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**

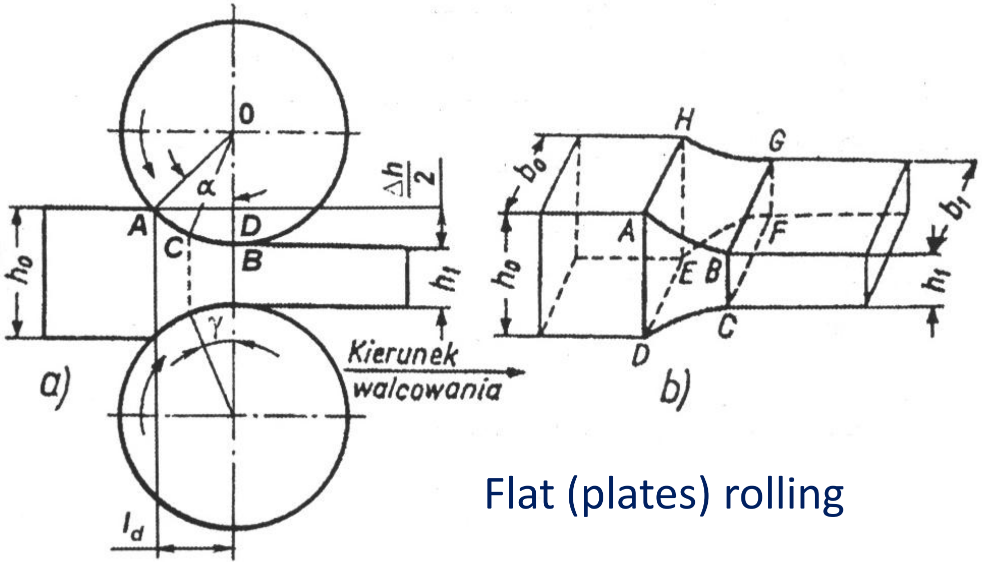
Metal: solid state remains in the whole process

4 groups of forming techniques:

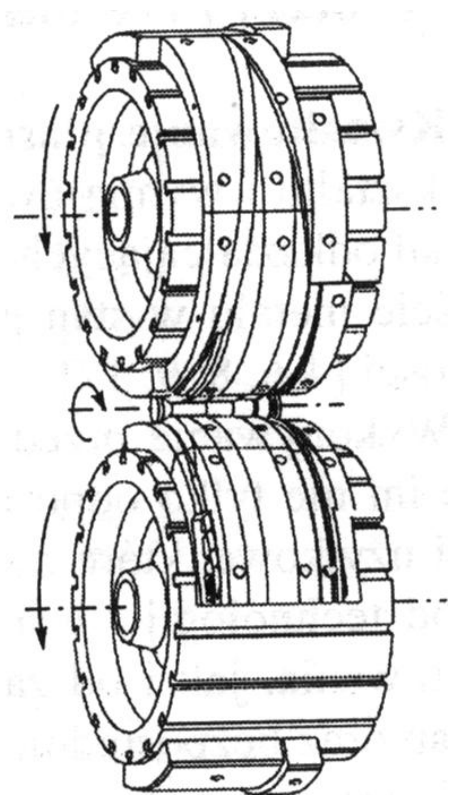
- Rolling,
- Forging & extrussion,
- Wire drawing,
- Deep drawing.

Bars shaping vs. Sheets shaping

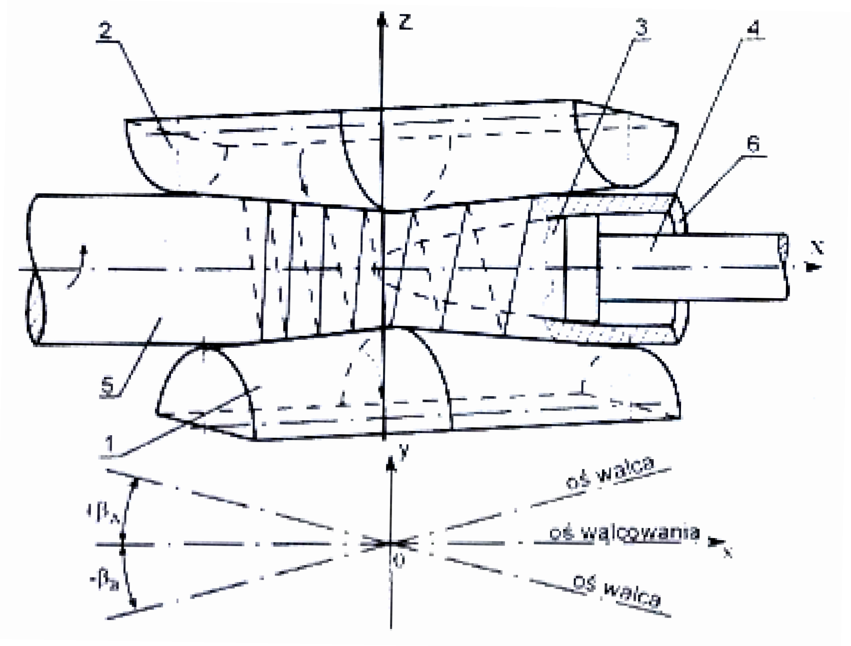
Rolling



Flat (plates) rolling

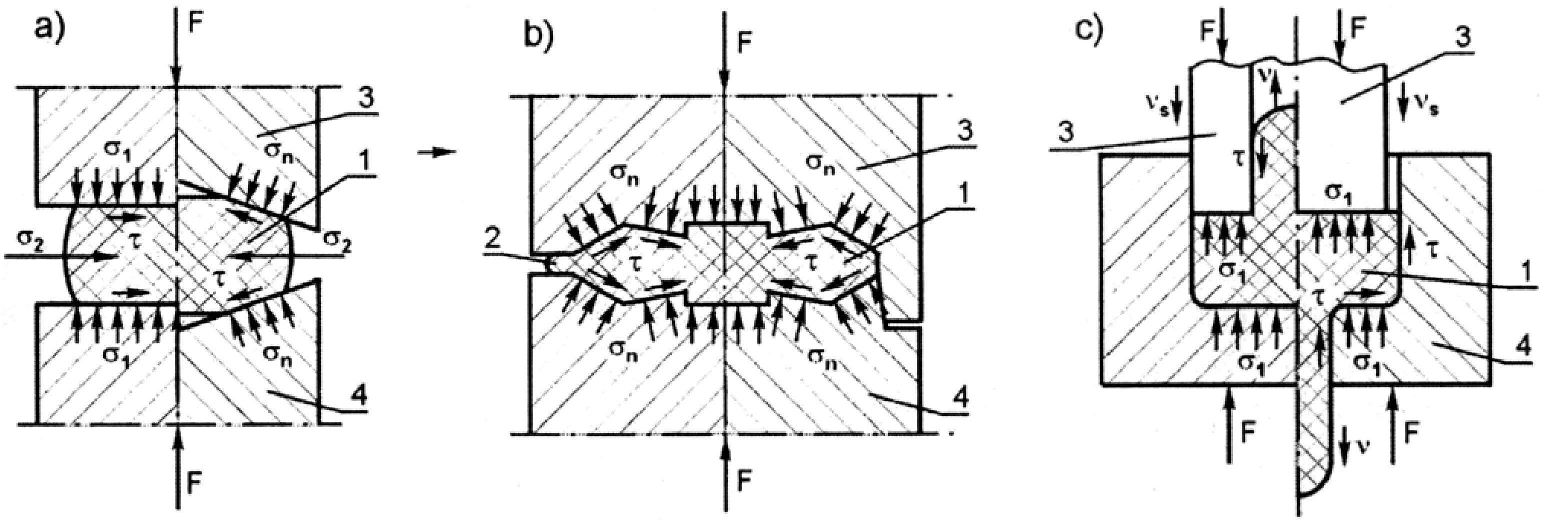


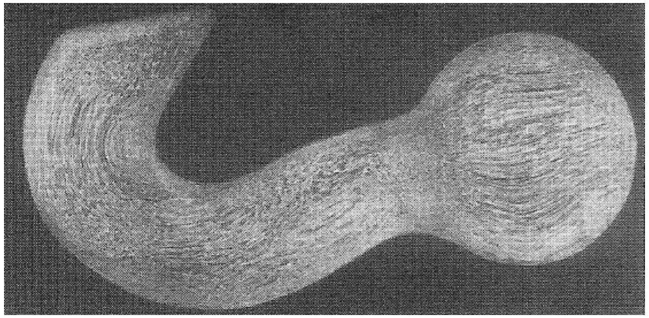
Cross rolling



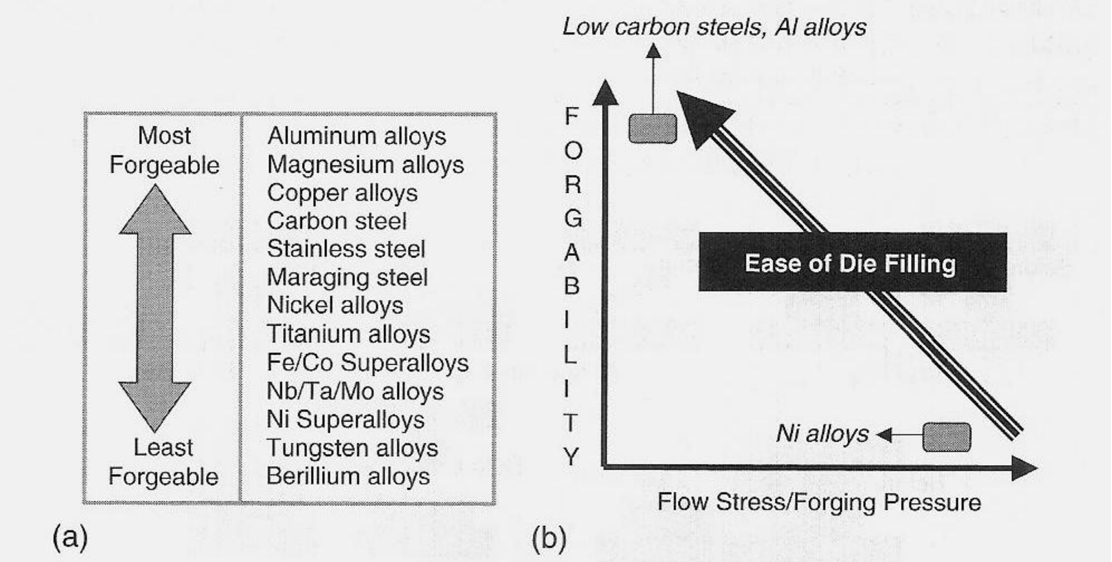
slant rolling (for tubes production)

Forging & extrussion





Macroetched structure of a hot forged hook



Most Forgeable	Aluminum alloys Magnesium alloys Copper alloys Carbon steel Stainless steel Maraging steel Nickel alloys Titanium alloys Fe/Co Superalloys Nb/Ta/Mo alloys Ni Superalloys Tungsten alloys Berillium alloys
Least Forgeable	

(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 forability and flow stress/forging pressure – applicable to closed die forging

Wire drawing

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

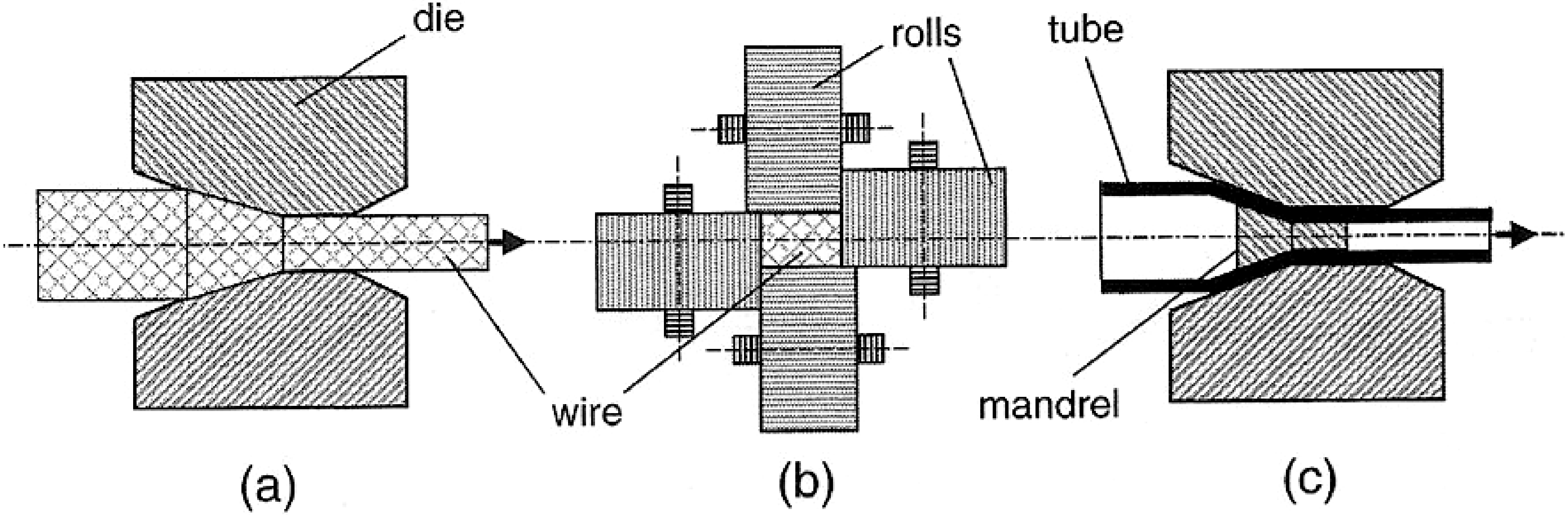
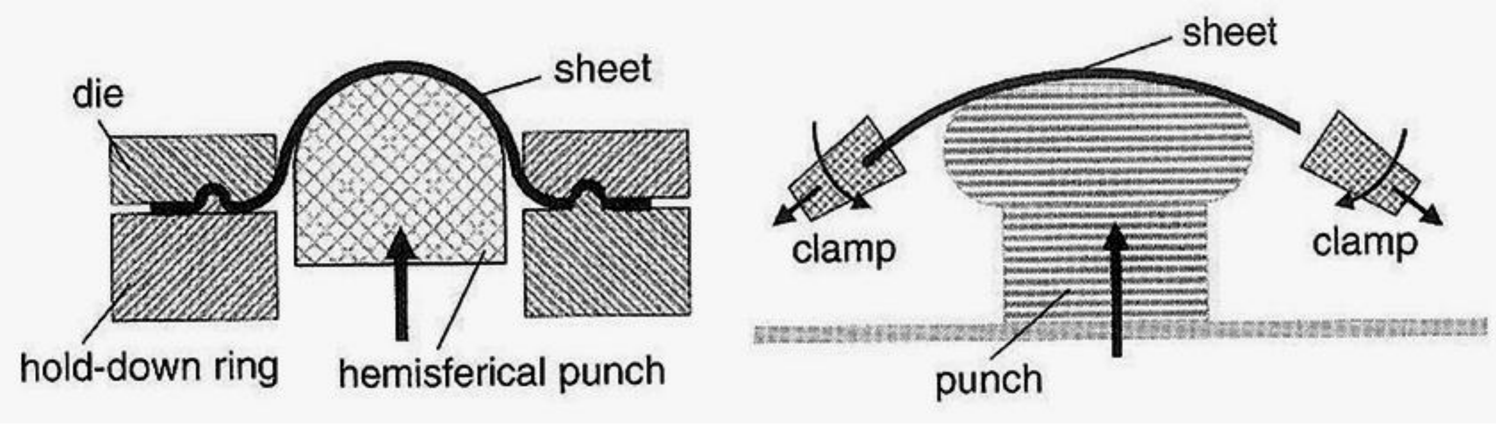
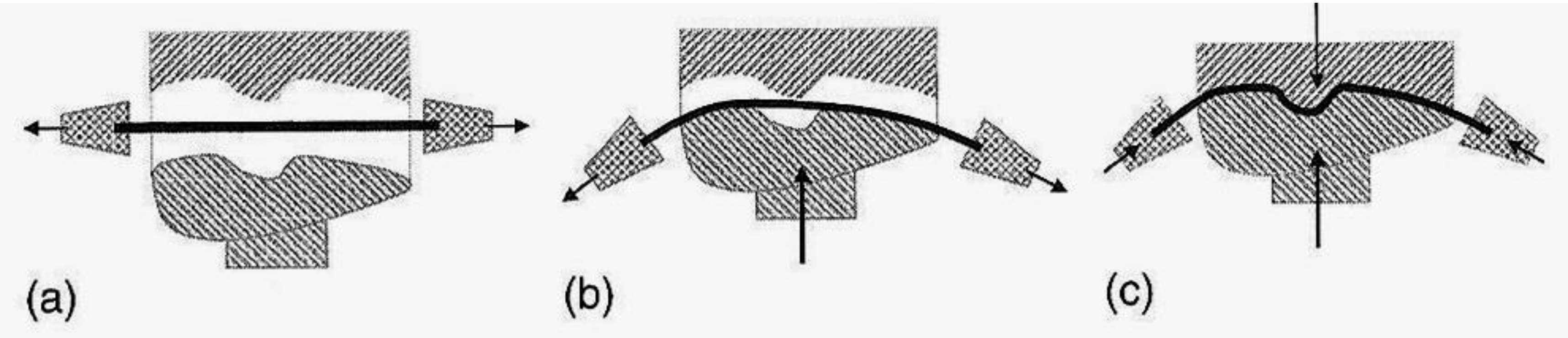


Illustration of some drawing operations: (a) conventional wire drawing with circular cross-section; (b) wire drawing with rectangular cross-section, using so-called ‘Turk’s’ head; (c) drawing using a floating mandrel.

Sheet metal forming



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



Complex stretch-forming operation using a male and female die

Metal Forming

Metal forming is divided into: (1) bulk and (2) sheet

Bulk: (1) significant deformation

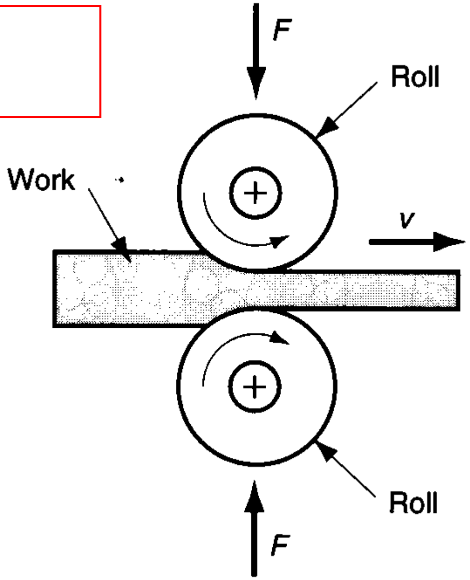
(2) massive shape change

(3) surface area to volume of the work is small

Sheet: Surface area to volume of the work is large

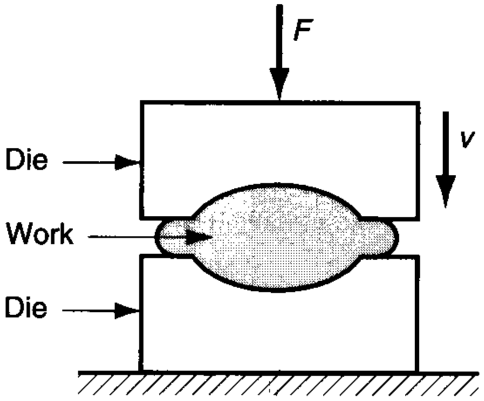
Bulk deformation processes

Rolling



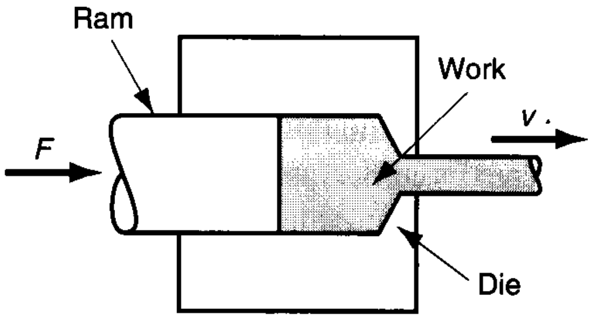
(a)

Forging



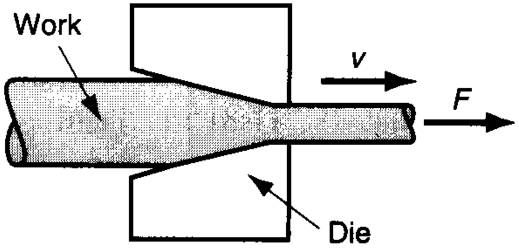
(b)

Extrusion



(c)

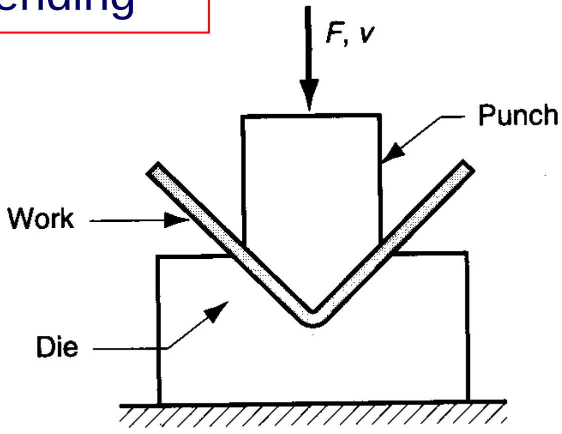
Wire drawing



(d)

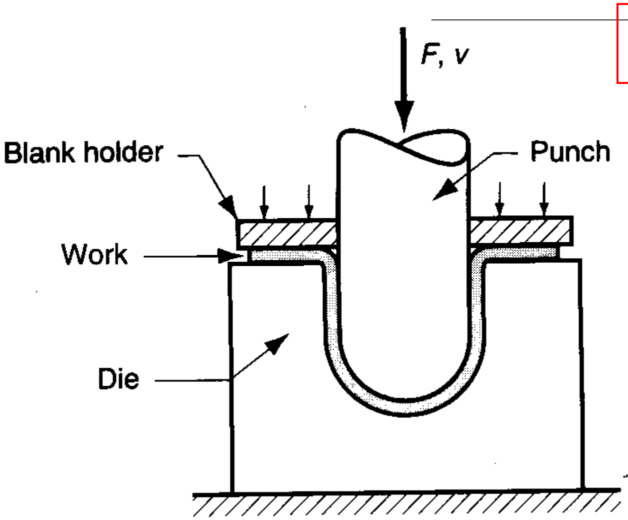
Sheet deformation processes

Bending



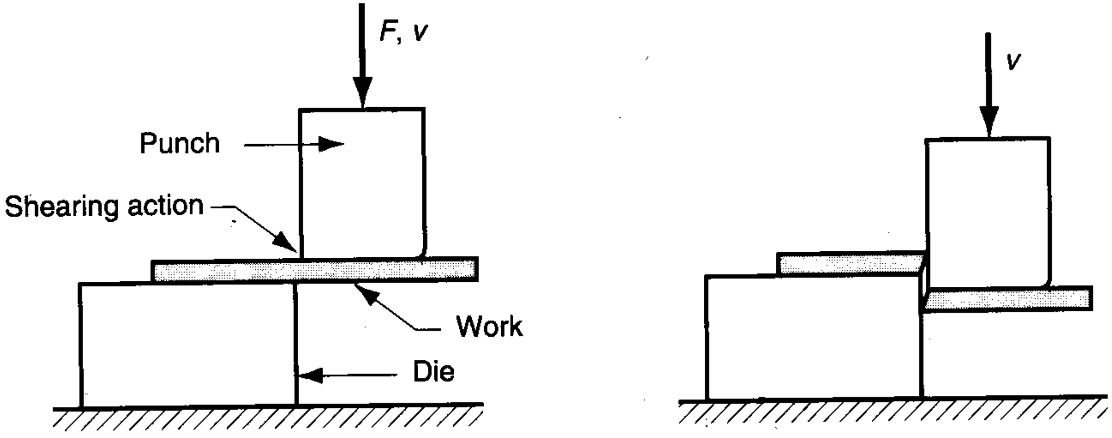
(a)

Deep drawing



(b)

Shearing



(1)

(2)

(c)

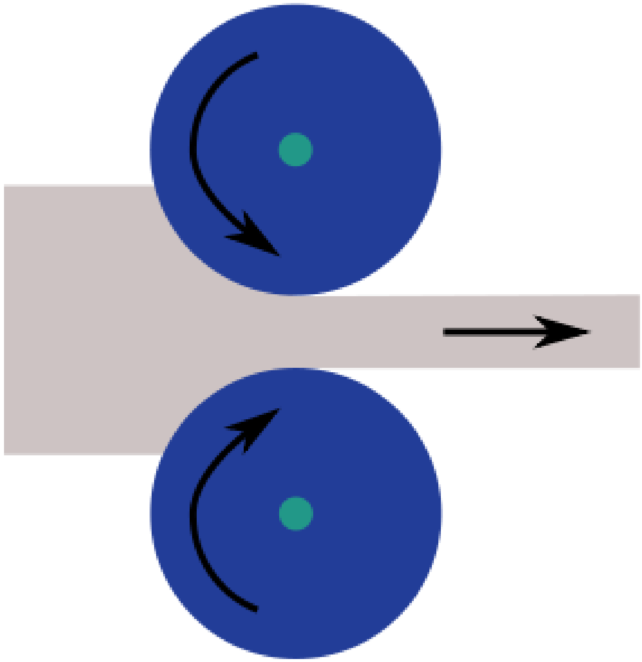
Technology
Selected forming techniques

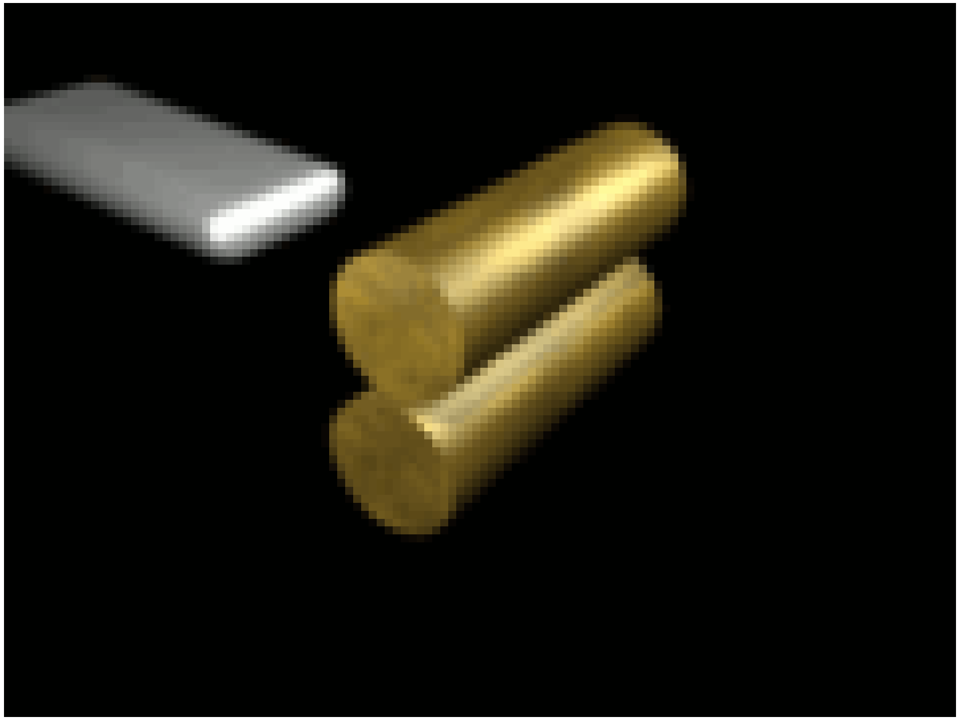
1. Rolling
2. Extrussion
3. Wire drawing
4. Forging
5. Pilgering
6. Sheet metal forming
7. Hydroforming
8. Superplstic formig
9. Other techniques

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 lenght up to a hindred kilometers)

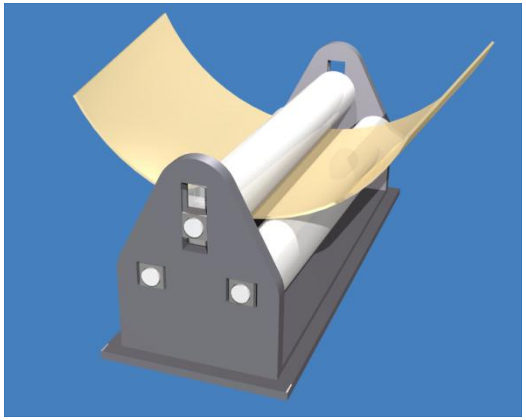
Flat rolling



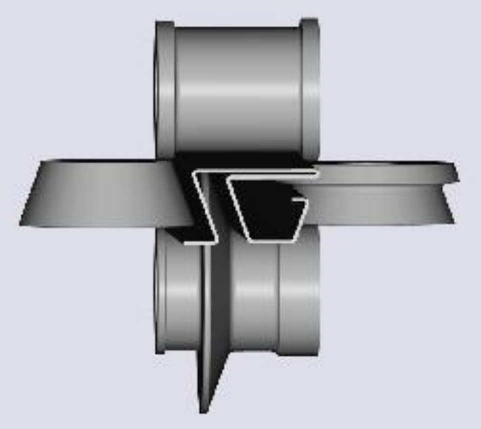


Both hot and cold rolling can lead to major improvements of the material properties by refining the microstructure.

Shaping of plates by rolling



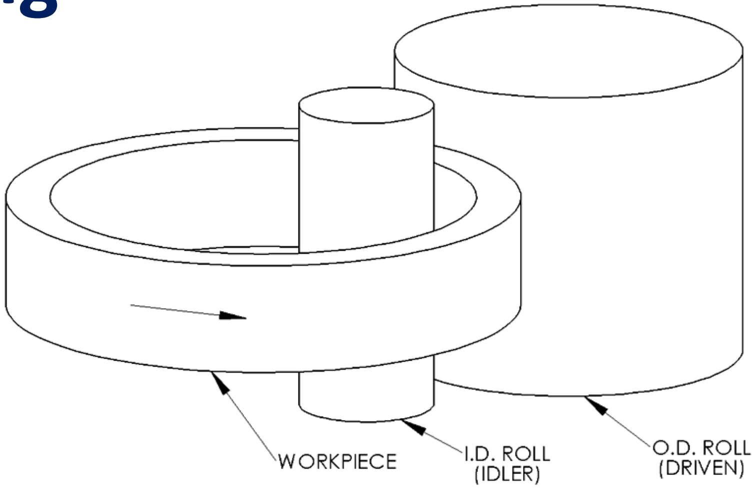
Roll bending



Roll forming

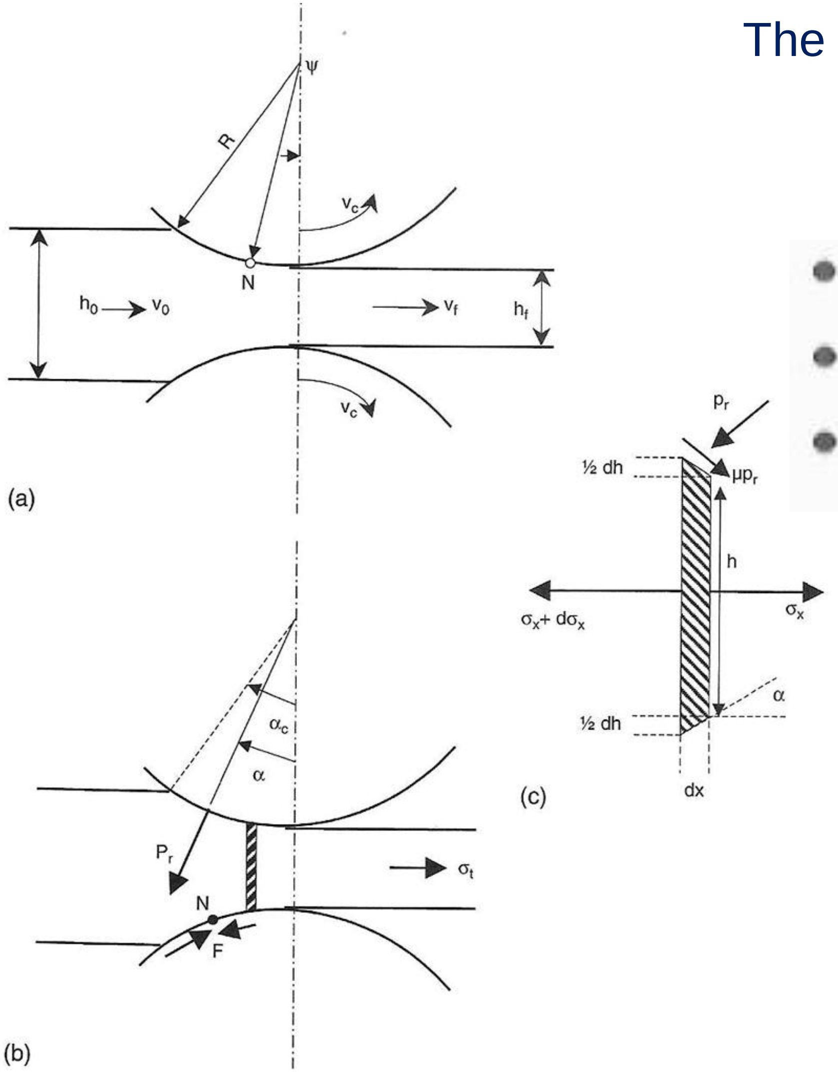
Bars rolling

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



A schematic of ring rolling

Flat rolling - mechanics



Basic geometry of flat rolling

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

$(\sigma_x + \mathrm{d}\sigma_x)(h + \mathrm{d}h) - h\sigma$	Due to longitudinal stress
$2(p_r \sin\alpha)(\mathrm{d}x/\cos\alpha)$	Due to radial pressure on both rolls
$2\mu(p_r \cos\alpha)(\mathrm{d}x/\cos\alpha)$	Due to friction against both rolls

The force balance gives:

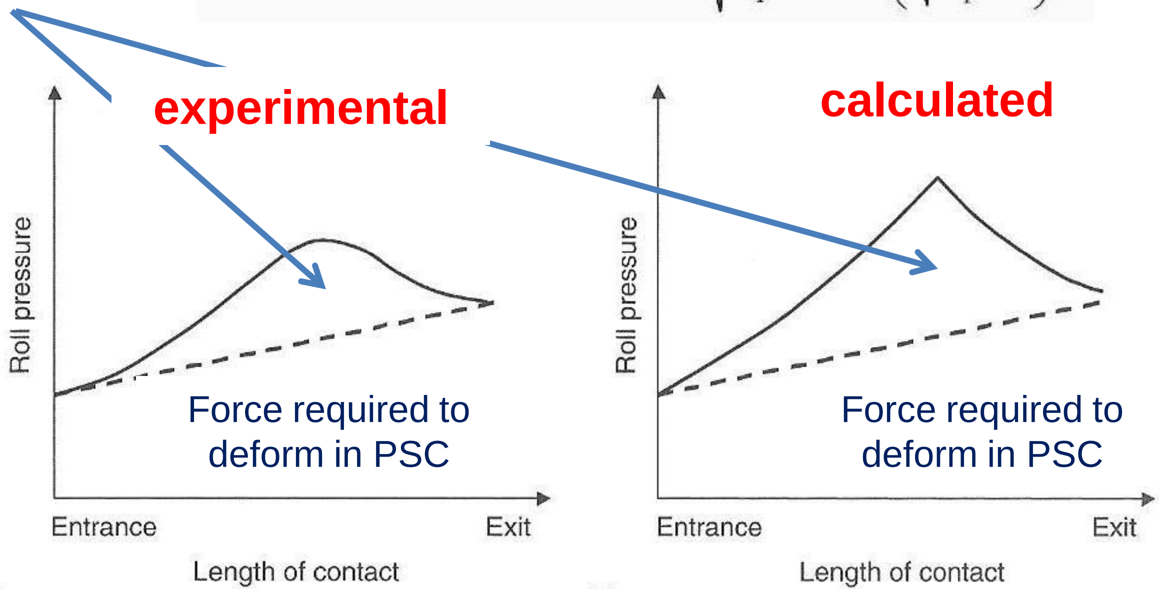
$$h\,\mathrm{d}\sigma_x + \sigma_x\,\mathrm{d}h + 2\mu p_r\,\mathrm{d}x \pm 2\mu p_r\,\mathrm{d}x = 0$$

Rigourous solution to thiis equation require numerical techniques, but an approximate analytiucal solution is given following Bland and Ford (1948) by tacking a small angle approximations sinα=α(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:

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

and on the exit side $$P=\frac{2\sigma_0\cdot h}{\sqrt{3\cdot h_f}}\cdot\exp\left[\mu H\right]$$

where the quantity $$H=2\sqrt{\frac{R}{h_f}\cdot\tan^{-1}\left(\sqrt{\frac{R}{h_f}}\cdot\alpha\right)}$$



Force required to overcome the friction

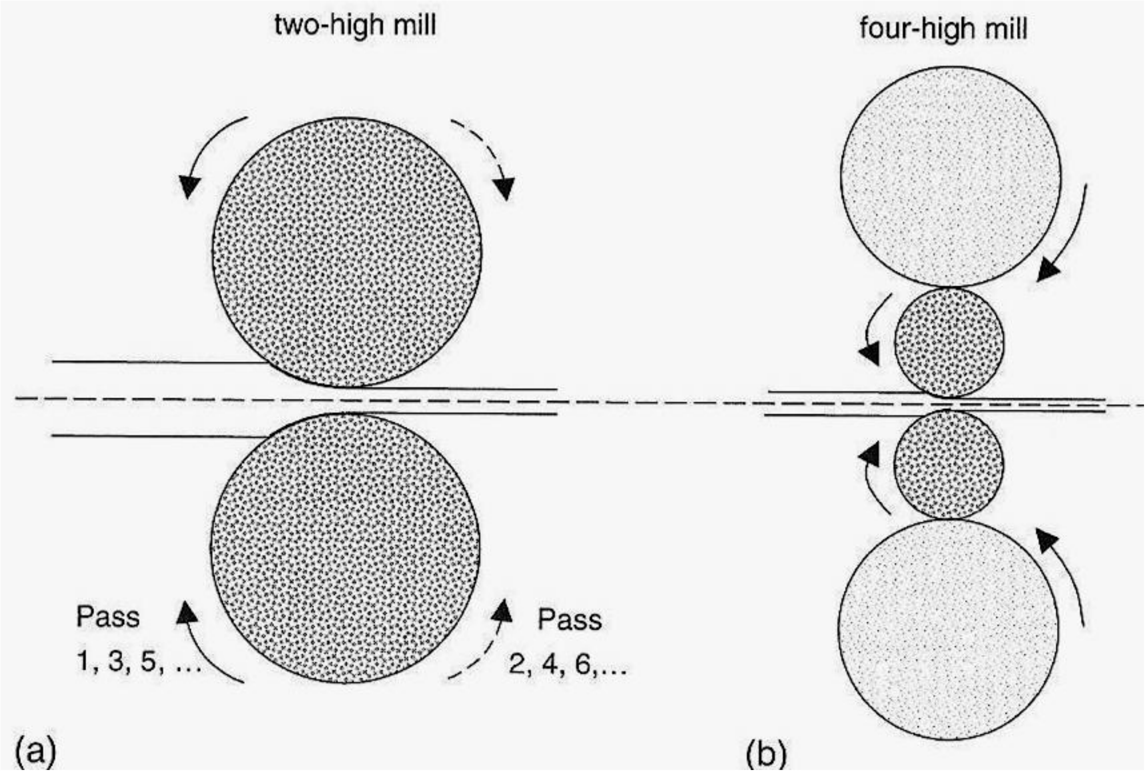
experimental

calculated

Force required to deform in PSC

Force required to deform in PSC

Rolling equipment: for plate, sheet and foils manufacturing



Preliminary milling (reversing)

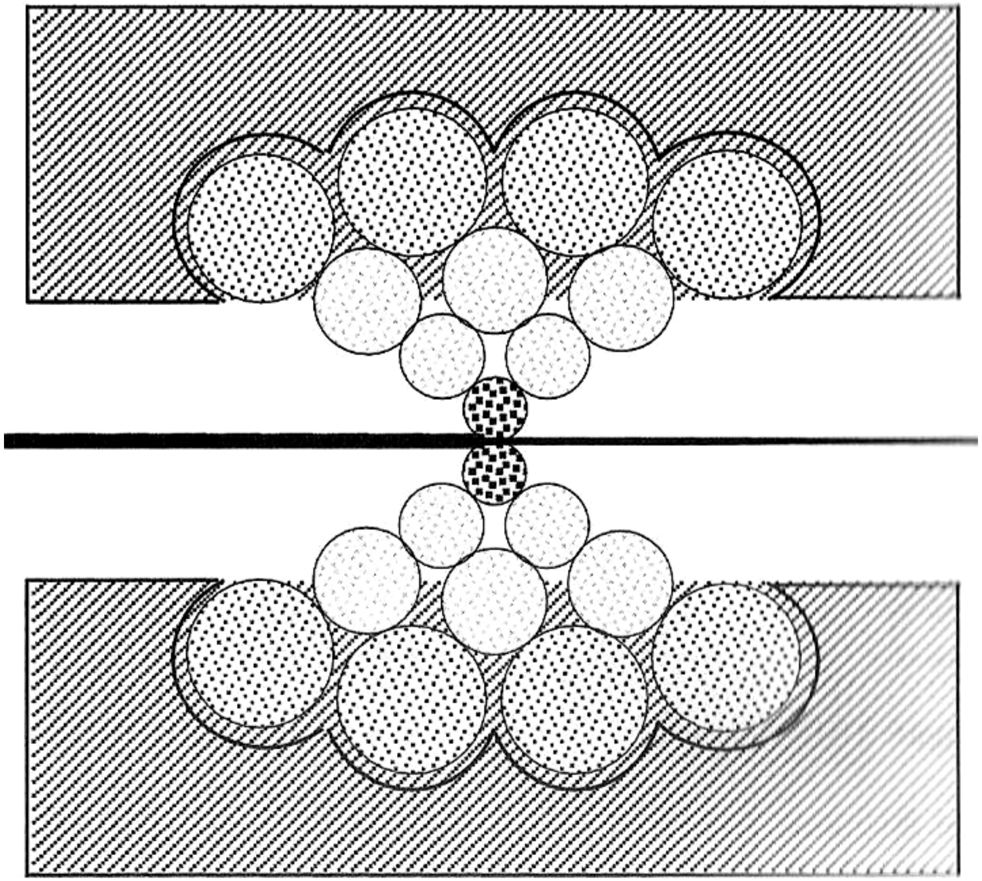
Schematic of a 2-high mill (a) and a 4-high mill (b)

Two-high **reversible** mill in which the direction of rotation of the rolls is reversed after each pass to enable the worpiece to be passed successively backwords 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 passess.

finishing milling (reversing)

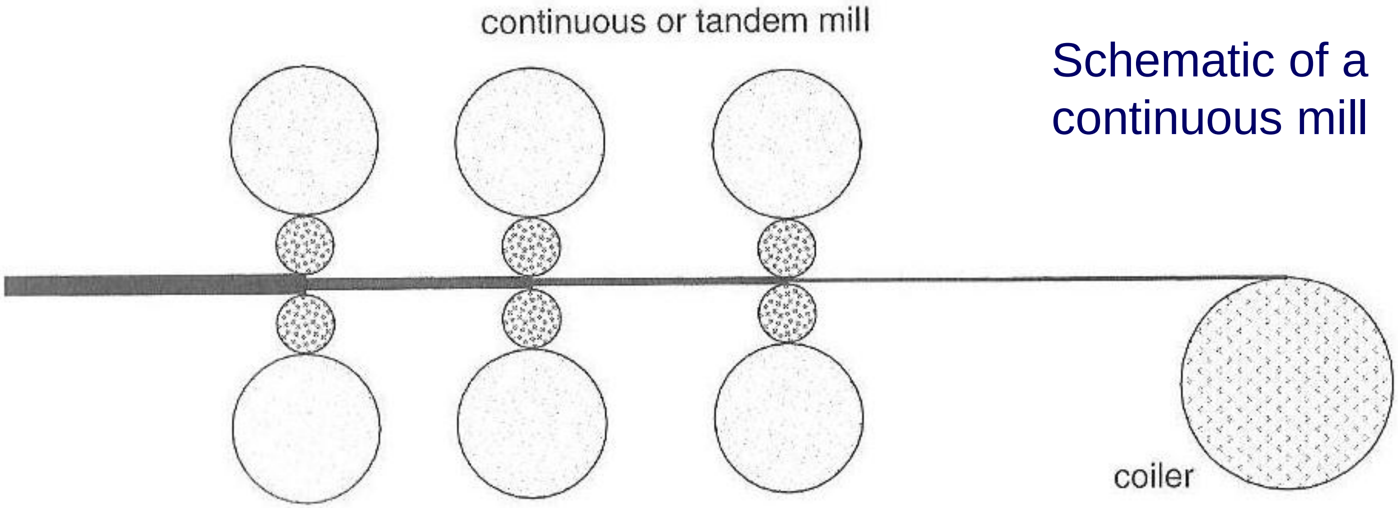


The Sendzimir mill, as an example of a cluster mill

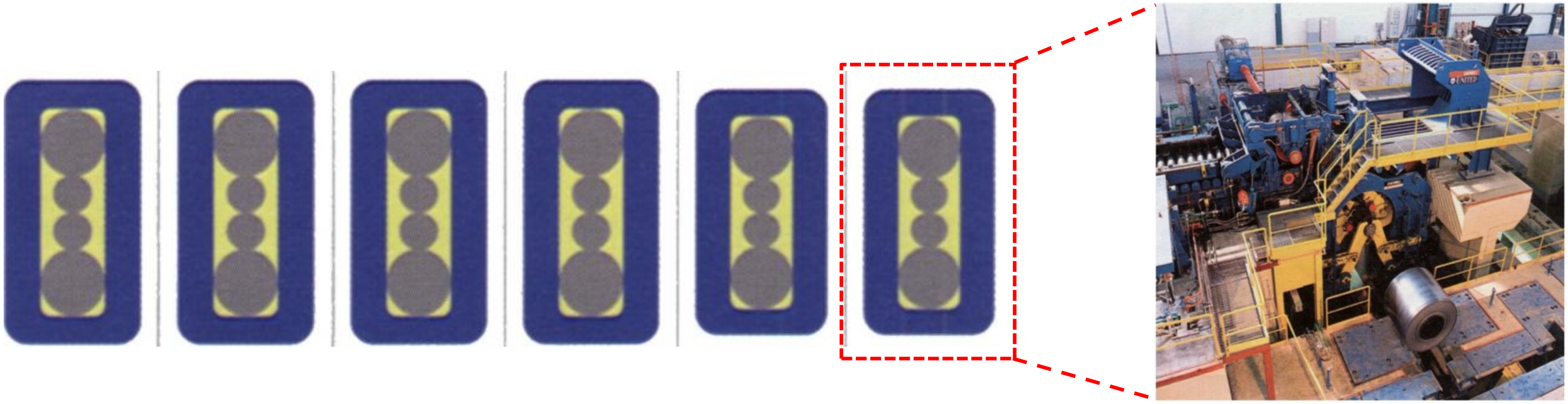
Higher strains per pass are carried out during subsequent rolling operations down to sheet or foil using smaller diameter rolls to reduce the required power. Each roll is supported by two backing rolls.

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.



Schematic of a continuous mill

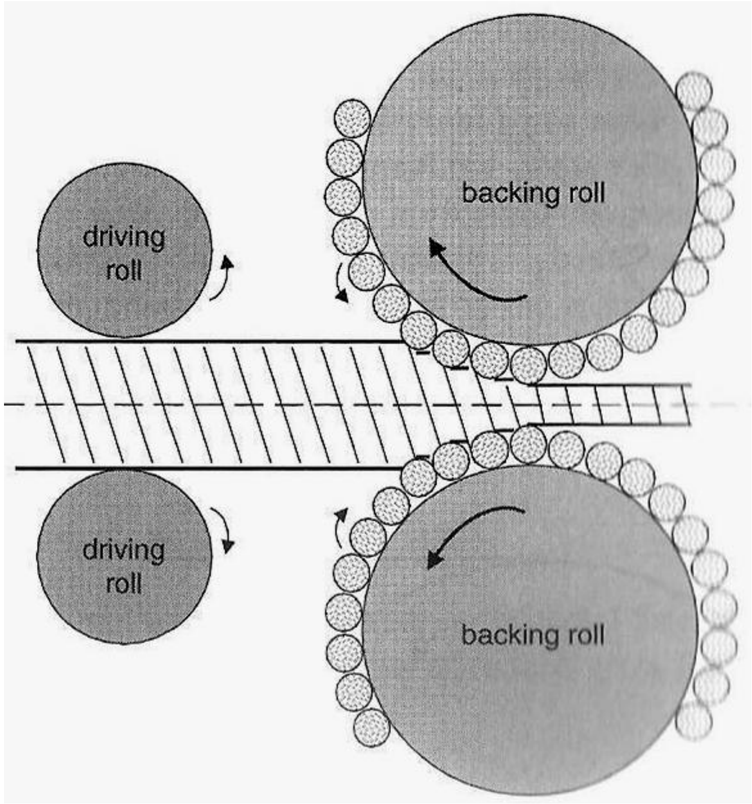


Hot & Cold rolling special cases

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).



Schematic of planetary mill

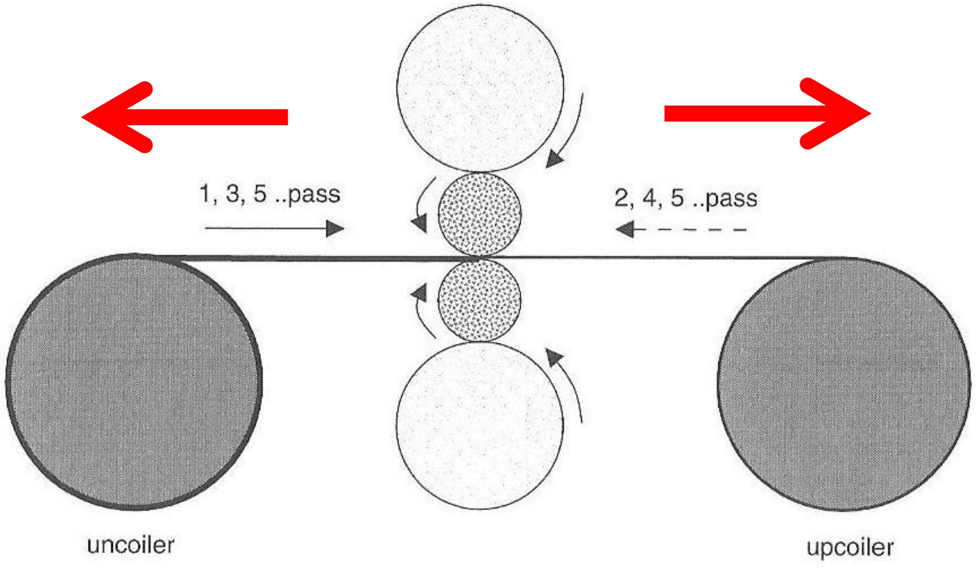
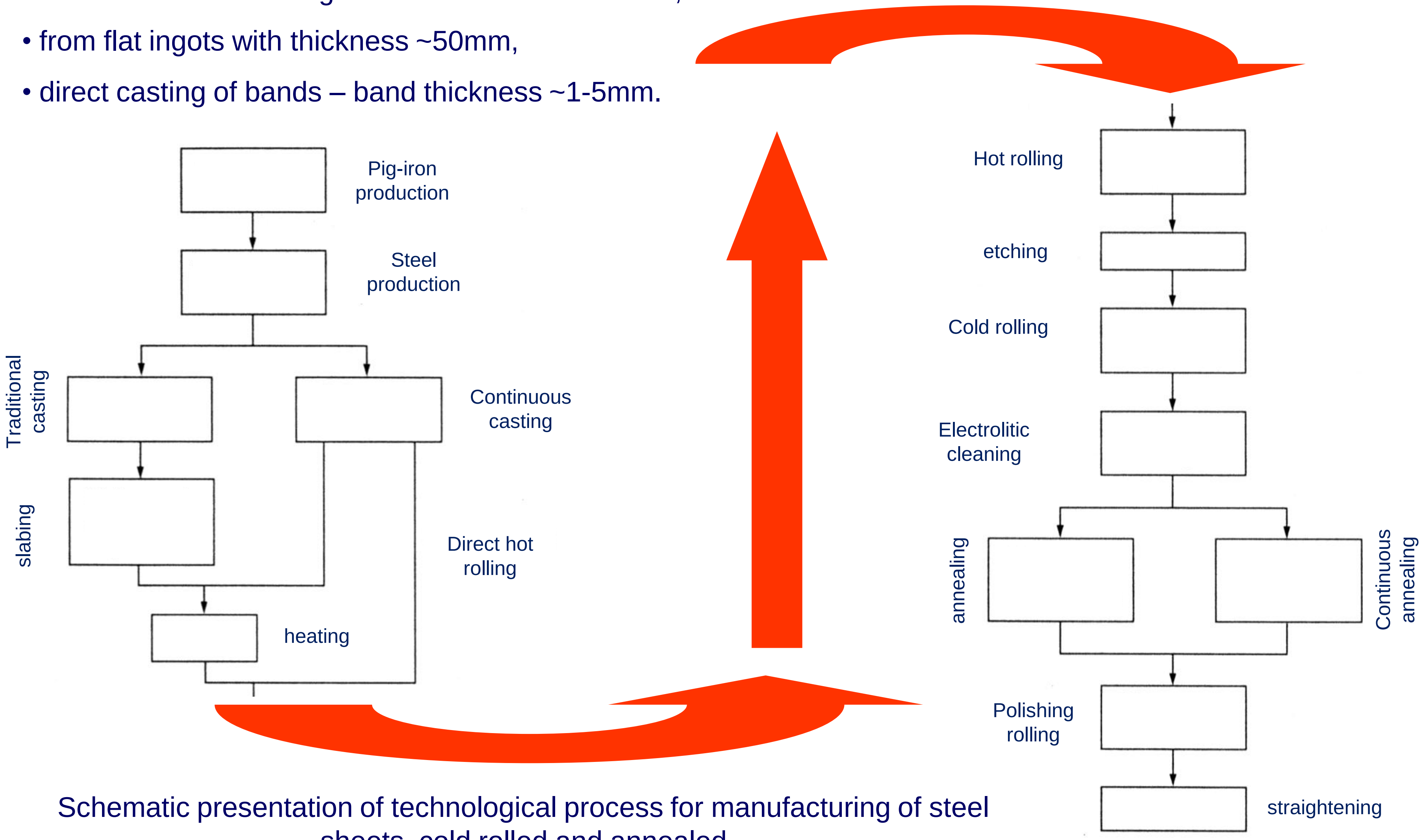


Illustration of a single-stand reversible cold rolling mill

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.



Pig-iron production

Steel production

Traditional casting

Continuous casting

slabing

Direct hot rolling

heating

Hot rolling

etching

Cold rolling

Electrolitic cleaning

annealing

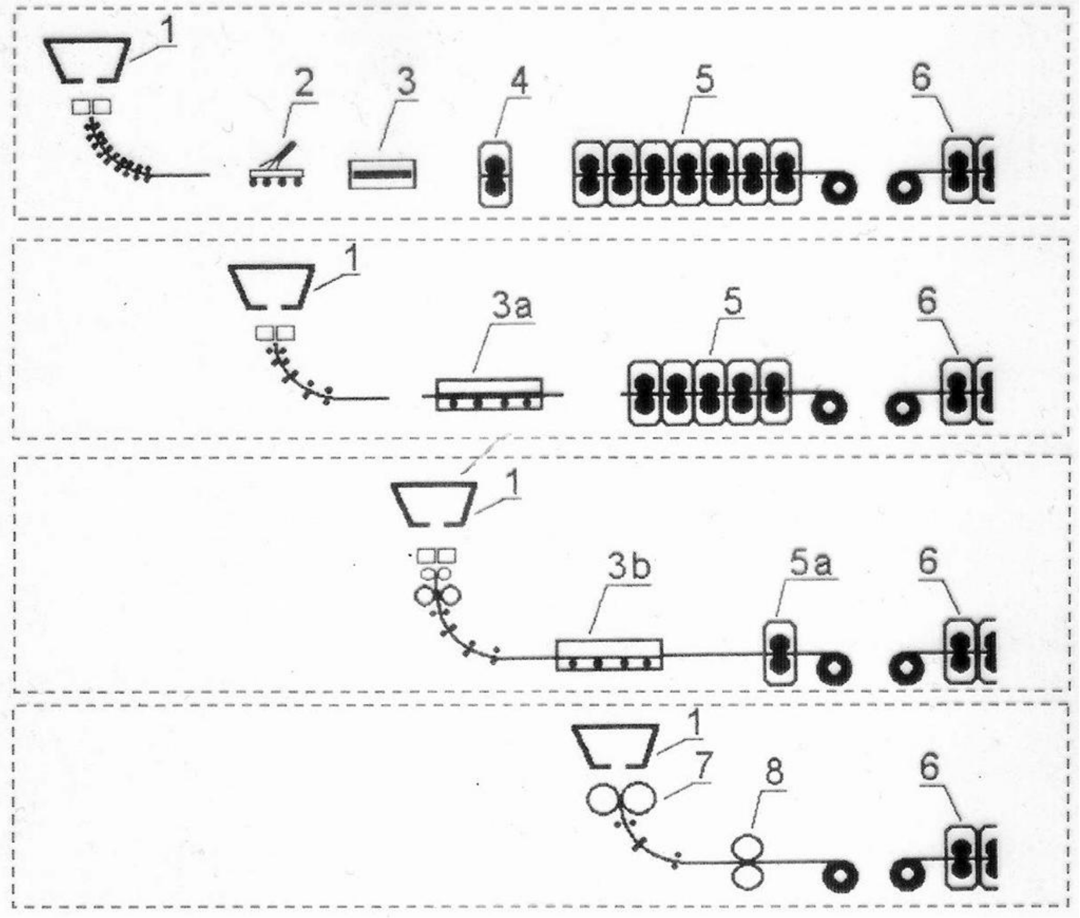
Continuous annealing

Polishing rolling

straightening

Schematic presentation of technological process for manufacturing of steel sheets cold rolled and annealed

Classification of high-production hot strip mills



Initial band thickess – 200-250mm

Initial band thickess – ~50mm

Initial band thickess – ~25mm

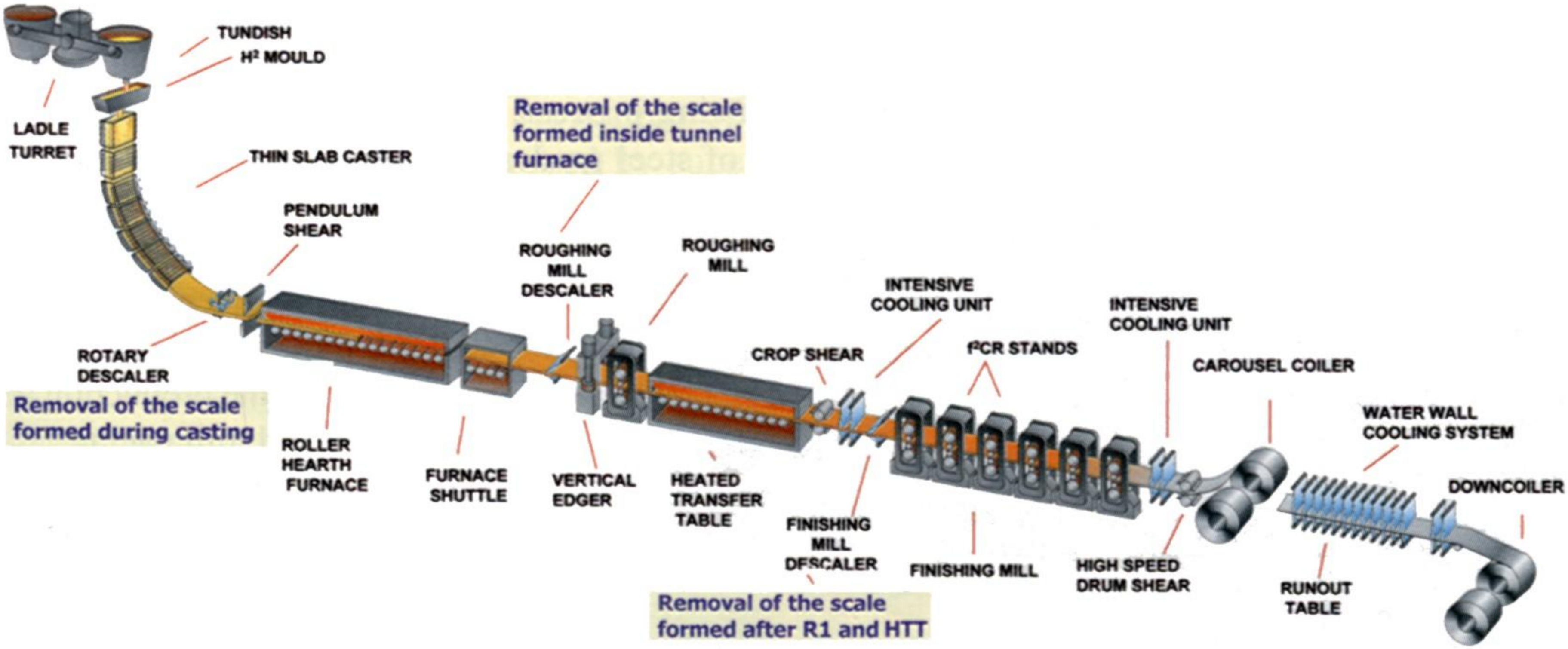
Fully continuous hot strip mill without reduction (initial band thickness – 2-5mm)

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

Rolling lines - Continuous casting + hot rolling for thin sheets production

Integrated line:

Continuous casting → band cutting → heating → hot direct rolling →cooling



Removal of the scale formed inside tunnel furnace

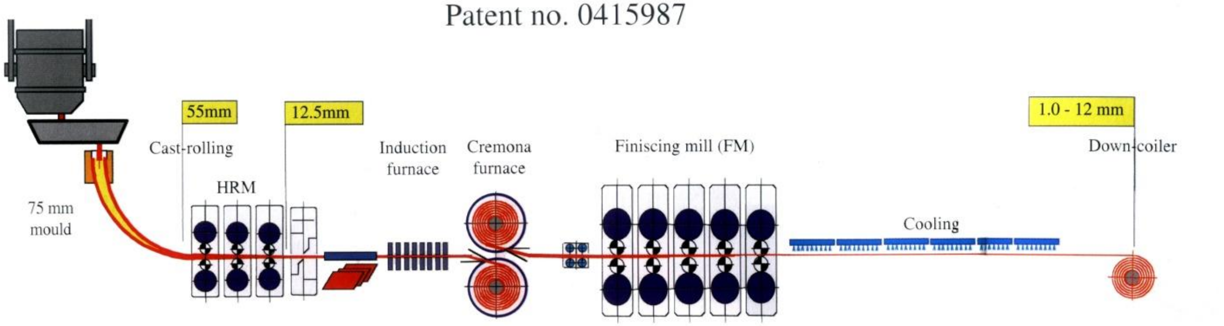
Removal of the scale formed during casting

Removal of the scale formed after R1 and HTT

Modern, integrated line for thin sheets production

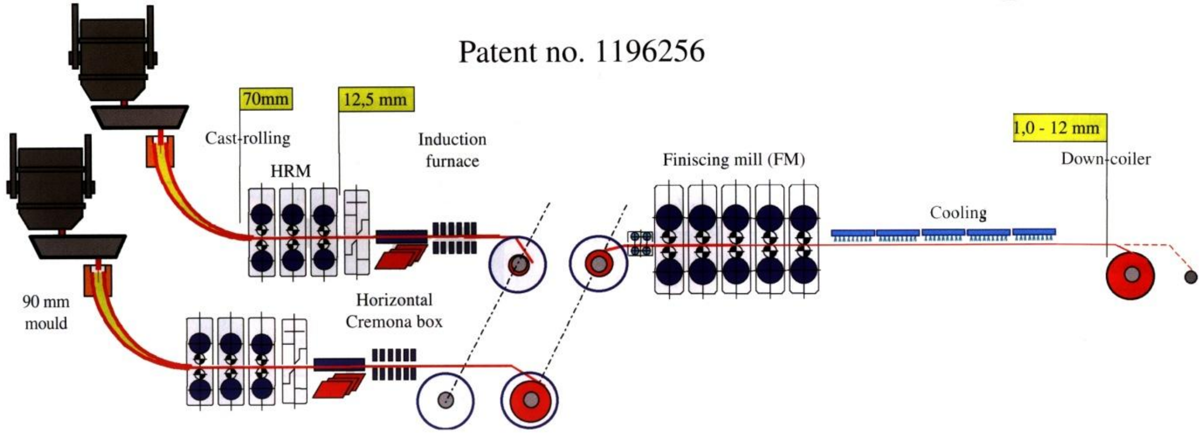
ISP® technology operating since 1992

Patent no. 0415987



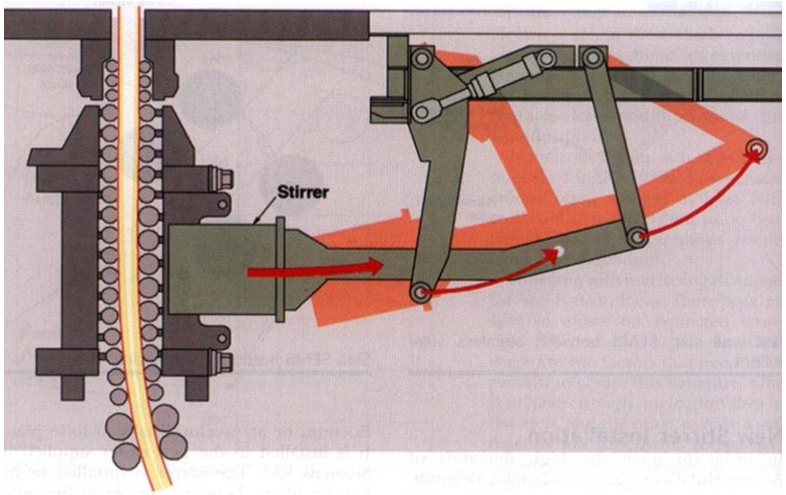
*** Single line, width 1300 mm, 1 million tpy**

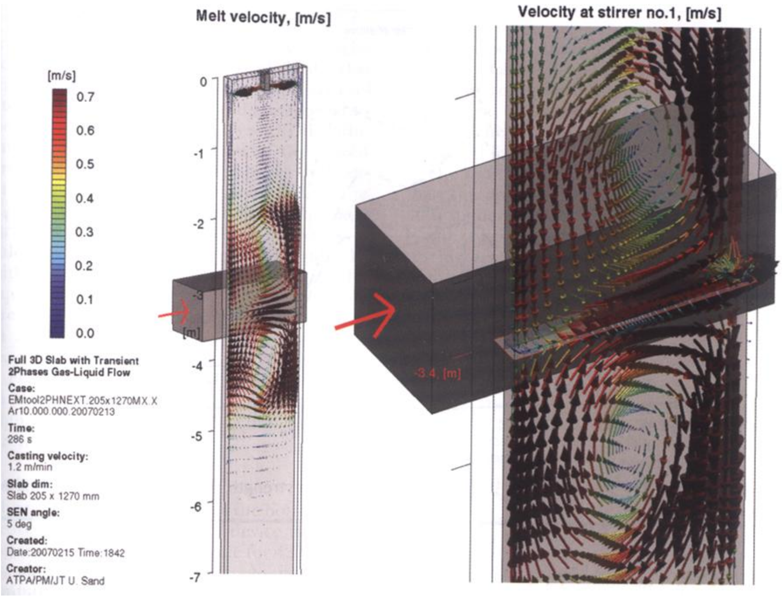
Patent no. 1196256

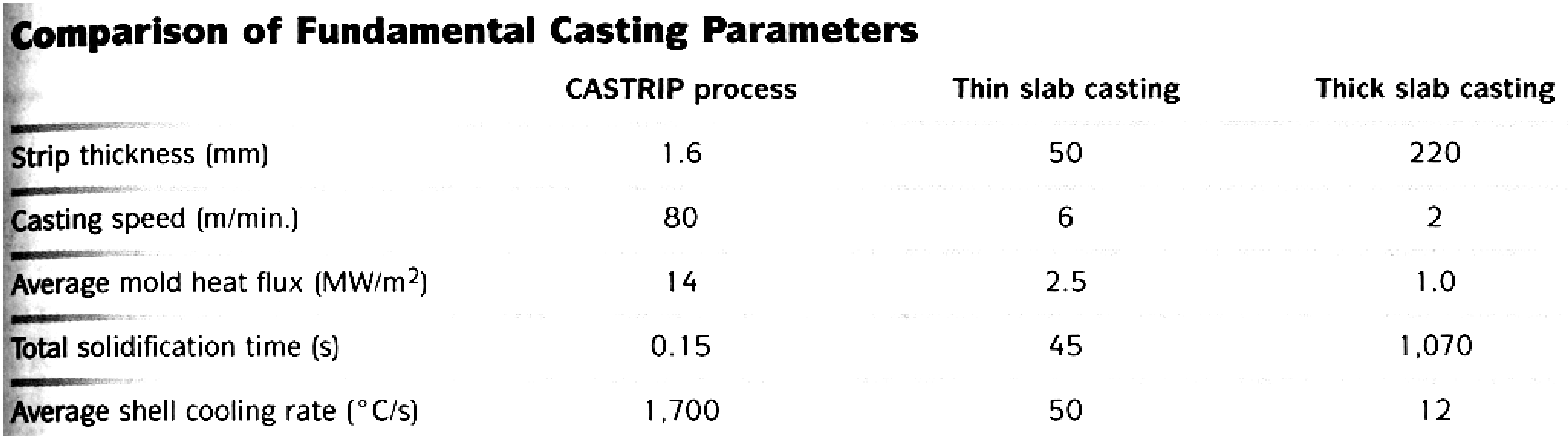


*** Double casting line, width 1850 mm, 3.2 million tpy**

Rolling lines - Continuous casting - devices



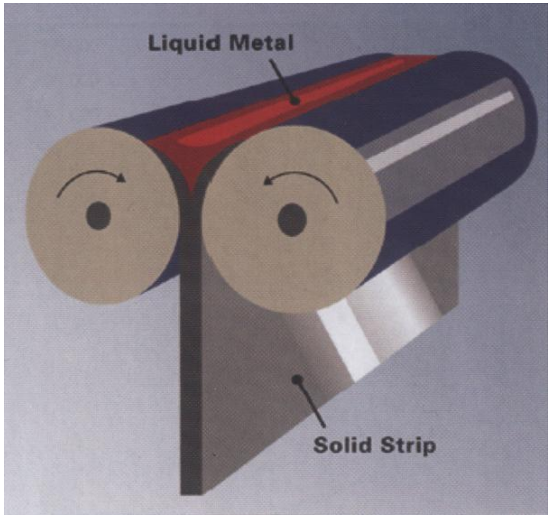


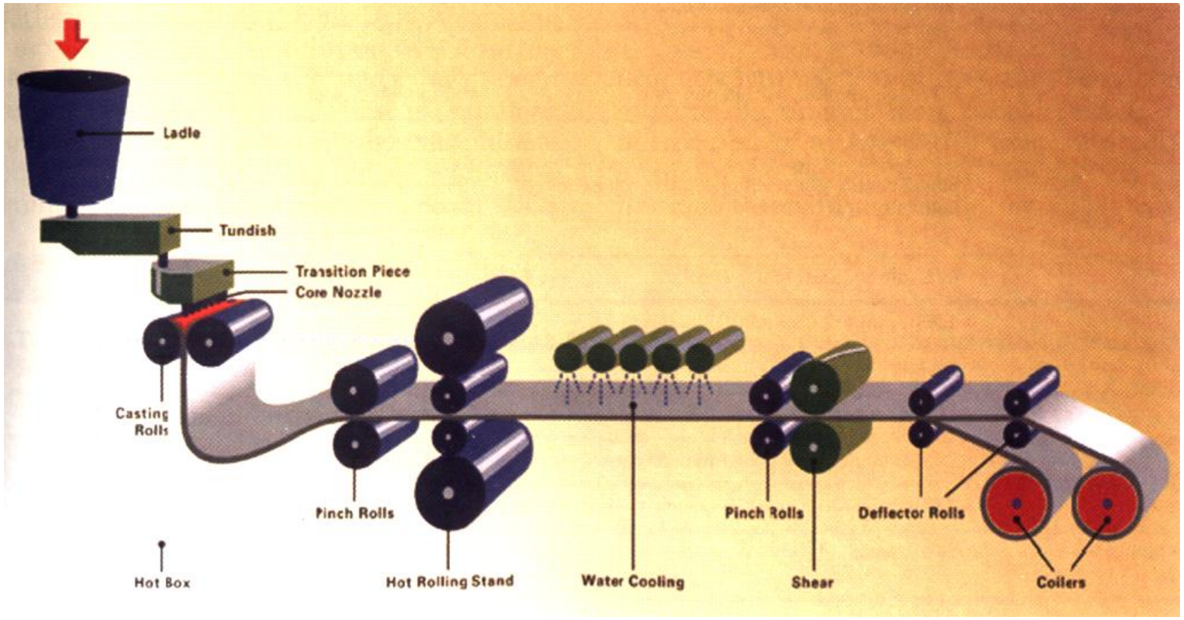


Comparison of Fundamental Casting Parameters

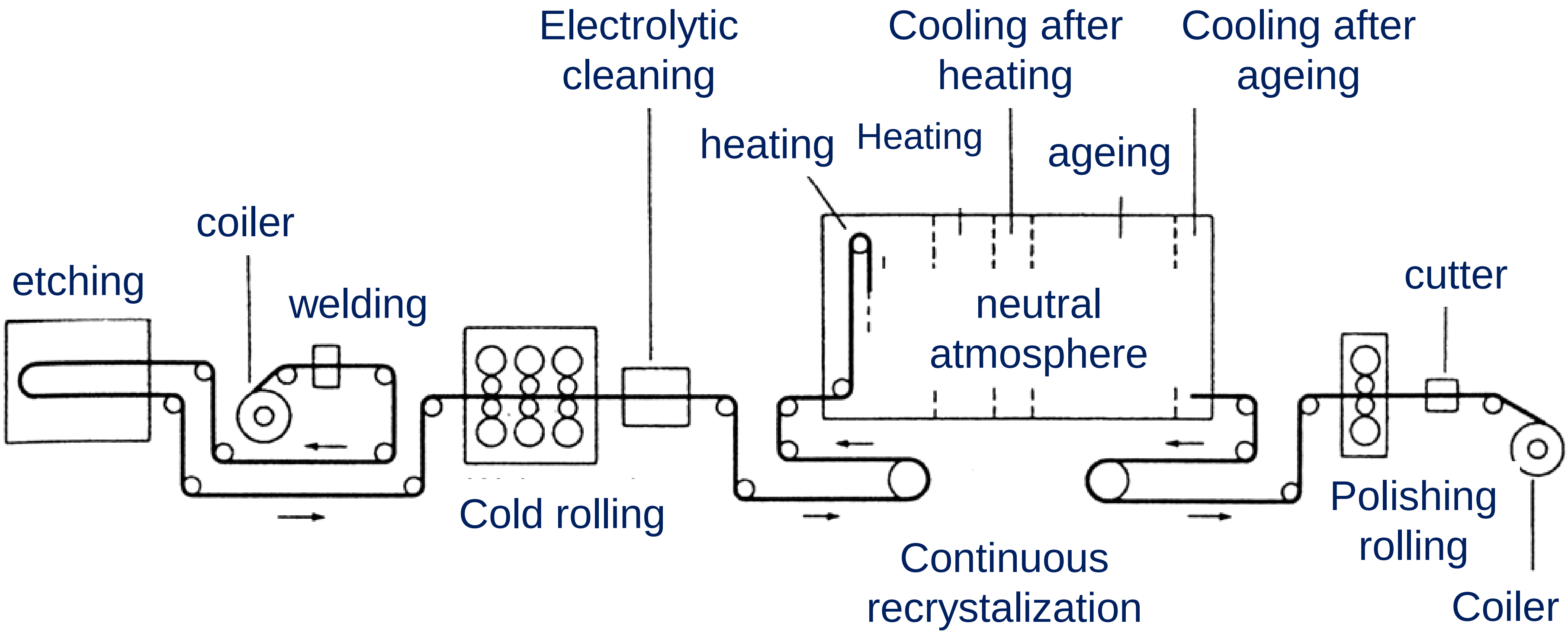
	CASTRIP process	Thin slab casting	Thick slab casting
Strip thickness (mm)	1.6	50	220
Casting speed (m/min.)	80	6	2
Average mold heat flux (MW/m^2)	14	2.5	1.0
Total solidification time (s)	0.15	45	1,070
Average shell cooling rate (°C/s)	1,700	50	12

Rolling lines - Continuous casting + hot rolling for thin sheets production

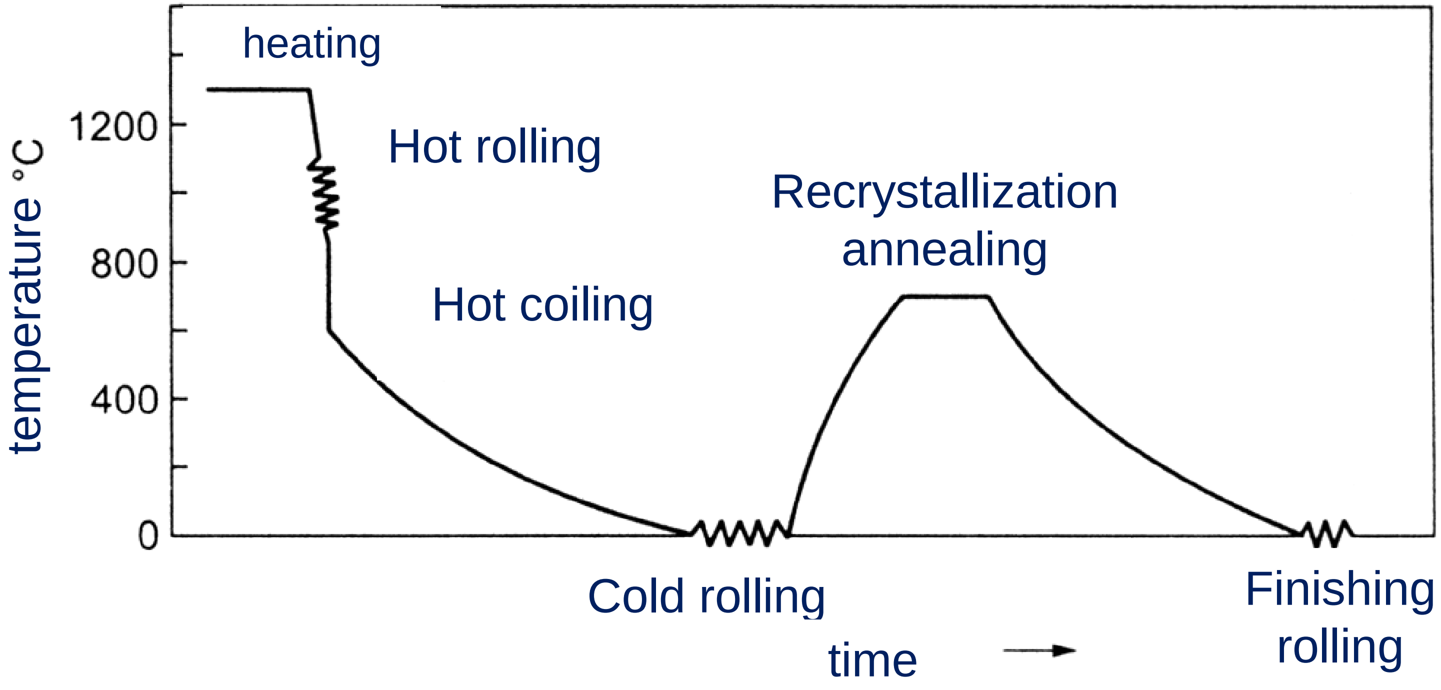




Cold rolling & continuous recrystallization of steel bands

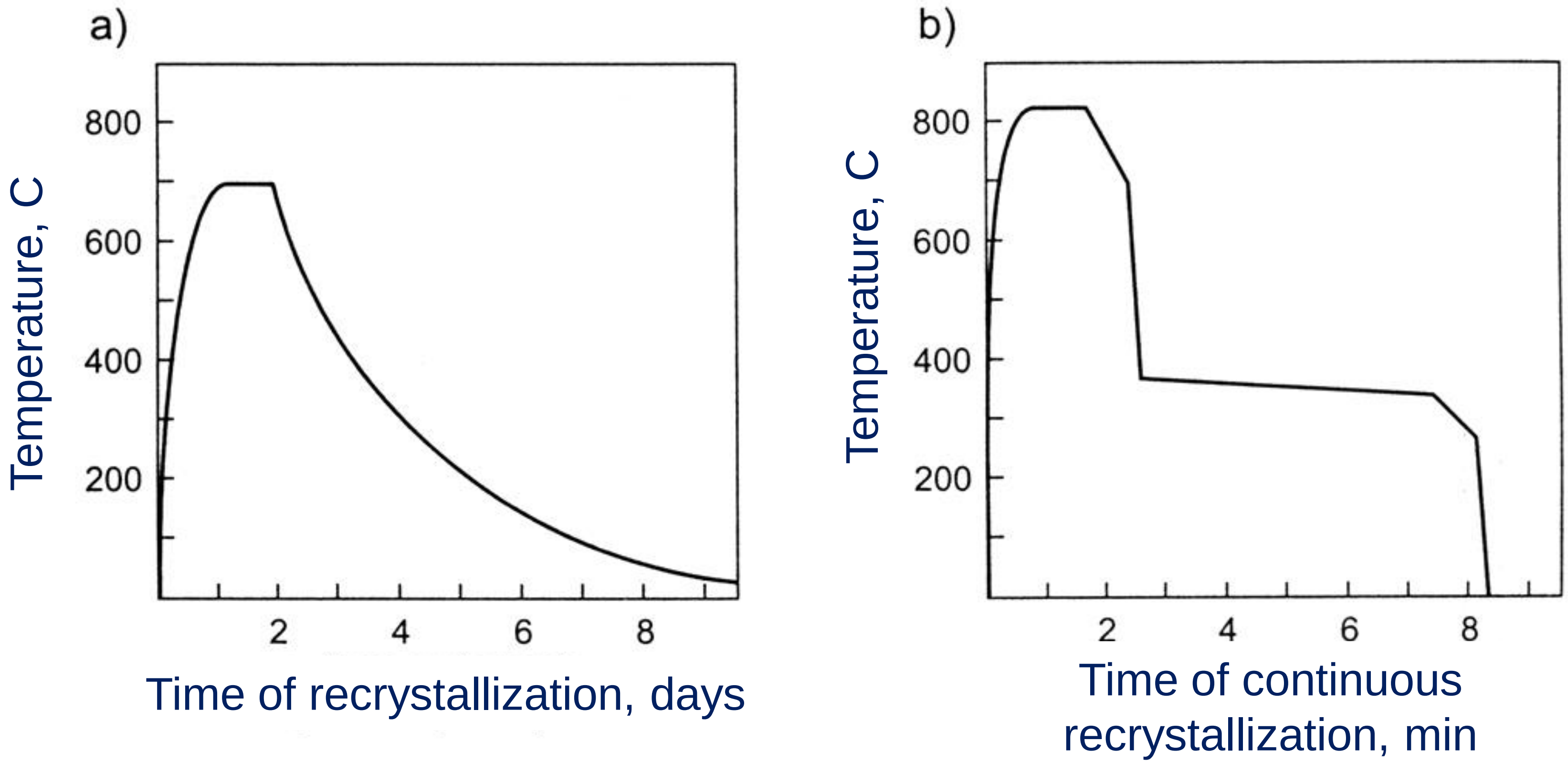


Steels for sheets



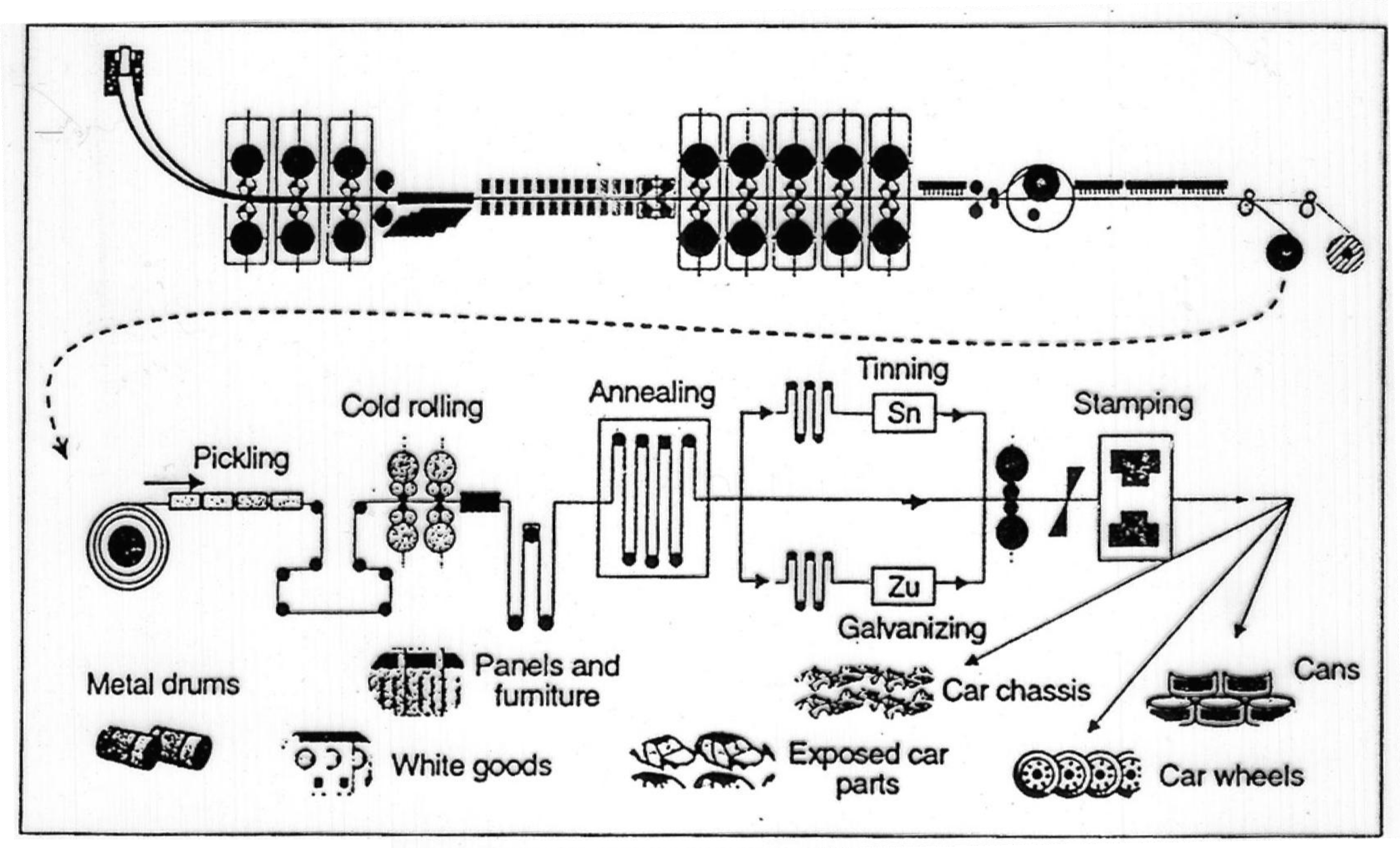
Temperature changes during hot & cold rolling and during recrystallization annealing

Steels for sheets



Temperature changes during recrystallization annealing

Integrated parts production: a look into the future



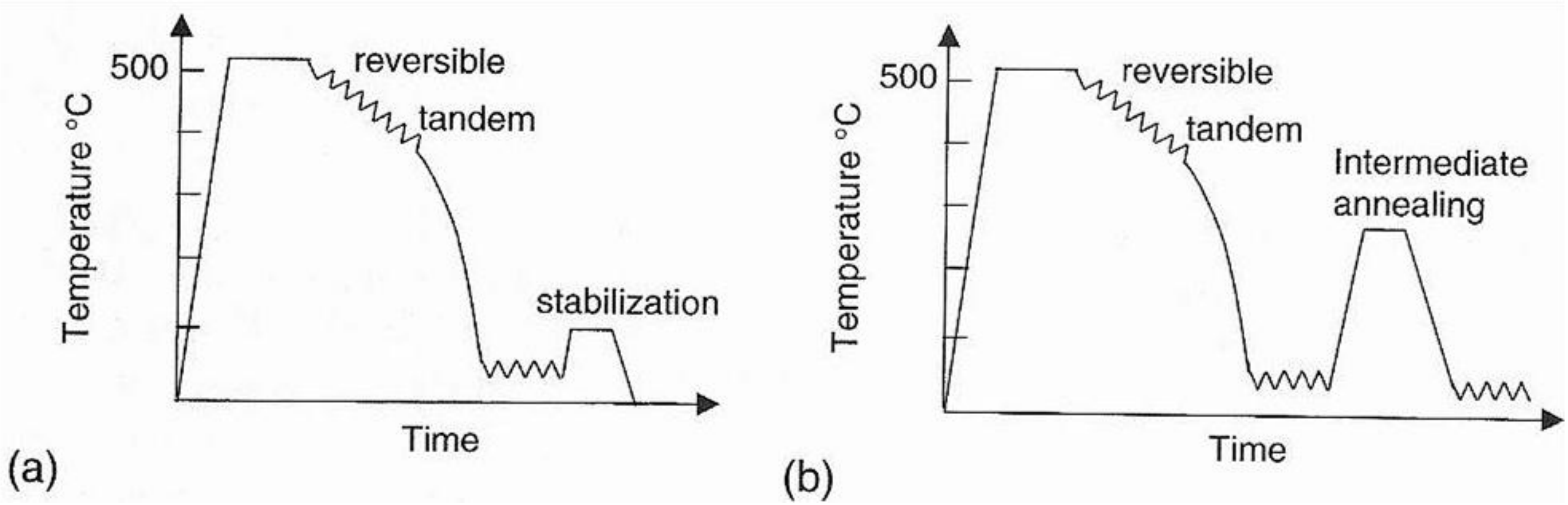
Typical rolling shedules - aluminium

Typical TM process

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

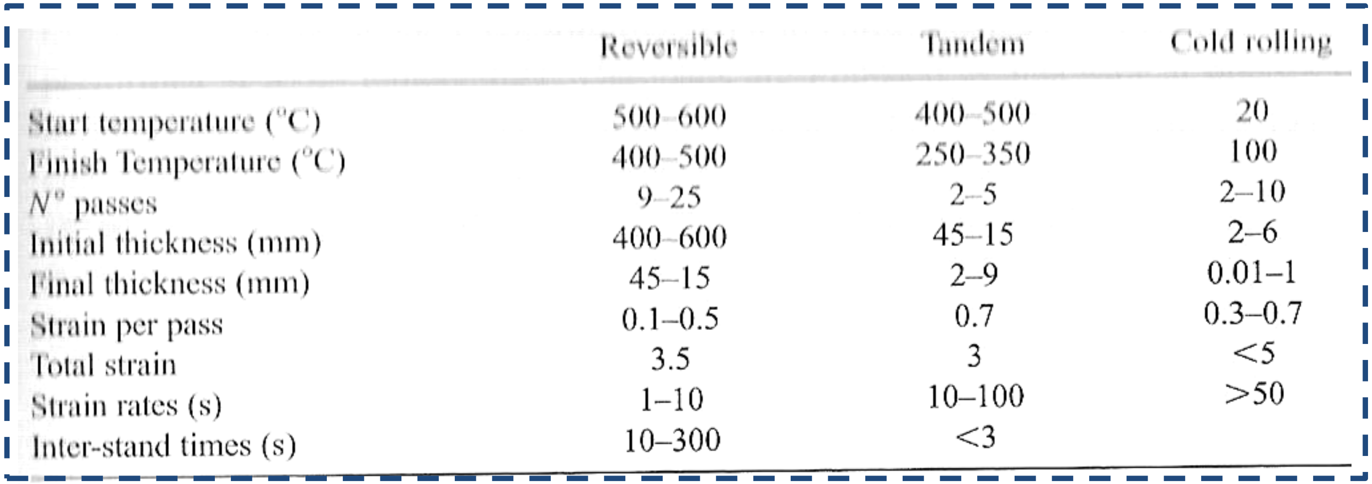
Hot rolling (up to 30-10mm) reversible rolling mill

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).



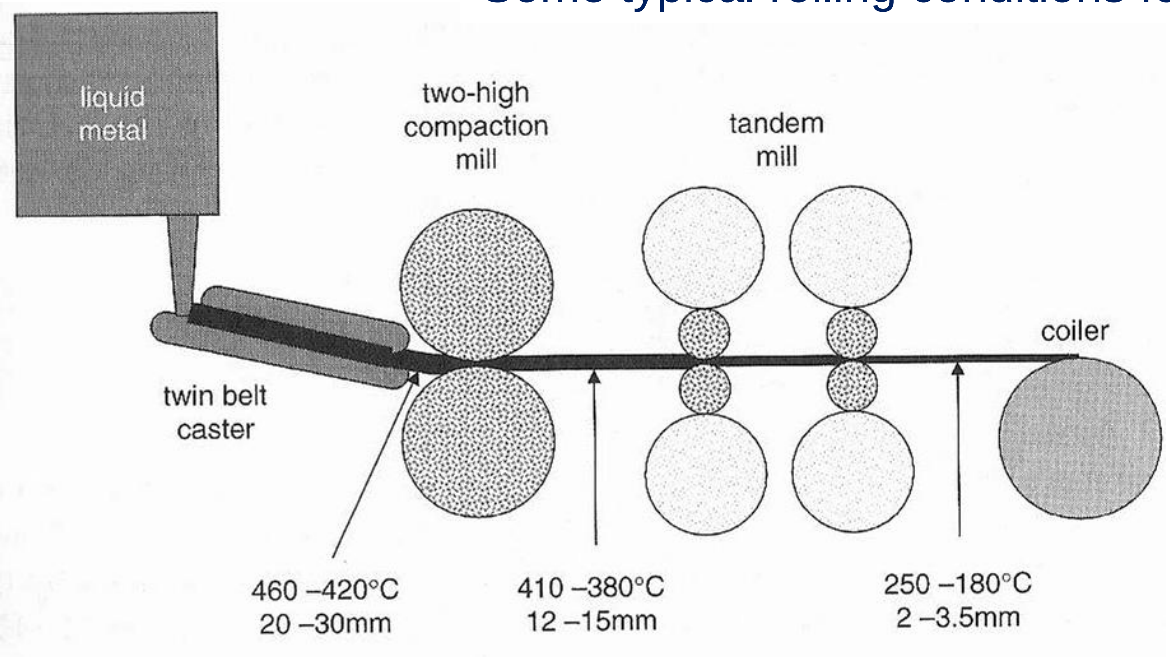
Schematic rolling shedules (**for TMP**) for the production of (a) can stock, (b) foil

Typical rolling shedules - aluminium



	Reversible	Tandem	Cold rolling
Start temperature (°C)	500–600	400–500	20
Finish Temperature (°C)	400–500	250–350	100
N° passes	9–25	2–5	2–10
Initial thickness (mm)	400–600	45–15	2–6
Final thickness (mm)	45–15	2–9	0.01–1
Strain per pass	0.1–0.5	0.7	0.3–0.7
Total strain	3.5	3	<5
Strain rates (s)	1–10	10–100	>50
Inter-stand times (s)	10–300	<3	

Some typical rolling conditions for Al alloys



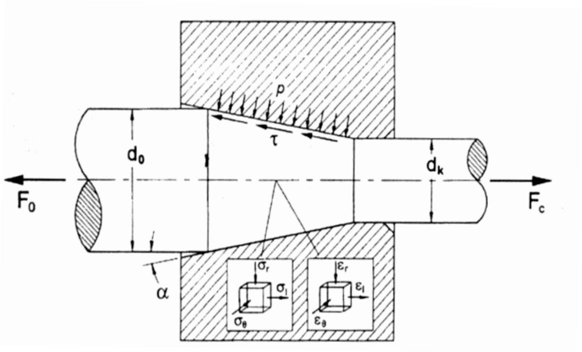
An increased proportion of the less strongly alloyed sheet products are now produced by continuous strip casting

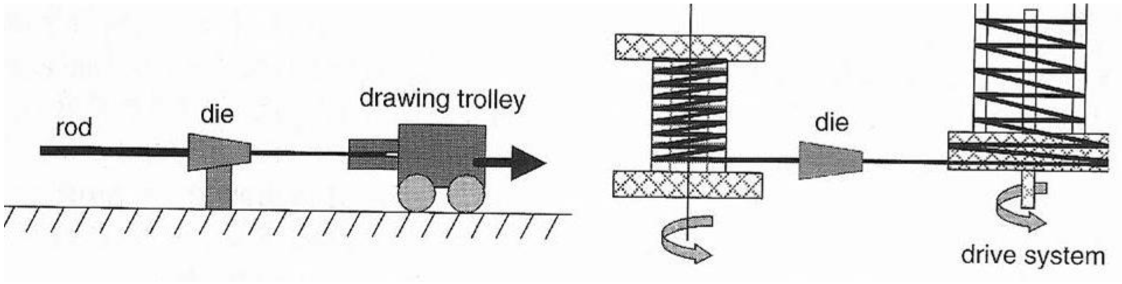
Schematic continuous strip casting line

Wire drawing

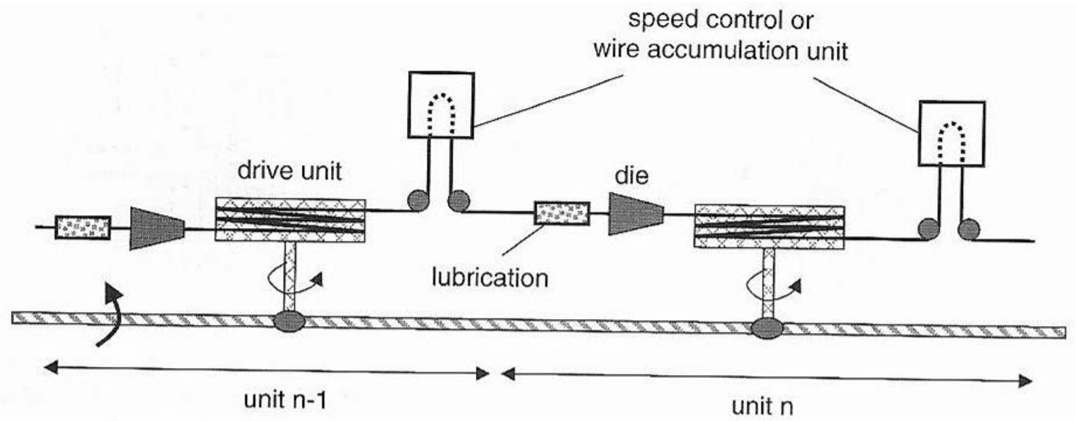
In a industrial production lines, a large reduction is obtained by pulling the wire or rod through a series of consequtive dies. In some cases an intermediate annealing treatment may be necessary.

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



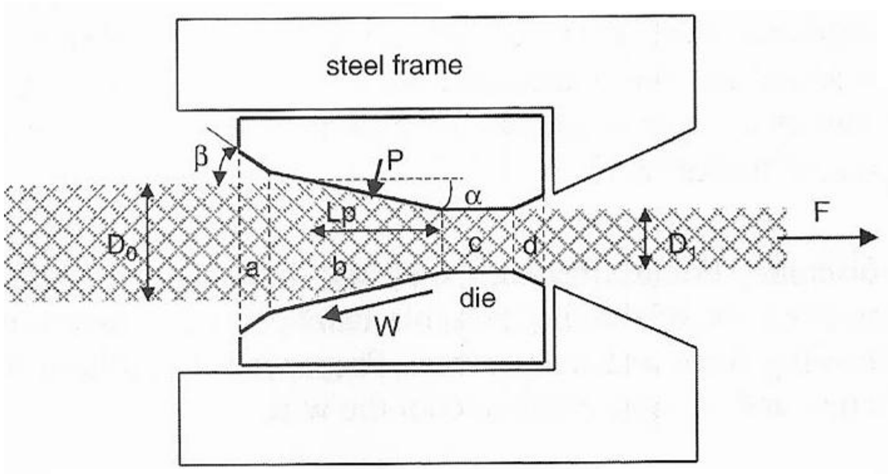


Draw bench (left) and single pass drawing equipment (right)



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

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

Parameter that express the degree of reduntant deformation (mean wire diameter in the defromation zone)

The driving force & the fracture stress

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

Friction stress

Siebel formula (1947)

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

Hoffman & Sachs formula (1947)

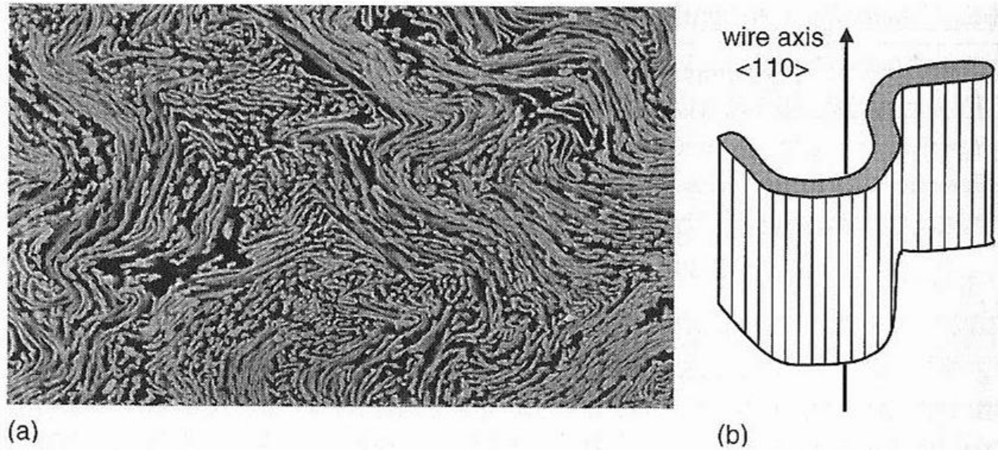
$$\sigma_F = \Phi\sigma_f\varepsilon(1 + \mu \cot g\alpha) \quad \text{with } \Phi = \frac{\Delta}{6} + 1$$

where: α in deg

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 lineary with strain.



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

Wire texture of bcc metals - <011> direction || wire axis (fibre texture)

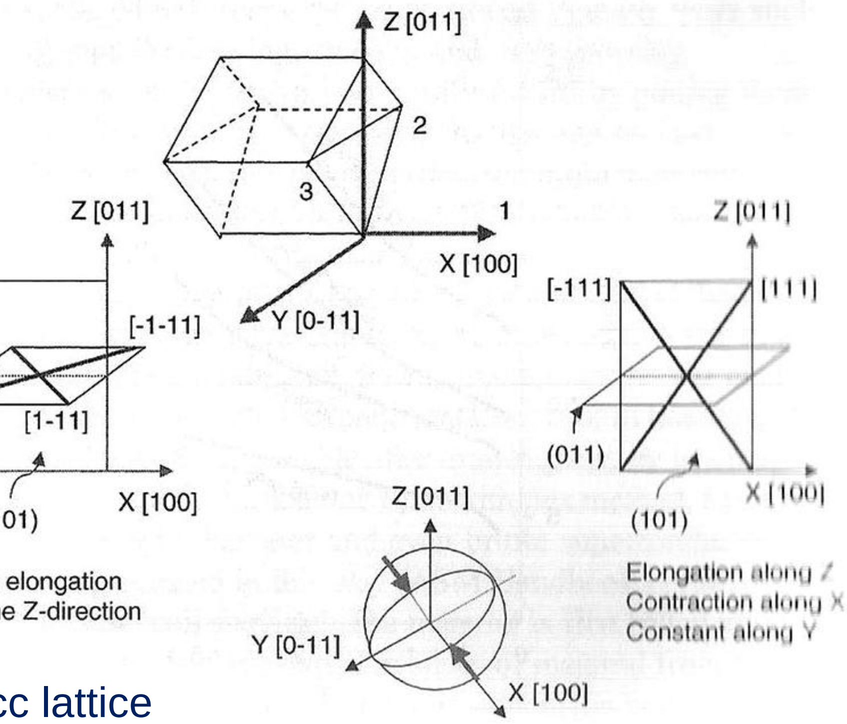


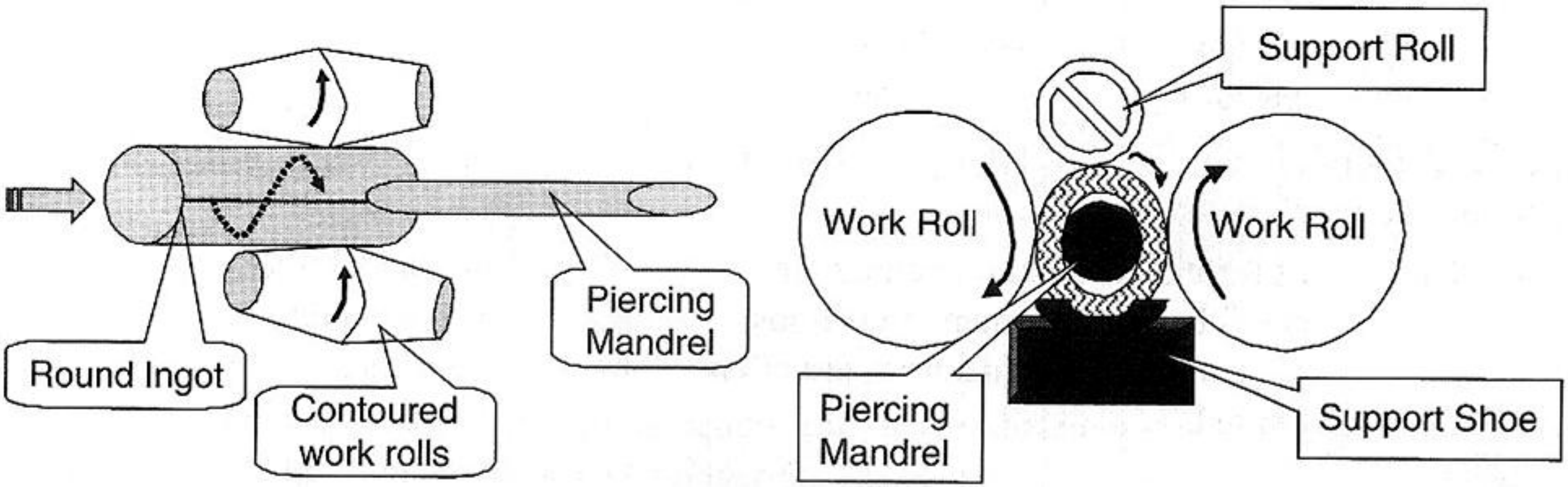
Illustration of the <111> slip directions in a bcc lattice with the [011] direction parallel to wire axis

‘Pierce rolling’

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

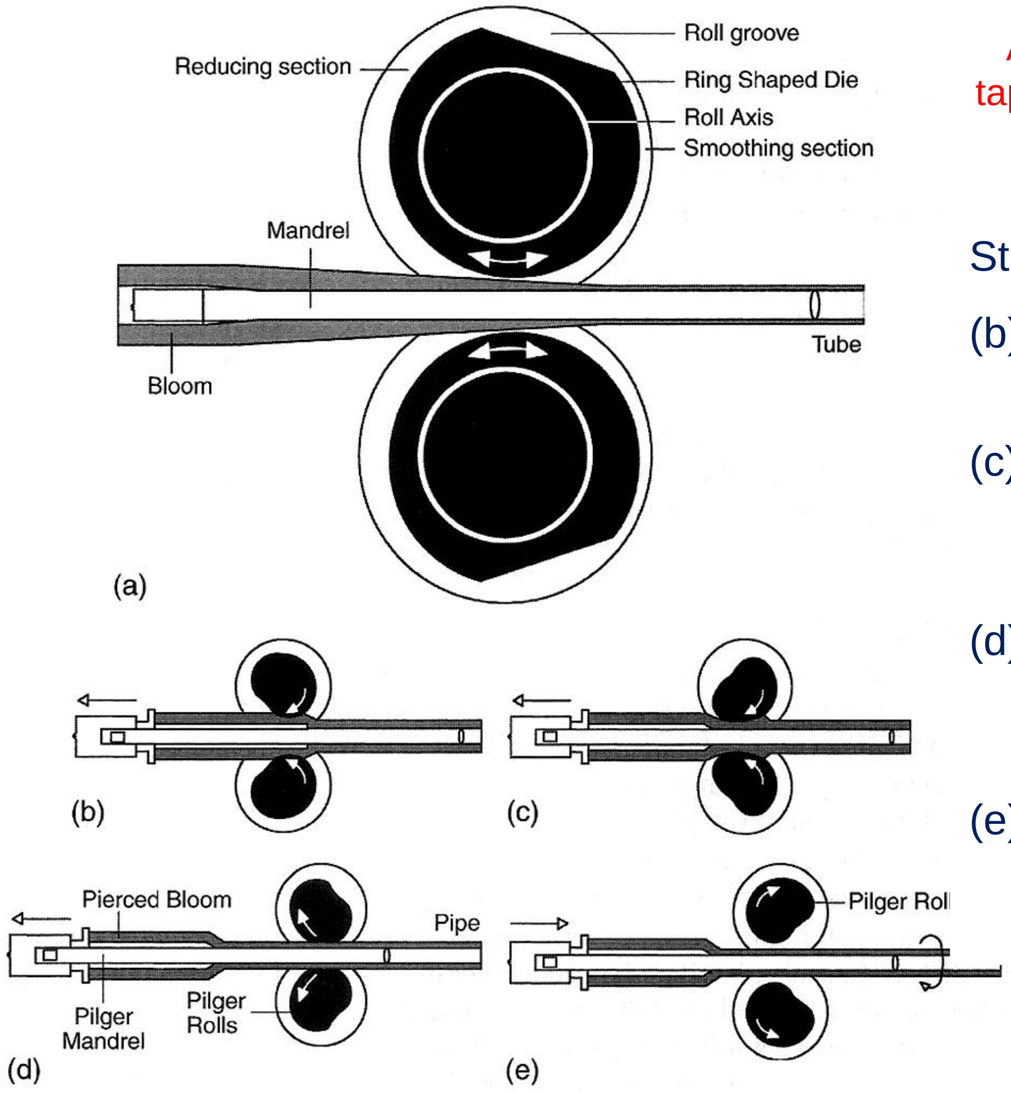
These work rolls are typically placed at an angle of 3-6deg around the hot billet.

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 axisymetric mandrel.

Stages:

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

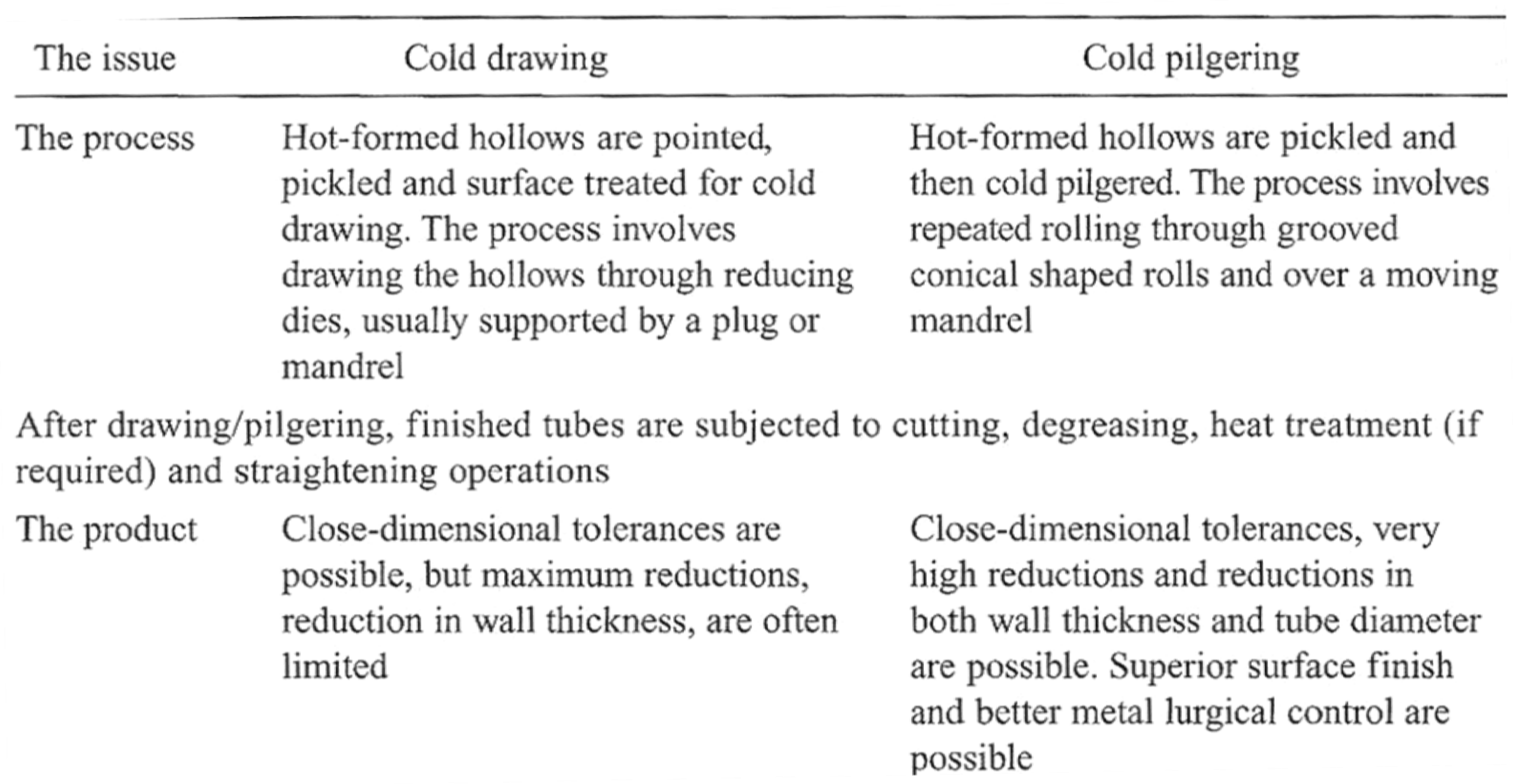
(c) Forging or pilgering – the grooved rolls forge out a small wave of material to the desired wall thickness

(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 hpllow 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

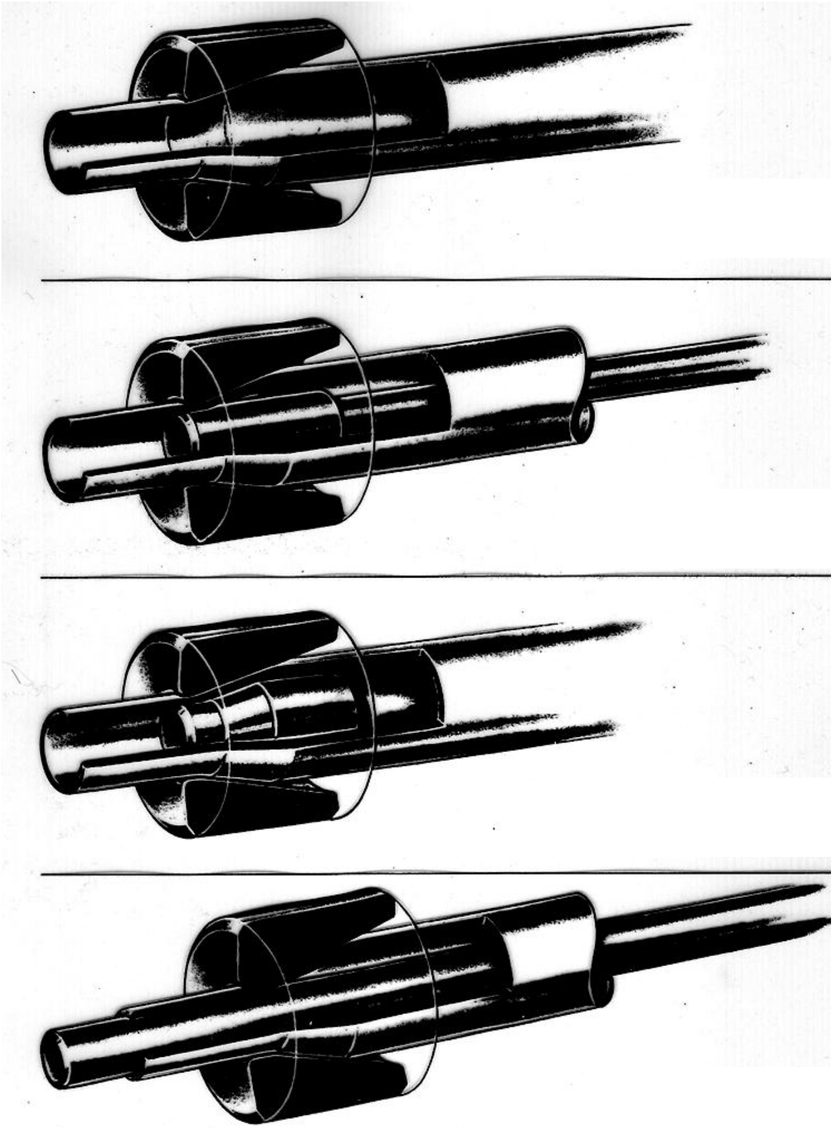


The issue	Cold drawing	Cold pilgering
The process	Hot-formed hollows are pointed, pickled and surface treated for cold drawing. The process involves drawing the hollows through reducing dies, usually supported by a plug or mandrel	Hot-formed hollows are pickled and then cold pilgered. The process involves repeated rolling through grooved conical shaped rolls and over a moving mandrel
After drawing/pilgering, finished tubes are subjected to cutting, degreasing, heat treatment (if required) and straightening operations		
The product	Close-dimensional tolerances are possible, but maximum reductions, reduction in wall thickness, are often limited	Close-dimensional tolerances, very high reductions and reductions in both wall thickness and tube diameter are possible. Superior surface finish and better metal lurgical control are possible

Summary:

typical advantages of pilgering involve reduced processing stages, superior product quality and excelent formability (i.e. high reductions are possible without intermediate annealing)

Tubes calibration - tubes drawing

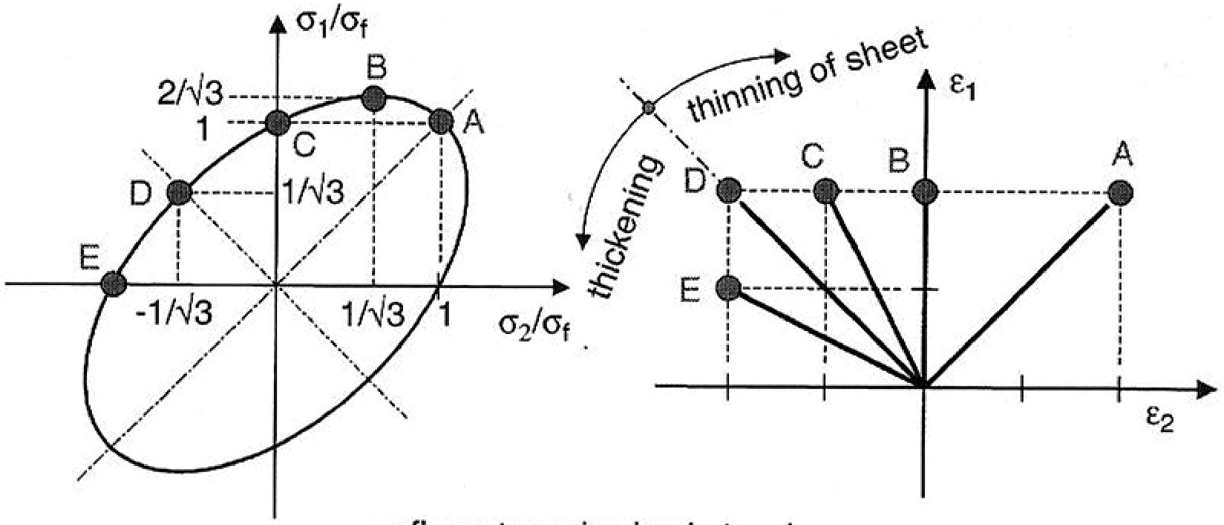


Sheet metal forming

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, aicraft 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, streching and deep drawing.



σ_f: flow stress in simple tension

A
Equal biaxial stretching
$\sigma_1 = \sigma_2 = \sigma_f$
$\varepsilon_2 = \varepsilon_1$ and $\varepsilon_3 = -2\varepsilon_2$

B
Plane strain
$\sigma_1 = (2/\sqrt{3})\sigma_f$
$\sigma_2 = (1/\sqrt{3})\sigma_f$
$\varepsilon_2 = 0$ and $\varepsilon_3 = -\varepsilon_1$

C
Uniaxial stretching
$\sigma_1 = \sigma_f \quad \sigma_2 = 0$
$\varepsilon_2 = \varepsilon_3 = -\varepsilon_1/2$

D
Drawing
(constant thickness)
$\sigma_1 = (1/\sqrt{3})\sigma_f$
$\sigma_2 = (-1/\sqrt{3})\sigma_f$
$\varepsilon_2 = -\varepsilon_1 \quad \varepsilon_3 = 0$

E
Uniaxial compression
$\sigma_1 = 1 \quad \sigma_2 = -\sigma_f$
$\varepsilon_2 = -2\varepsilon_1 \quad \varepsilon_3 = \varepsilon_1$

Anizotropy

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

$$r = \frac{\varepsilon_2}{\varepsilon_3} = \frac{\ln \frac{b}{b_0}}{\ln \frac{g}{g_0}} \qquad r = \frac{\varepsilon_2}{\varepsilon_3} = \frac{\ln \frac{b}{b_0}}{\ln \frac{l_0 b_0}{lb}}$$

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:

$$r_m = \frac{r_o + 2r_{45} + r_{90}}{4}$$

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:

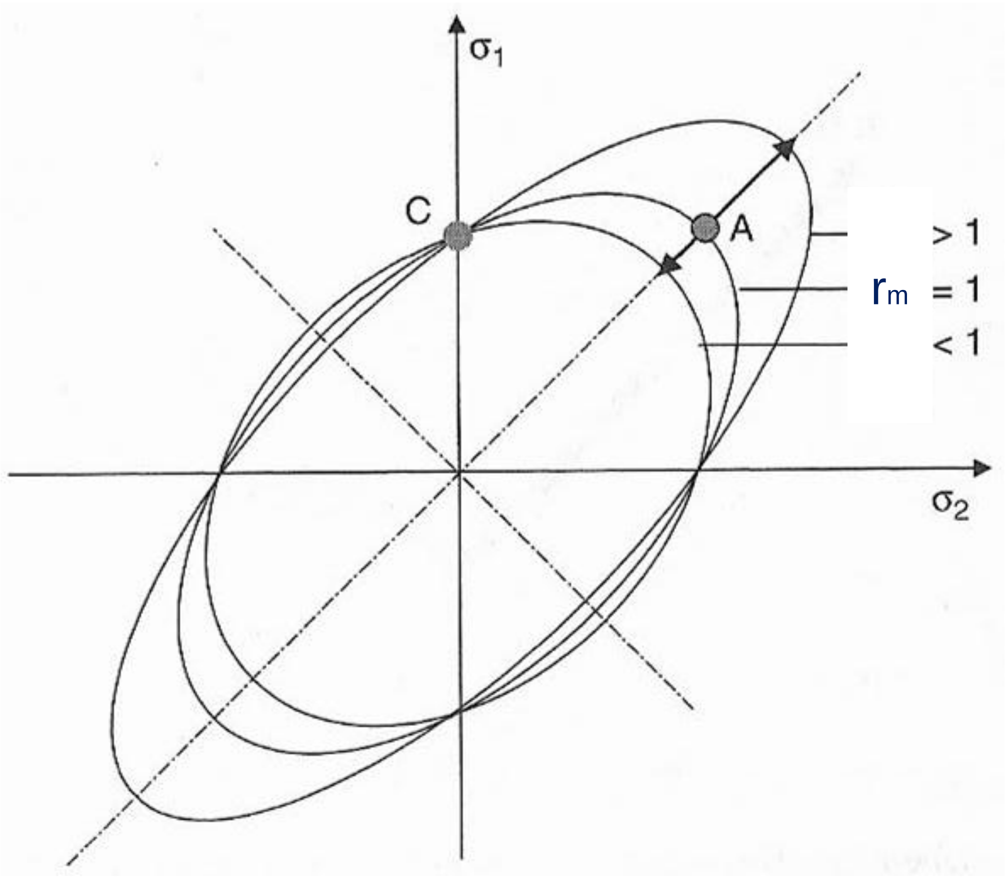
$$\Delta r = \frac{r_0 + r_{90} - 2r_{45}}{4}$$

Hardening coefficient 'n':

$$\sigma = k\varepsilon^n$$

Anizotropy

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



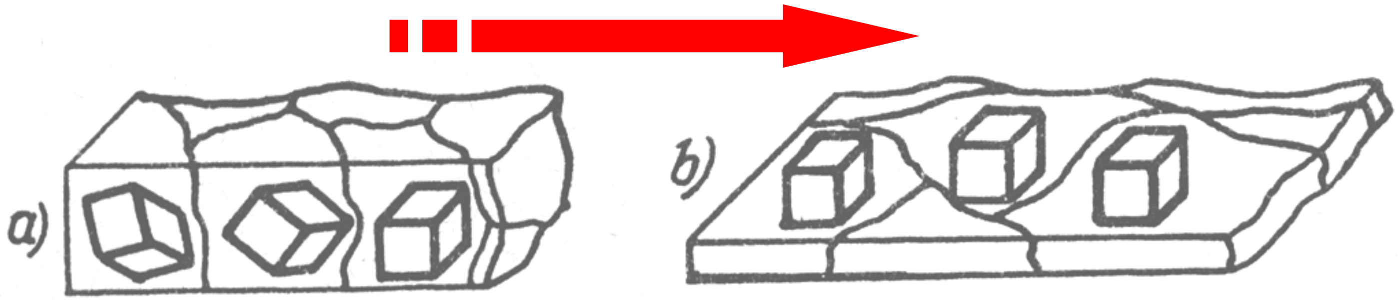
Plastic anisotropy will change the shape of the yield locus.

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

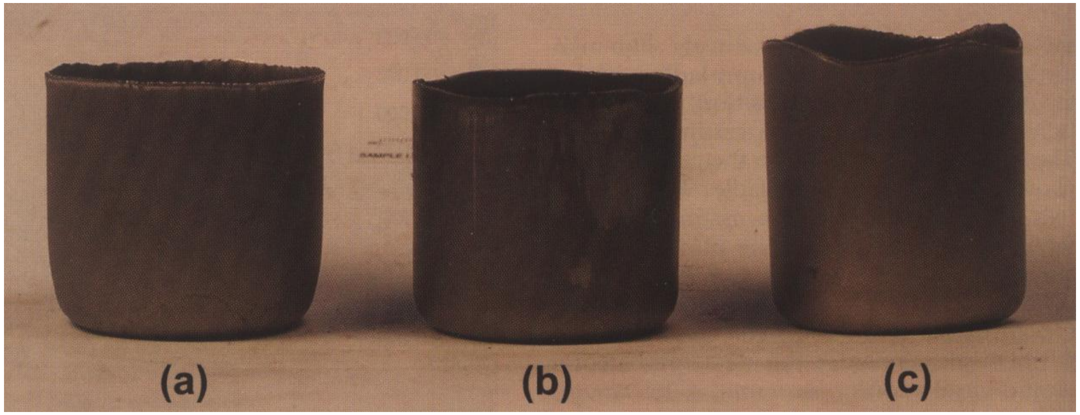
Sheet metal forming sheets rolling - texture

Rolling direction

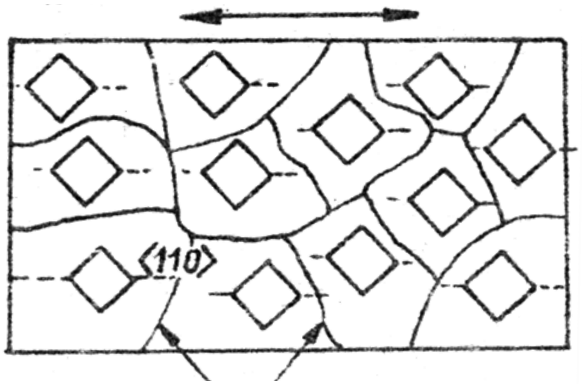


a) Random distribution of grain orientation vs. b) textured material

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



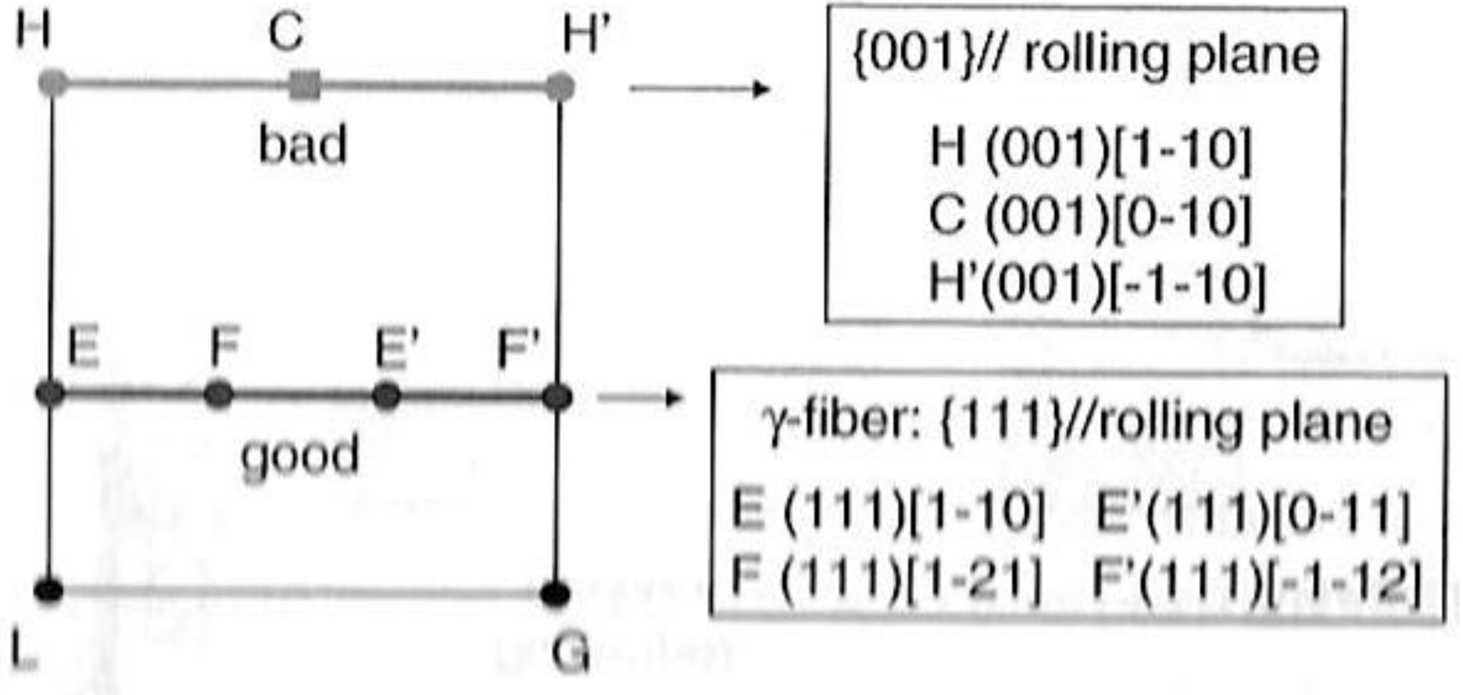
Rolling direction



Grain boundaries

(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)



{001}// rolling plane

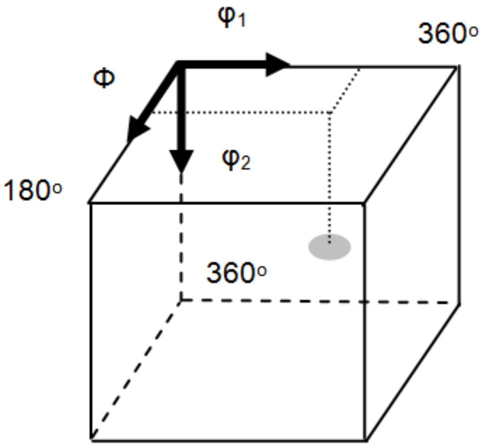
H (001)[1-10]
C (001)[0-10]
H'(001)[-1-10]

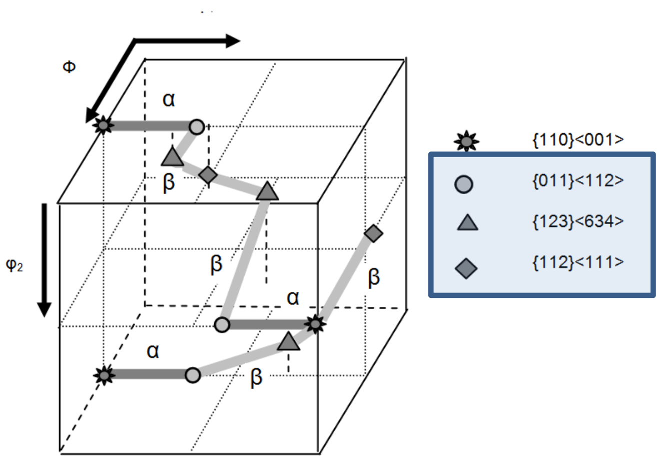
γ-fiber: {111}//rolling plane

E (111)[1-10] E'(111)[0-11]
F (111)[1-21] F'(111)[-1-12]

Fi2=45deg section of Euler space, with crystallographic orientations that are **‘good**’ and
‘bad’ for the deep drawibility of a low-carbon steel sheets

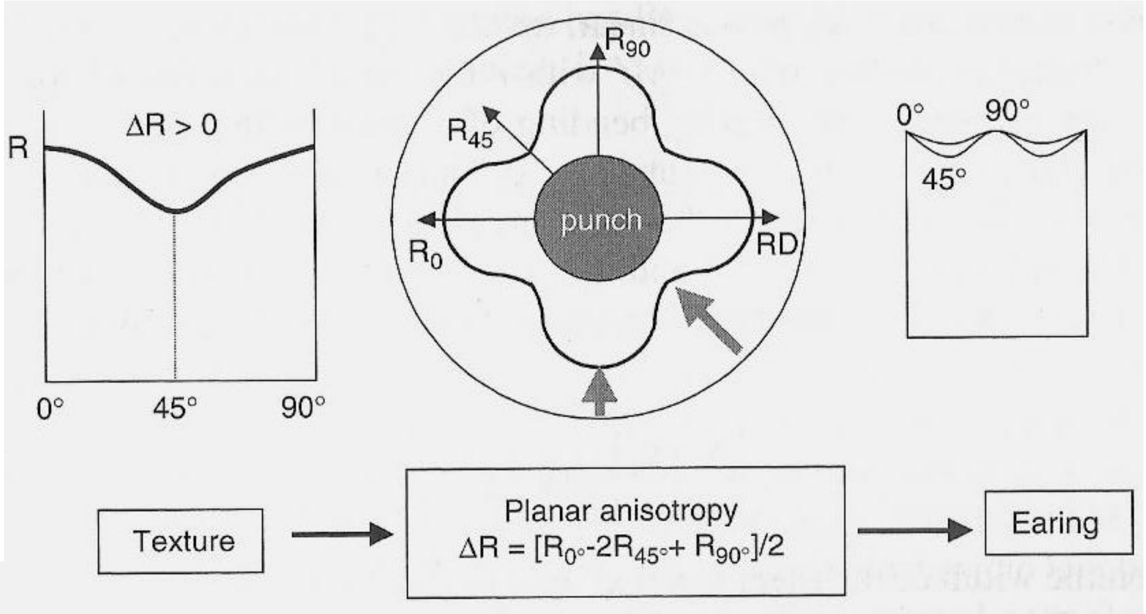
Deep drawing and texture (case of Al)





β-fibre

Case of the fcc metals with cube texture



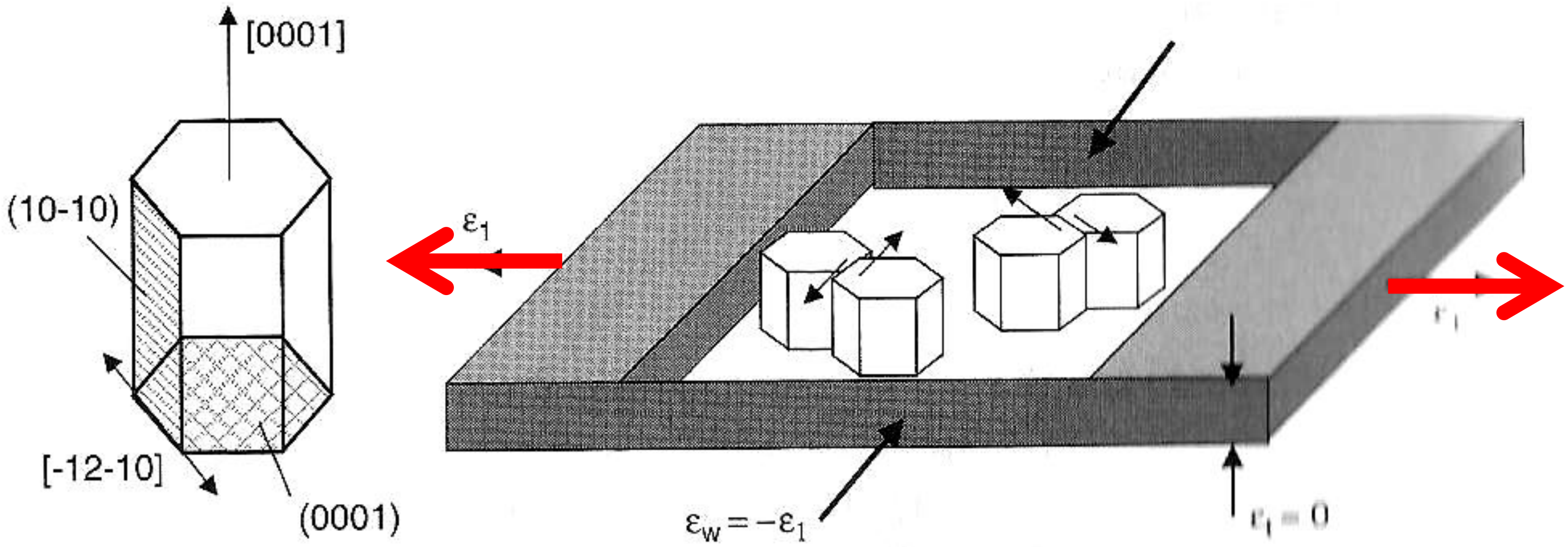
Influence of r-value:
Cube grains stimulate the 0/90deg ears, while orientations belonging to **β-fibre give rise to 45deg ears**.
The Al sheets are processed in order to achieve good balance between both (**cube + β-fibre**) in order to get ΔR~0 and to minimize earing

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

$$\left(1+r\right)\sigma_p^2 = (1+r)\sigma_1^2 - 2r\sigma_1\sigma_2 + (1+r)\sigma_2^2$$

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

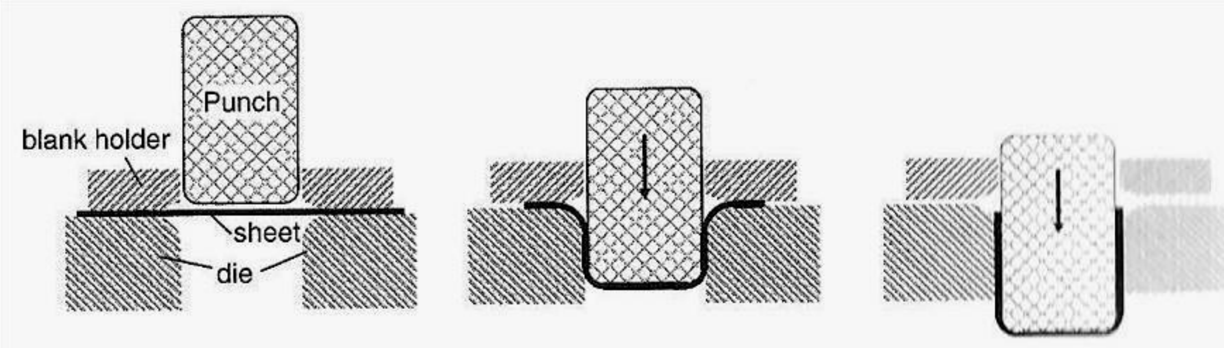
for r=1

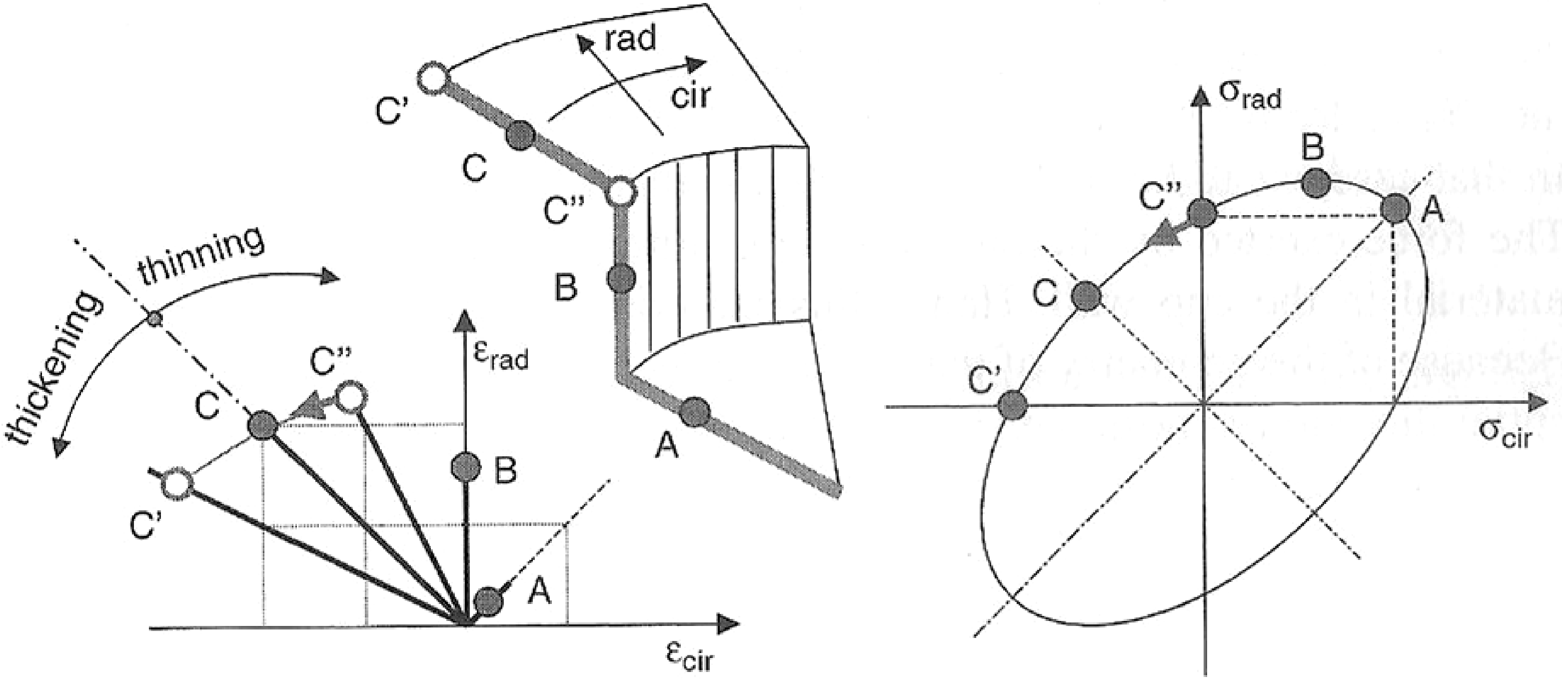
$$\sigma_p^2 = \sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2$$

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

$$\sigma_m = \frac{1}{3}(\sigma_1 + \sigma_2)$$

Deep drawing of a cylindrical cup from a circular blank

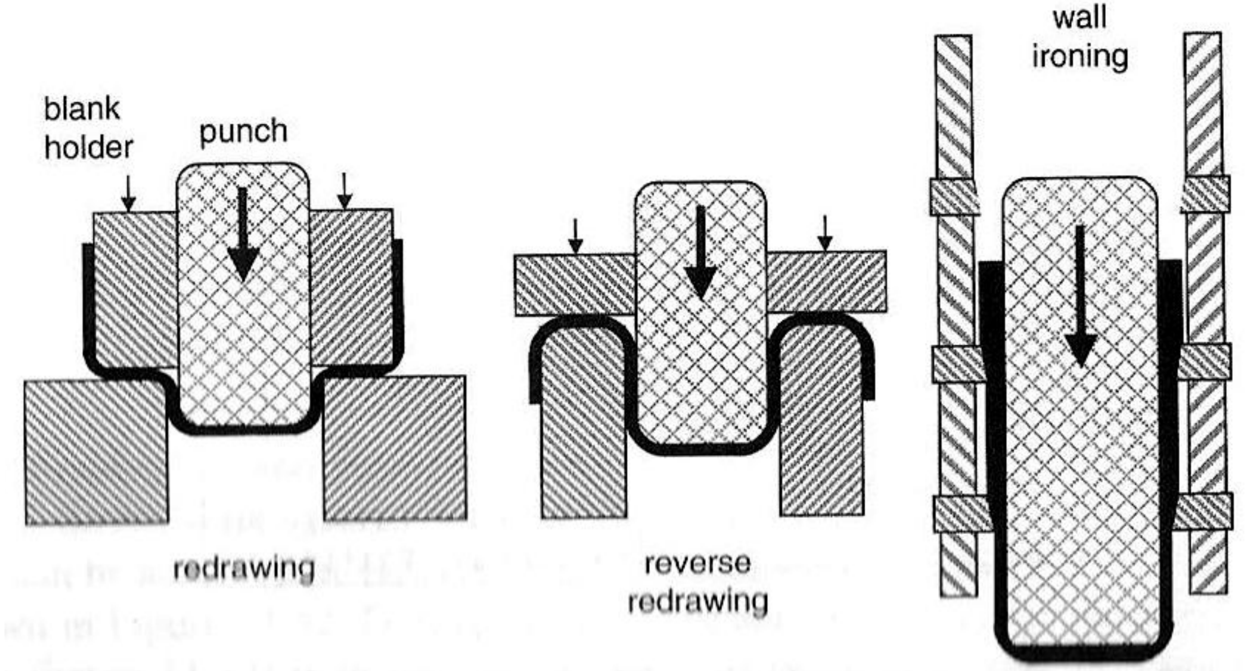




Stress and strain state in various points of the cup during deep drawing. Possible compressive stresses in flange and wall are not into account

Redrawing & ironing

Redrawing, reverse redrawing and wall ironing to produce deeper cups

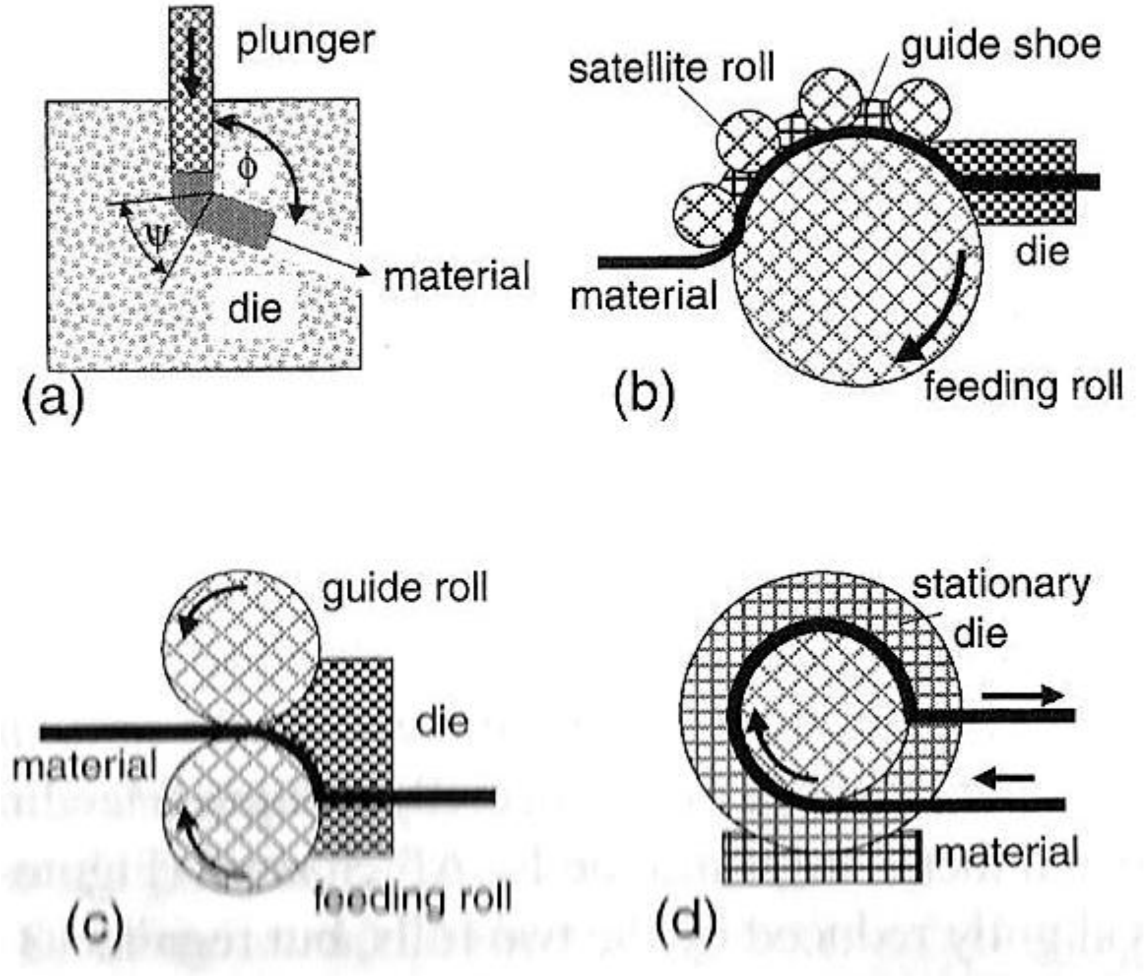


redrawing - several consequtive passes are applied. After each pass, the cup radius decreases and the cup hight increases,

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

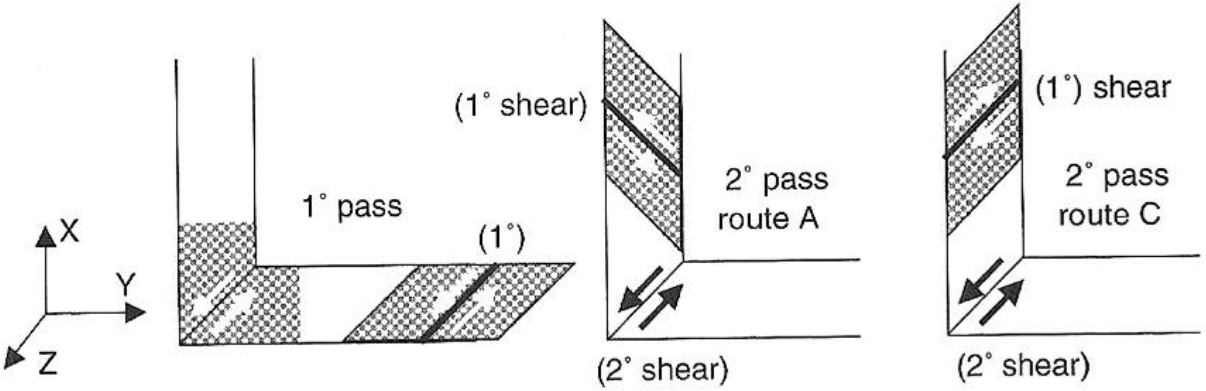
In **wall-ironing**, the cup passes through a series of ring-shaped dies

SPD methods

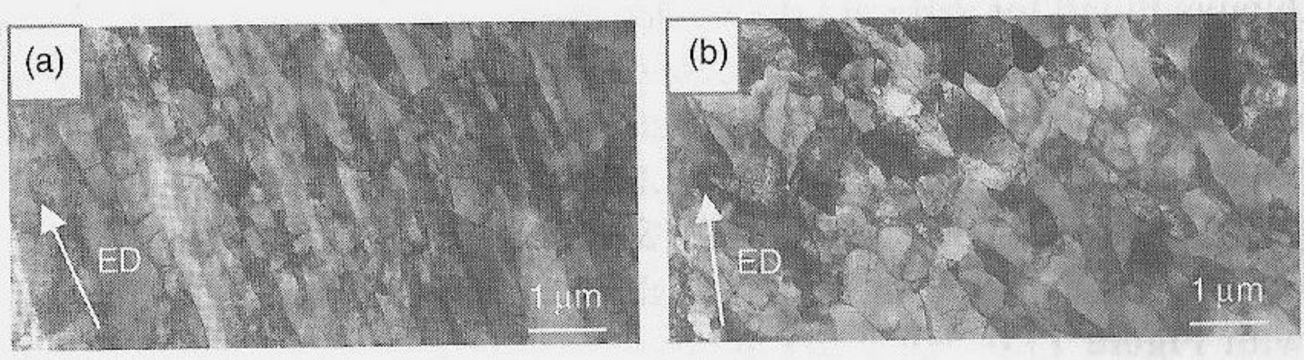


Schematic illustration of (a) lab-scale ECAP die, (b) the conshearing process, (c) continuous confined strip shearing, and (d)the ECAP-conform set up

SPD methods



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



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