2. Technology

Metal Forming
Technology: Metal Forming

- Metal forming includes a large group of manufacturing processes in which plastic deformation is used to change the shape of metal work pieces.

- Plastic deformation: a permanent change of shape, i.e., the stress in materials is larger than its yield strength.

- Usually a die is needed to force deformed metal into the shape of the die.
Metal Forming

• Metal with low yield strength and high ductility is in favor of metal forming

• One difference between plastic forming and metal forming is

**Plastic**: solids are heated up to be polymer melt

**Metal**: solid state remains in the whole process
4 groups of forming techniques:

- Rolling,
- Forging & extrusion,
- Wire drawing,
- Deep drawing.

Bars shaping vs. Sheets shaping
Rolling

Flat (plates) rolling

Cross rolling

slant rolling (for tubes production)
(a) Relative forgability for different metals and alloys. This information can be directly used for open die forgings. (b) Ease of die filling as a function of relative forgability and flow stress/forging pressure – applicable to closed die forging.
Wire drawing

In a conventional wire drawing process, the diameter of a rod or wire is reduced by pulling it through a conical die.

Illustration of some drawing operations: (a) conventional wire drawing with circular cross-section; (b) wire drawing with rectangular cross-section, using so-called ‘Turk’s’ head; (c) drawing using a floating mandrel.
Sheet metal forming

Equi-biaxial stretching using a clamped sheet and a hemispherical punch (left) and a schematic of an industrial stretch-forming operation (right).

Complex stretch-forming operation using a male and female die
Metal forming is divided into: (1) bulk and (2) sheet

**Bulk:** (1) significant deformation
(2) massive shape change
(3) surface area to volume of the work is small

**Sheet:** Surface area to volume of the work is large
Bulk deformation processes

Rolling

Extrusion

Forging

Wire drawing
Sheet deformation processes

Bending

Deep drawing

Shearing
Technology
Selected forming techniques

1. Rolling
2. Extrusion
3. Wire drawing
4. Forging
5. Pilgering
6. Sheet metal forming
7. Hydroforming
8. Superplastic forming
9. Other techniques
Rolling

From an economic point of view, rolling is the most important metal working and shaping technique; it can be used to roll large ingots from half a meter thickness down to a few microns in the case of Al foil (of total length up to a hundred kilometers).

Flat rolling

Both hot and cold rolling can lead to major improvements of the material properties by refining the microstructure.
Shaping of plates by rolling

Roll bending

Roll forming

Bars rolling

Cross-sections of continuously rolled structural shapes, showing the change induced by each rolling mill

A schematic of ring rolling
Flat rolling - mechanics

The horizontal components of forces acting on a element of metal situated in the roll gap at a position described by the angle $\alpha$ are:

- Due to longitudinal stress
- Due to radial pressure on both rolls
- Due to friction against both rolls

The force balance gives:

$$h \sigma_x + \sigma_x \, dh + 2 \mu p_r \, dx \pm 2 \mu p_r \, dx = 0$$
Rigorous solution to this equation requires numerical techniques, but an approximate analytical solution is given following Bland and Ford (1948) by taking small angle approximations $\sin \alpha = \alpha$ (in rad) and $P_r = P$ and assuming that the variation in flow stress is small compared with the variation in roll pressure so that one obtains:

\[
\text{on the entrance side} \quad P = \frac{2\sigma_0 h}{\sqrt{3h_0}} \cdot \exp[\mu(H_0 - H)]
\]

and on the exit side

\[
P = \frac{2\sigma_0 h}{\sqrt{3h_f}} \cdot \exp[\mu H]
\]

where the quantity

\[
H = 2\sqrt{\frac{R}{h_f}} \cdot \tan^{-1}\left(\sqrt{\frac{R}{h_f}} \cdot \alpha\right)
\]
Rolling equipment: for plate, sheet and foils manufacturing

Preliminary milling (reversing)

Schematic of a 2-high mill (a) and a 4-high mill (b)

Two-high reversible mill in which the direction of rotation of the rolls is reversed after each pass to enable the workpiece to be passed successively backwards and forwards.

Application:

First stages of hot rolling ingots in the primary rolling. Typically 500mm → 30mm (total strain 2.8) in a series of 10-20 passes.
Higher strains per pass are carried out during subsequent rolling operations down to sheet or foil using smaller diameter rolls to reduce the required power. Each roll is supported by two backing rolls.

A Sendzimir mill is an example of such a cluster mill used to roll very thin sheet or foil.
• High rates of production can be achieved in a continuous mill using a series of rolling mills denoted tandem mills.
• Each set of rolls is placed in a stand and since the input and output speeds of the strip at each stand are different, the strip between them moves at different (usually rapidly increasing) velocities.
For large reductions - planetary mill. PM is made up of two large backing rolls surrounded by several small planetary rolls.

During a single pass (at high temperatures) the slab undergoes a large number of reductions so that it is, in effect, rolled down to strip in one pass.

More flexible cold rolling is performed in 4-high single stand reversing mills with coilers at both ends (and which can also provide front and back tension).

Illustration of a single-stand reversible cold rolling mill
Steels – hot & cold rolling of flat steel products

1. Manufacturing process:
   - traditional - from flat ingots with thickness ~200mm,
   - from flat ingots with thickness ~50mm,
   - direct casting of bands – band thickness ~1-5mm.

Schematic presentation of technological process for manufacturing of steel sheets cold rolled and annealed
Classification of high-production hot strip mills

Comparison of layouts of compact hot strip mills (b)-(e) with layout of semi-continuous hot strip mill (a)

Initial band thickness – 200-250mm

Initial band thickness – ~50mm

Initial band thickness – ~25mm

Fully continuous hot strip mill without reduction (initial band thickness – 2-5mm)
Rolling lines - Continuous casting + hot rolling for thin sheets production

Integrated line:
Continuous casting → band cutting → heating → hot direct rolling → cooling

Modern, integrated line for thin sheets production
**ISP® technology**
**operating since 1992**

Patent no. 0415987

* Single line, width 1300 mm, 1 million tpy

Patent no. 1196256

* Double casting line, width 1850 mm, 3.2 million tpy
### Comparison of Fundamental Casting Parameters

<table>
<thead>
<tr>
<th></th>
<th>CASTRIP process</th>
<th>Thin slab casting</th>
<th>Thick slab casting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strip thickness (mm)</td>
<td>1.6</td>
<td>50</td>
<td>220</td>
</tr>
<tr>
<td>Casting speed (m/min.)</td>
<td>80</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Average mold heat flux (MW/m²)</td>
<td>14</td>
<td>2.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Total solidification time (s)</td>
<td>0.15</td>
<td>45</td>
<td>1,070</td>
</tr>
<tr>
<td>Average shell cooling rate (°C/s)</td>
<td>1,700</td>
<td>50</td>
<td>12</td>
</tr>
</tbody>
</table>
Rolling lines - Continuous casting + hot rolling for thin sheets production
Cold rolling & continuous recrystallization of steel bands
Steels for sheets

Temperature changes during hot & cold rolling and during recrystallization annealing

- **Steels for sheets**
- **Temperature changes during hot & cold rolling and during recrystallization annealing**

Diagram showing:
- Heating
- Hot rolling
- Hot coiling
- Recrystallization annealing
- Cold rolling
- Time
- Finishing rolling

Temperature changes timeline:
- Heating to high temperature
- Decrease to hot rolling temperature
- Hot coiling
- Increase for recrystallization annealing
- Decrease during cold rolling
- End of finishing rolling
Temperature changes during recrystallization annealing

Steels for sheets

Temperature, °C

Time of recrystallization, days

Temperature, °C

Time of continuous recrystallization, min
Integrated parts production: a look into the future
**Typical rolling schedules - aluminium**

**Typical TM process**

Homogenization of ingot at 500-600°C/(few hours)

Hot rolling (up to 30-10mm) reversible rolling mill

Cold rolling – reversible 4-high cold mill between two coilers. (The ‘softer’ alloys are rolled to a thickness 15-20µm. To obtain very thin packaging foil of about 6µm thickness, the foil is doubled up and re-rolled. Intermediate annealing is frequently needed to achieve large cold rolling reductions).

Schematic rolling schedules (for TMP) for the production of (a) can stock, (b) foil
Some typical rolling conditions for Al alloys

<table>
<thead>
<tr>
<th></th>
<th>Reversible</th>
<th>Tandem</th>
<th>Cold rolling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start temperature (°C)</td>
<td>500–600</td>
<td>400–500</td>
<td>20</td>
</tr>
<tr>
<td>Finish Temperature (°C)</td>
<td>400–500</td>
<td>250–350</td>
<td>100</td>
</tr>
<tr>
<td>Number of passes</td>
<td>9–25</td>
<td>2–5</td>
<td>2–10</td>
</tr>
<tr>
<td>Initial thickness (mm)</td>
<td>400–600</td>
<td>45–15</td>
<td>2–6</td>
</tr>
<tr>
<td>Final thickness (mm)</td>
<td>45–15</td>
<td>2–9</td>
<td>0.01–1</td>
</tr>
<tr>
<td>Strain per pass</td>
<td>0.1–0.5</td>
<td>0.7</td>
<td>0.3–0.7</td>
</tr>
<tr>
<td>Total strain</td>
<td>3</td>
<td></td>
<td>&lt;5</td>
</tr>
<tr>
<td>Strain rates (s)</td>
<td>1–10</td>
<td>10–100</td>
<td>&gt;50</td>
</tr>
<tr>
<td>Inter-stand times (s)</td>
<td>10–300</td>
<td>&lt;3</td>
<td></td>
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An increased proportion of the less strongly alloyed sheet products are now produced by continuous strip casting.
Wire drawing

In an industrial production line, a large reduction is obtained by pulling the wire or rod through a series of consecutive dies. In some cases, an intermediate annealing treatment may be necessary.

In some cases, an intermediate annealing treatment may be necessary. Some materials (e.g. tungsten wire for incandescent lamp filaments) are drawn at high temperature.

Draw bench (left) and single pass drawing equipment (right)

Continuous wire drawing machine of the ‘non-slip-type’
Wire drawing

Geometry of a drawing die

\[ r = \frac{D_0^2 - D_1^2}{D_0^2} = 1 - \left( \frac{D_1}{D_0} \right)^2 = 1 - \left( \frac{1}{\exp(\varepsilon)} \right) \]

\[ \varepsilon = \ln \left( \frac{D_0}{D_1} \right)^2 = \ln \left[ \frac{1}{1 - r} \right] \]

Reduction and true strain

\[ \Delta = \frac{D_g}{L_p} = \sin \alpha \left[ 1 + (1 - r)^{0.5} \right]^2 \]

The driving force & the fracture stress

\[ F = \sigma_f \ln \left( \frac{D_0}{D_1} \right)^2 \cdot \frac{\pi D_1^2}{4} \quad \text{or} \quad \sigma_F = \sigma_f \ln \left( \frac{D_0}{D_1} \right) = \sigma_f \varepsilon \]

Friction stress

Siebel formula (1947)

\[ \sigma_F = \sigma_f \left[ \varepsilon + \left( \frac{\mu}{\alpha} \right) \varepsilon + \left( \frac{2}{3} \right) \alpha \right] \quad \text{with} \ \alpha \ \text{in radians} \]

Hoffman & Sachs formula (1947)

\[ \sigma_F = \Phi \sigma_f \varepsilon (1 + \mu \cot \alpha \varepsilon) \quad \text{with} \ \Phi = \frac{\Lambda}{6} + 1 \]

where: \( \alpha \) in deg

Parameter that express the degree of redundant deformation (mean wire diameter in the deformation zone)
Wire drawing - some important metallurgical problems

During wire drawing of fcc metals, classical strain hardening of the wire takes place – saturation stress is reached.

During drawing bcc metals (e.g. low carbon steel) - after a parabolic transition, the stress increases linearly with strain.

Curling effect in perlitic steel (a) view parallel with the wire axis, (b) scheme of a cementite lamella after wire drawing

Illustration of the <111> slip directions in a bcc lattice with the [011] direction parallel to wire axis
‘Pierce rolling’

A pierce rolling mill consists of two contoured work rolls, driven at the same direction.

These work rolls are typically placed at an angle of 3-6deg around the hot billet.

The roll gap is closed respectively from top and bottom by a support roll (not driven) and support shoe.

Schematic of pierce rolling at two cross-sections
Pilgering

A pilger stand has typically two rolls (dies) with a tapered groove around their circumferences. Mother hollow or tubes are rolled repeatedly over an axisymmetric mandrel.

Stages:

(b) Start of rolling – hollow mandrel assembly is ‘bitten’ by the grooved rolls,

(c) Forging or pilgering – the grooved rolls forge out a small wave of material to the desired wall thickness

(d) Polishing – the soothing section of the gooved rolls, reels or polishes the forged wall.

(e) Advancing or feed – roll and mandrel movements are reversed and a fresh section of the mother hollow is ‘bitten’.

(a) Schematic of pilgering equipment. (b)-(e) different stages of pilgering. (b) start of rolling or the ‘bitte’, (c) forging or pilgering, (d) polishing, (e) advancing or feed.
Comparison between cold drawing and cold pilgering

<table>
<thead>
<tr>
<th>The issue</th>
<th>Cold drawing</th>
<th>Cold pilgering</th>
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<tbody>
<tr>
<td>The process</td>
<td>Hot-formed hollows are pointed, pickled and surface treated for cold drawing. The process involves drawing the hollows through reducing dies, usually supported by a plug or mandrel</td>
<td>Hot-formed hollows are pickled and then cold pilgered. The process involves repeated rolling through grooved conical shaped rolls and over a moving mandrel</td>
</tr>
<tr>
<td>After drawing/pilgering, finished tubes are subjected to cutting, degreasing, heat treatment (if required) and straightening operations</td>
<td>Close-dimensional tolerances, very high reductions and reductions in both wall thickness and tube diameter are possible. Superior surface finish and better metalurgical control are possible</td>
<td></td>
</tr>
<tr>
<td>The product</td>
<td>Close-dimensional tolerances are possible, but maximum reductions, reduction in wall thickness, are often limited</td>
<td>Close-dimensional tolerances, very high reductions and reductions in both wall thickness and tube diameter are possible. Superior surface finish and better metalurgical control are possible</td>
</tr>
</tbody>
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Summary:
typical advantages of pilgering involve reduced processing stages, superior product quality and excellent formability (i.e. high reductions are possible without intermediate annealing)
Tubes calibration - tubes drawing
Sheet metal forming

Large quantities of thin sheets are produced at relatively low cost by rolling mills. They are transformed into familiar products, such as beverage cans, car bodies, metal desks, domestic appliances, aircraft fuselages, etc., by sheet metal forming.

Many of these processes involve a rather complex deformation path. In most cases, the latter can be considered as a superposition of some ‘elementary’ processes like bending, stretching and deep drawing.
Anizotropy

Ration between plastic strain in the width over plastic strain in the thicckness direction in uniaxial tension (Lankford’s coefficient):

\[ r = \frac{\varepsilon_2}{\varepsilon_3} = \frac{\ln \frac{b}{b_0}}{\ln \frac{g}{g_0}} \]

\[ r = \frac{\varepsilon_2}{\varepsilon_3} = \frac{\ln \frac{b}{b_0}}{\ln \frac{l_0b_0}{lb}} \]

Since the \( r_m \) value of most materials depends on the direction in the surface plane of the sheet a mean \( r_m \) value can be calculated as:

\[ r_m = \frac{r_0 + 2r_{45} + r_{90}}{4} \]

The \( r_m \) value is called ‘the normal anisotropy’

The planar anisotropy reflects the variation of ‘r’ in the plane of the sheet and can be defined as:

\[ \Delta r = \frac{r_0 + r_{90} - 2r_{45}}{4} \]

Hardening coefficient ‘n’:

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

Influence of plastic (normal) anisotropy on the shape of the yield locus

Plastic anisotropy will change the shape of the yield locus.

Uniaxial yield stress (point C) is not affected by a change in mean $r$-value, but that
the biaxial yield stress (point A) increases with increasing ‘$r_m$‘ value
Sheet metal forming sheets rolling - texture

Rolling direction

(a) Random distribution of grain orientation vs. (b) textured material

Strong Goss\{100\}<011> component in rolled sheets

(a) sheet without anizotropy, and (b) with strong anizotropy, i.e. strong cube\{100\}<001> texture in rolled sheets
Deep drawing and texture (low carbon steel)

Fi2=45deg section of Euler space, with crystallographic orientations that are ‘good’ and ‘bad’ for the deep drawibility of a low-carbon steel sheets
Deep drawing and texture (case of Al)

Influence of r-value:
Cube grains stimulate the $0/90\text{deg}$ ears, while orientations belonging to $\beta$-fibre give rise to $45\text{deg}$ ears.
The Al sheets are processed in order to achieve good balance between both (cube + $\beta$-fibre) in order to get $\Delta R\sim0$ and to minimize earing.
Sheet metal forming — plastic anisotropy

Ti- hcp structure up to 882 C. The case of sheets with \{0001\}||rolling plane (assumed random distribution of crystallographic orientations round [0001] axis)

Deformation - basal s.s. \{0001\}<1-210> + prismatic s.s. – \{10-10\}<uvwk>

In none of these cases, any deformation in the [0001] direction occur

Slip systems in pure Ti. In uniaxial tension, the fibre texture prohibits thinning in the thickness direction
Yield criterion vs. plastic flow law

\[(1 + r)\sigma_p^2 = (1 + r)\sigma_1^2 - 2r\sigma_1\sigma_2 + (1 + r)\sigma_2^2\]

\[
\frac{d\varepsilon_1}{(1 + r)\sigma_1 - r\sigma_2} = \frac{d\varepsilon_2}{(1 + r)\sigma_2 - r\sigma_1} = \frac{d\varepsilon_3}{-\sigma_1 - \sigma_2} = \frac{d\varepsilon}{(1 + r)\sigma_p}
\]

for \(r=1\)

\[\sigma_p^2 = \sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2\]

\[
\frac{d\varepsilon_1}{\sigma_1 - \sigma_m} = \frac{d\varepsilon_2}{\sigma_2 - \sigma_m} = \frac{d\varepsilon_3}{\sigma_3 - \sigma_m} = \frac{d\varepsilon}{\frac{2}{3}\sigma_p}
\]

\[\sigma_m = \frac{1}{3}(\sigma_1 + \sigma_2)\]
Deep drawing of a cylindrical cup from a circular blank

Stress and strain state in various points of the cup during deep drawing. Possible compressive stresses in flange and wall are not into account.
Redrawing & ironing

Redrawing, reverse redrawing and wall ironing to produce deeper cups

**redrawing** - several consecutive passes are applied. After each pass, the cup radius decreases and the cup height increases.

When the cup is turned inside out after each pass, the process is called ‘**reverse redrawing**’.

In **wall-ironing**, the cup passes through a series of ring-shaped dies.
SPD methods

Schematic illustration of (a) lab-scale ECAP die, (b) the conshearing process, (c) continuous confined strip shearing, and (d) the ECAP-conform set up
SPD methods

Interactions of subsequent shear deformations in the first and second ECAP pass.

TEM micrographs in plane XY of IF steel after 8 passes (a) via route A and (b) route C