complete filling of the forging cavity without generating **excessive pressures** against the die that may cause it to fracture.
**Closed-die design**

**Considerations**
- workpiece volume and weight
- number of preforming steps and their configuration
- flash dimensions in preforming and finishing dies
- the load and energy requirement for each forging operation, for example; the flow stress of the materials, the fictional condition, the flow of the material in order to develop the optimum geometry for the dies.
# Shape classification

<table>
<thead>
<tr>
<th>Shape class 1</th>
<th>Subgroup</th>
<th>101</th>
<th>102</th>
<th>103</th>
<th>104</th>
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<td>No subsidiary elements</td>
<td><img src="image1" alt="Shape" /></td>
<td><img src="image2" alt="Shape" /></td>
<td><img src="image3" alt="Shape" /></td>
<td><img src="image4" alt="Shape" /></td>
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<td><img src="image5" alt="Shape" /></td>
<td><img src="image6" alt="Shape" /></td>
<td><img src="image7" alt="Shape" /></td>
<td><img src="image8" alt="Shape" /></td>
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<td>Spherical and cubical</td>
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<table>
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<th>212</th>
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<tbody>
<tr>
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<td>No subsidiary elements</td>
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<tr>
<td>l=b=h</td>
<td>With hub and hole</td>
<td><img src="image14" alt="Shape" /></td>
<td><img src="image15" alt="Shape" /></td>
<td><img src="image16" alt="Shape" /></td>
<td><img src="image17" alt="Shape" /></td>
<td><img src="image18" alt="Shape" /></td>
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<td>Parts with circular, square and similar contours</td>
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<tr>
<td>Disc shape with unilateral element</td>
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</table>

<table>
<thead>
<tr>
<th>22</th>
<th>Disc shape with bilateral element</th>
<th>222</th>
<th>223</th>
<th>224</th>
<th>225</th>
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</table>
| Cross piece with short arms upset heads and long shapes (flanges, volves) ETC.
# Shape classification

<table>
<thead>
<tr>
<th>Shape class 3. Abnormal shape</th>
<th>Sub-group</th>
<th>No subsidiary elements</th>
<th>Subsidiary elements parallel to axis of principal shape</th>
<th>With open or closed fork element</th>
<th>With subsidiary elements asymmetrical to axis of principal shape</th>
<th>With two or more subsidiary elements of similar size</th>
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<tr>
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<td>Shape group</td>
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<td>Parts with pronounced longit axis length groups:</td>
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<td>2. At length</td>
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<tr>
<td>1 = 3 ... 8b</td>
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<td>335</td>
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</tr>
</tbody>
</table>
Die set and forging steps for automobile engine connecting rod

- **Preforming** of a round piece in an open die arrangement.
- Rough shape is formed using a block die.
- Finishing die gives final tolerances and surface finish.
- Removal of flash (excess metal).

Steering knuckle  Rail  Flange


See simulation
General considerations for preform design

- Metal used = Metal preform + Flash.
- Concave radii of the preform > radii on the final forging part.
- Cross section of the preform should be higher and narrower than the final cross section.

- Shapes with thin and long sections or projections (ribs and webs) are more difficult to process due to
  - higher surface area per unit volume
  - increasing friction
  - temperature effects.

Some typical nomenclature
General considerations for preform design

- Smooth metal flow – *symmetry dies*
- Avoid shape change
  - *Minimum flash* to do the job.
  - *Tapered or drafted* to facilitate removal of the finished piece.
- *Draft allowance* is approximately 3-5° outside and 7-10° inside.
- *Counterlock* to prevent side thrust.
**Die materials**

**Required properties**

- Thermal shock resistance
- Thermal fatigue resistance
- High temperature strength
- High wear resistance
- High toughness and ductility
- High hardenability
- High dimensional stability during hardening
- High machinability

**Die materials**: alloyed steels (with Cr, Mo, W, V), tool steels, cast steels or cast iron. (Heat treatments such as nitriding or chromium plating)

1) **Carbon steels** with 0.7-0.85% C are appropriate for small tools and flat impressions.
2) **Medium-alloyed tool steels** for hammer dies.
3) **Highly alloyed steels** for high temperature resistant dies used in presses and horizontal forging machines.
# Die materials

<table>
<thead>
<tr>
<th>Forging materials</th>
<th>Steels</th>
<th>Copper and copper alloys</th>
<th>Light alloys</th>
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<tbody>
<tr>
<td></td>
<td>DIN</td>
<td>AISI</td>
<td>DIN</td>
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<td>Forging dies</td>
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<td></td>
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<tr>
<td>C70 W2</td>
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<tr>
<td>C85 W2</td>
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<td>60MnSi4</td>
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<td>X30WCrV53</td>
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<td>40CrMnMo7</td>
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<td>X38CrMoV51</td>
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<td>Die inserts</td>
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<td>55NiCrMoV6</td>
<td>6F2</td>
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<td>X30WCrV93</td>
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<td>X32CrMoV33</td>
<td>H10</td>
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<tr>
<td>X37CrMoW51</td>
<td>H12</td>
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<td></td>
</tr>
</tbody>
</table>


To increase die life
1) Improving die materials such as using composite die or
2) Using surface coating or self-lubricating coatings

Ultra hard surface coatings

- Improve die life.
- Reduce energy input.
- Reduce die-related uptime and downtime.
- Reduce particulate emission from lubricants.

http://www.eere.energy.gov/industry/supporting_industries/pdfs/innovative_die_materials.pdf
Die failures

- Different parts of dies are liable to permanent deformation and wear resulting from mechanical and thermal fatigue

Wear (abrasion)
Thermal fatigue
Mechanical fatigue
Permanent deformation
Metal flow in forging

Finite element analysis of upsetting an aluminium cylinder

Schematic representation of shear band formation in compression of a cylinder.

Increasing reduction

Deformation bands associated with plastic instability.
Metal flow in forging

Grain structure resulting from (a) forging, (b) machining and (c) casting.

Fibre structure in forged steels
Metal flow in forging

- Identify the *neutral surface*
- Metal flows away from the neutral surface in a direction perpendicular to the die motion.
**Metal flow in forging**

- **Cold forging**

  - Forging of nut and bolt

  **Step I**

  **Step II**

  **Step III**

  **Step IV**

[Image: www.qform3d.com]
Metal flow in forging

- Cold forging
- Forging of nut and bolt

Step I
Step II
Step III

www.qform3d.com
Metal flow in forging

Hot forging

Titanium alloy being forged at 930°C to produce preliminary turbine blade pre-form.

Suck in flaw


www.qform3d.com
Metal flow in forging

- AISI 1040 being forged from a square bar at 1200°C to produce a shaft.

- Extensive metal flow into flash
- Incomplete fill up at the upper part
Metal flow in forging

Hot forging

- DIN/C43 being forged from a round bar at 1250°C to produce a shaft fork.

- Possible die filling with minimum flash used.

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**Metal flow in forging**

**Forging from compact bar**

- Powder compact bar of 0.78 density being forged.
- The density increases first in the intermediate area then spread throughout the cross section.
Forces in metal forging

Friction between two surfaces

\[ \mu = \frac{F}{P} = \frac{\tau_i A_r}{PA_r} = \frac{\tau_i}{p} \] ...

Where
\( \mu \) = frictional coefficient
\( \tau \) = the shearing stress at the interface
\( P \) = the load normal to the interface
\( F \) = the shearing force
\( A_r \) = summation of asperity areas in contact
\( p \) = the stress normal to the interface
Forces in metal forging

The calculation of forging load can be considered in three cases:

1. **No friction**
2. **Small friction**
3. **Sticky friction**
No friction

\[ D_0^2 h_o = D^2 h \]

\[ P = \sigma_o A \quad \text{....Eq. 2} \]

Where

- \( P \) is the compressive force
- \( \sigma_o \) is the yield stress of the metal
- \( A \) is the cross sectional area of the metal.

\[ P = \frac{4P}{\pi D^2} \rightarrow \frac{4Ph}{\pi D_o^2 h_o} = \frac{4\sigma_o Ah}{\pi D_o^2 h_o} \quad \text{....Eq. 3} \]
Small friction

- **Small friction (homogeneous forging)**

- **Assumption:**
  - no barrelling
  - small thickness,

Then

- frictional conditions on the top and bottom faces of the disk are \( \rightarrow \) a constant coefficient of Coulomb friction;

![Diagram of frictional forces](image)

\[ \mu = \frac{\tau}{p} \]

...Eq. 4

Where

\( \mu \) = frictional coefficient

\( \tau \) = the shearing stress at the interface

\( p \) = the stress normal to the interface
Small friction

• Small friction (non-homogeneous forging)

Functions of a metal working lubricant
- Reduces deformation load
- Increases limit of deformation before fracture
- Controls surface finish
- Minimises metal pickup on tools
- Minimises tool wear
- Thermally insulates the workpiece and the tools
- Cools the workpiece and/or tools
Small friction

Forging stress
\[ \sigma_y = \sigma_o \exp\left(\frac{2\mu}{h}(a - x)\right) \]

….Eq. 5

Average forging pressure
\[ \bar{p} = \sigma_o \left(1 + \frac{\mu a}{h}\right) \]

….Eq. 6

Friction hill
\[ \sigma_o \exp\left(\frac{2\mu a}{h}\right) \]

\[ \sigma_o \exp\left(\frac{2\mu}{h}(a - x)\right) \]

Forcing pressure
\[ \frac{a}{h} \]

x = -a, x = 0, x = a
High friction (Sticky friction)

Forging stress

\[ \sigma_y = \sigma_o \left( \frac{a-x}{h} + 1 \right) \]  
...Eq. 7

Average forging pressure

\[ p = \frac{2}{\sqrt{3}} \sigma_o \left( \frac{a}{2h} + 1 \right) \]  
...Eq. 8

Friction hill

\[ \sigma_o \left( \frac{a}{h} + 1 \right) \]

\[ \sigma_o \left( \frac{a-x}{h} + 1 \right) \]

Forcing pressure

\[ x = -a \quad x = 0 \quad x = a \]
A block of lead 25x25x150 mm$^3$ is pressed between flat dies to a size 6.25x100x150 mm$^3$. If the uniaxial flow stress $\sigma_o = 6.9$ MPa and $\mu = 0.25$, determine the pressure distribution over the 100 mm dimension (at $x = 0$, 25 and 50 mm) and the total forging load in the sticky friction condition.

$$\sigma_y = \frac{2}{\sqrt{3}} \sigma_o \exp\left[\frac{2\mu}{h}(a - x)\right]$$

where

$$\sigma_o = \frac{2}{\sqrt{3}} \sigma_o$$

At the centreline of the slab ($x = 0$)

$$\sigma_{max} = \frac{2(6.9)}{\sqrt{3}} \exp\left[\frac{2(0.25)}{6.25}(50 - 0)\right] = 435\text{MPa}$$

Likewise, at 25 and 50 mm, the stress distribution will be 58.9 and 8.0 MPa respectively.
The mean forging load (in the sticky friction condition) is

\[ P = \frac{2}{\sqrt{3}} \sigma_o \left( \frac{a}{2h} + 1 \right) \]

We calculate the forging load on the assumption that the stress distribution is based on 100 percent sticky friction. Then

The forging load is \( P \) = stress x area

= \((39.8 \times 10^6) (100 \times 10^{-3}) (150 \times 10^{-3})\)

= 597 kN

= 61 tonnes.
Defects in forging

- **Incomplete die filling.**
- **Die misalignment.**
- **Forging laps.**
- **Incomplete forging penetration—should forge on the press.**
- **Microstructural differences resulting in pronounced property variation.**
- **Hot shortness**, due to high sulphur concentration in steel and nickel.
- **Residual stresses**
Forging of automobile parts

- Metals to be forged
- Shape and size
- Forging temperature
- Strain rate
- Forging load
- Lubrication

- Die design
- Die materials
- Die life
Part II: Sheet metal forming

- **Permanent deformation** by cold forming (RT).
- Complex 3D 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.
- **High rate of production** and **formability**
Classification of sheet-metal forming

Classification (Base on operation)

Blanking
Punching
Stretching
Deep drawing
Classification of sheet-metal forming

Classification (Base on operation)

Coining

Stamping

Ironing
Classification of sheet-metal forming

Classification (Base on operation)

Folding  Bending  Roll forming of sheet  Wiping down a flange
**Tooling**

**Basic tools**

- **Punch** → A *convex tool* for making holes by shearing, making surface or displacing metal with a hammer.

- **Die** → A *concave die* (female part).

**Die materials:**

- High alloyed steels heat treated for the punches and dies.
**Compound and transfer dies**

**Compound dies**
- Several operations in one stroke.
- Combined processes and create a complex product in one shot.
- Stamping processes of thin sheets.

**Transfer dies**
- Also called *compound dies*.
- The part is moved from station to station within the press for each operation.
Introduction to metal forming

Die set consists of

1) Punch holder
2) Die block
3) Pilot
4) Striper plate

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

- Progressive forming
- Hydroforming
- Stretch forming
- Explosive forming
- Stamping
- Shearing and blanking
- Bending and contouring
- Spinning process
- Deep drawing
Progressive forming

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

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• Using **Rubber** or **polyurethane** pad as dies.

• Single - action hydraulic press.

• Pressure medium- **water** or **oil**.

• Transmits a nearly uniform hydrostatic pressure against the sheet.

• **Pressure** ~ 10 MPa or higher
Stretch forming

- Using **tensile forces**, normally for uniform cross section.
- Required materials with **appreciable ductility**.
Explosive forming

- **Explosive charge** is detonated in medium (water) at an appropriate **standoff distance** from the sheet blank at a very high velocity.
- The shockwave propagating from the explosion serves as a **friction-less punch**
Stamping

- **Key factors:** data collections on die sets, die failure and material handling damage and machine failure to identify weak areas in the stamping process.

- Materials require good ductility, work hardening and strength
Stamping

- Multi-cone design giving structural integrity and rigidity equivalent to a steel beam panel at half the weight, and without cutouts.
Shearing and blanking

Clearance (normally 2-10% thickness)

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

- **Proper** clearance
- **Insufficient** clearance
- **Excessive** clearance
Bending and contouring

Wiper rolls
Form block
Clamp
Tension
Bending and contouring

- Outer surface → strained.
- Inner surface → contracted.

\( R \) \( \text{thickness on bending} \)

\( b/h \) \( \text{biaxiality} \)

Strain, ductility

Cracks occur near the centre of the sheet

Springback
Spinning process

- 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,
Deep drawing

- Shaping flat sheets into **cup-shaped articles**.

**Examples:** bathtubs, shell cases, automobile panels.

A cup is subjected to three different types of deformation.

**Lamp cover**

**Stresses and deformation in a section from a drawn cup**
Deep drawing

- **Die radius** – \(10 \times \text{sheet thickness}\).
- **Punch radius** – Clearance between punch and die \(~10-20\% > \text{sheet thickness}\).
- **Hold-down pressure** – \(~2\% \text{ of } \sigma_y \text{ and } \sigma_u\).
- **Lubrication of die side**.
- **Material properties** - low yield stress, high work hardening rates.
Forming limit criteria

- Stretching of circles into ellipses after punching
- Percentage changes in these strains are compared in the diagram.

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

Forming limit diagram
Defects in formed parts

Springback problem

φ ~ 55° for an isotropic material in pure tension

Localised necking in a strip in tension

ε_u = 2n

Crack near punch & shoulder

Edge condition

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**Introduction to metal forming**

- **Stretcher strain in low-carbon steel.**
- **Earing in drawn can**
- **Radial crack**
- **Surface blemish (orange peel)**
- **Wrinkling**
- **Mechanical fibering**
References

- Lecture notes, Sheffield University, 2003.
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