Rolling versus other processes:

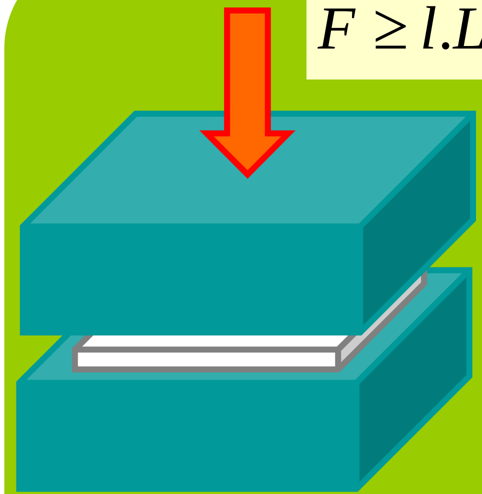
a brief analysis

What are the advantages of rolling processes?

On a few alternatives

Flat Products:free forging

$$F \geq l.L.\sigma_0$$



$$L_{contact} \approx \sqrt{R.\Delta h}$$

L = 5 m

l = 2 m

σ_0 = 100 MPa

F = 10^9 N = 100 000 T !!

$L_{contact}$ = 120 mm si R = 500 mm
h 100 → 70 mm

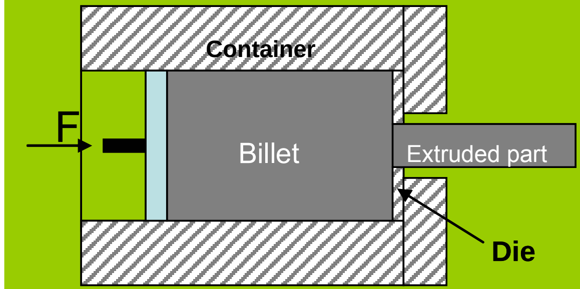
l = 2 m

σ_0 = 100 MPa

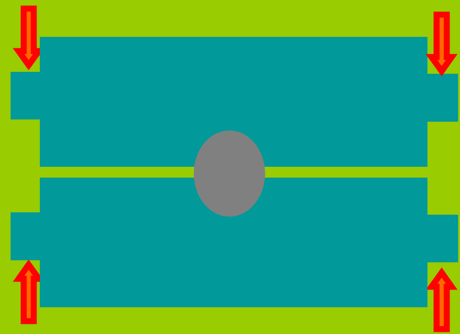
F = 2 400 T

Long Products : extrusion

$$F \geq S_0.Ln\frac{S_0}{S_f}.\sigma_0$$



$$F \geq l.L.\sigma_0$$



Φ 100 → Φ 70

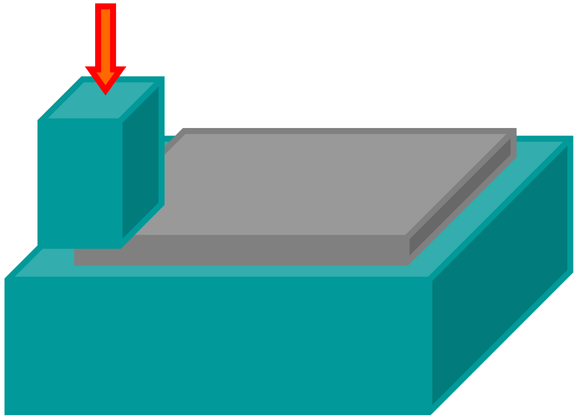
F > 56 T

2 passes are necessary :

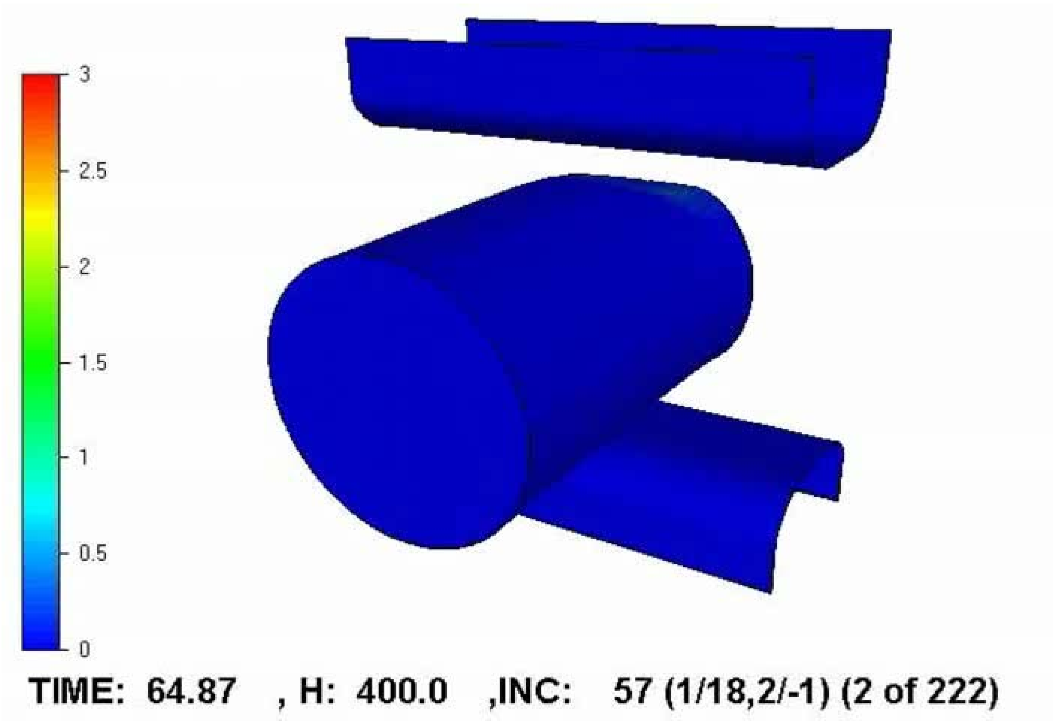
Φ 100	110x60
↓	↓
60x110	Φ 70
77 T	49 T

Rolling deforms a small amount of metal at a time → moderate forces

Incremental processes obtain the same result : rolling vs cogging / hammering



Flat Products : very small productivity.
But it was the only process to form flat plates(« lames ») for minting e.g. until Leonardo invented the rolling mill by the end of the XVIth century



Long Products : still intensively used

Example: « Elongation » of Zr, Ti bars
(not far from here, in Ugine !)

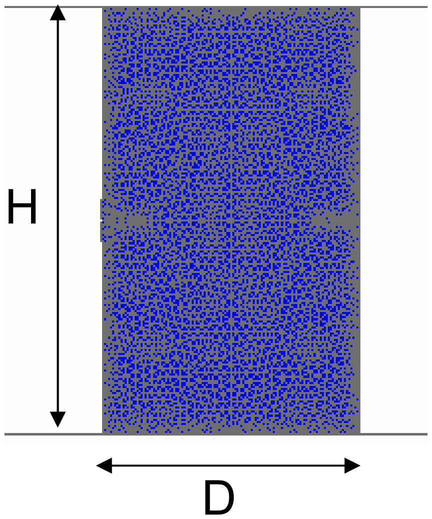
On strain, stress and temperature heterogeneity

Deformation is most of the time heterogeneous

Depending on geometrical ratios

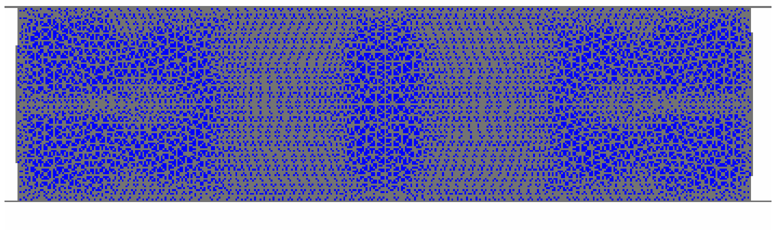
Compression of cylinders

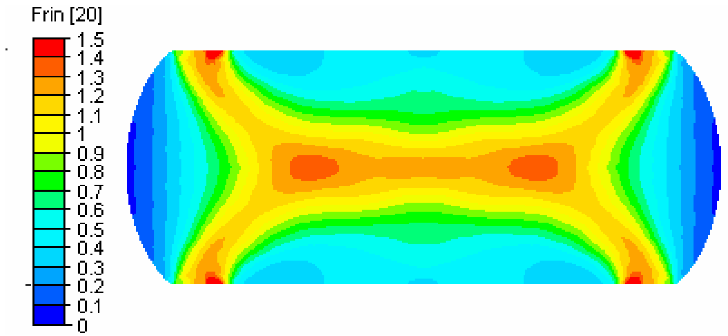
H/D 1.64 → 0.58



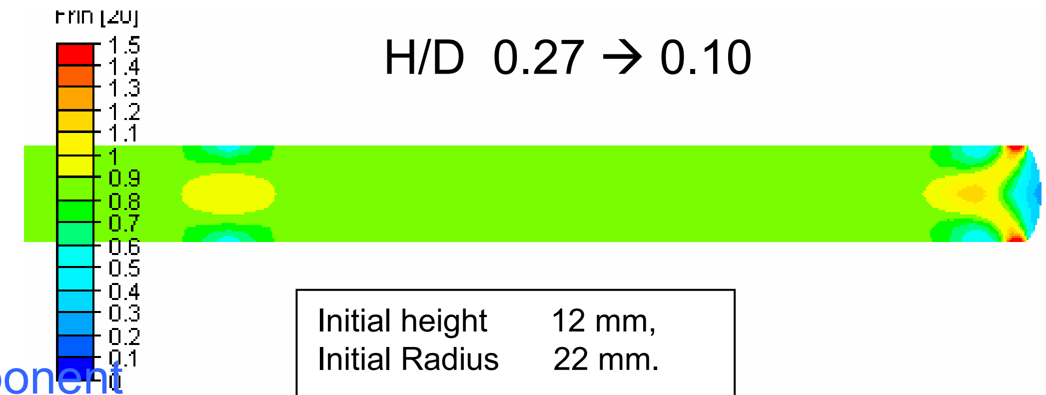
Initial height 72 mm,
Initial Radius 22 mm.

Reduction 50%





H/D 0.27 → 0.10



Initial height 12 mm,
Initial Radius 22 mm.

Reduction 50%

If H/D is « large » :

- strain and strain rate are very heterogeneous
- strain unavoidably includes a notable shear component

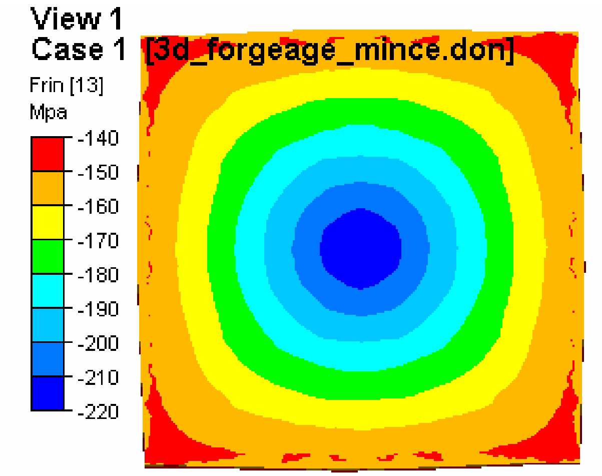
Stresses are heterogeneous

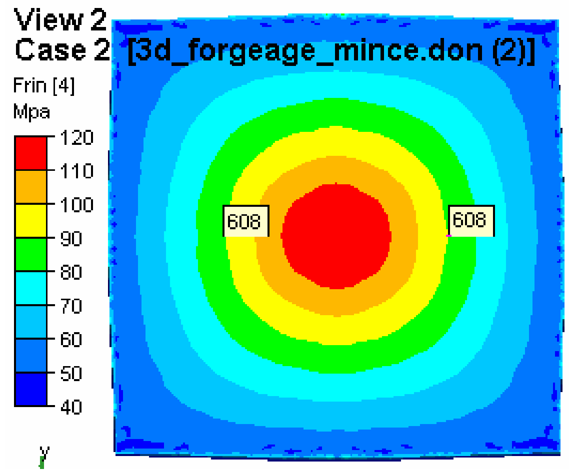
Depending on friction

Compression of a thin parallelepiped

a) Low friction (μ=0.02)

$\Delta\sigma_n$ = 80 MPa



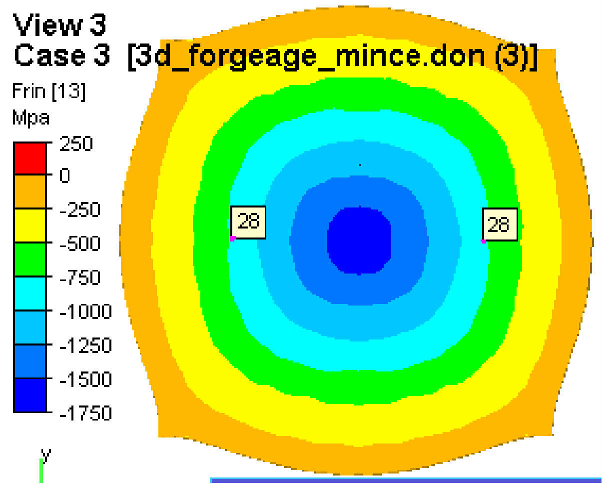


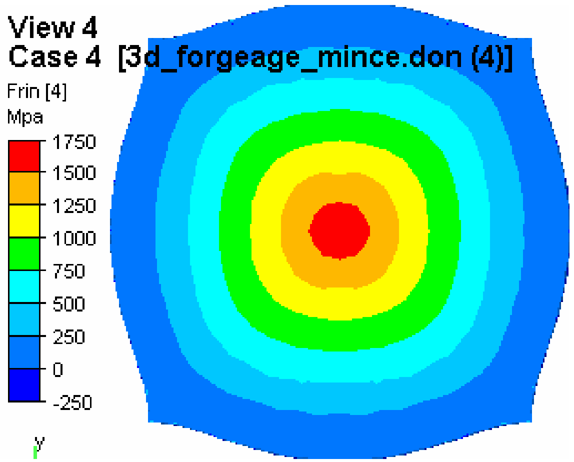
Δp_h = 80 MPa

Normal stress

Hydrostatic pressure

$\Delta\sigma_n$ = 1750 MPa





Δp_h = 1750 MPa

b) High friction (μ = 0.2)

Friction is the major source of stress heterogeneity – and often of the major part of the stress

$$\dot{\varepsilon} = \begin{pmatrix} \frac{V}{2h} & \approx 0 & \approx 0 \\ \approx 0 & \frac{V}{2h} & \approx 0 \\ \approx 0 & \approx 0 & -\frac{V}{h} \end{pmatrix} \Rightarrow \quad s = \begin{pmatrix} -\frac{1}{2}s_{zz} & \approx 0 & \approx 0 \\ \approx 0 & -\frac{1}{2}s_{zz} & \approx 0 \\ \approx 0 & \approx 0 & s_{zz} \end{pmatrix}$$

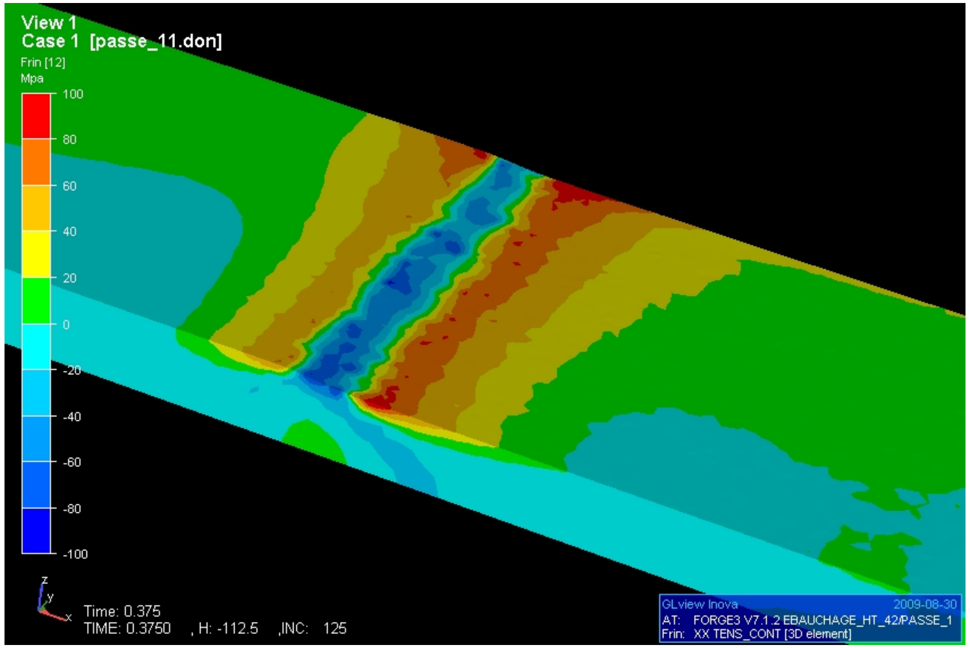
$$\sqrt{\frac{3}{2}\sum_{i,j=1}^{3} s_{ij}^2} = \sigma_0 = \frac{3}{2}\left|s_{zz}\right| \rightarrow s_{zz} = -\frac{2}{3}\sigma_0$$

- stress deviator is homogeneous – as is strain rate tensor
- stress heterogeneity is concentrated in p_h, and is due to friction

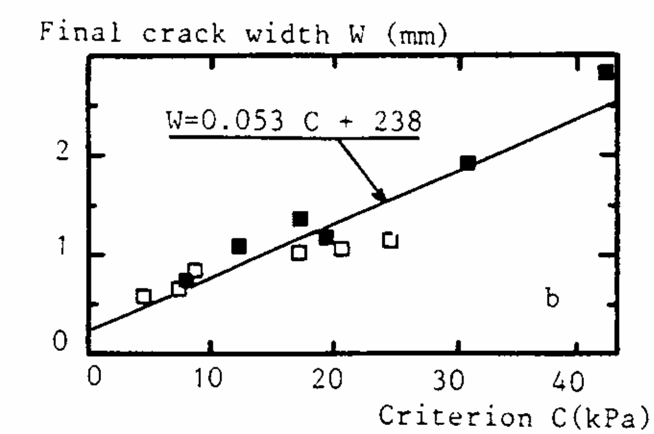
$$\bar{\sigma}_{zz} \approx \left(1 + \frac{\sqrt{2} + Ln(1+\sqrt{2})}{3.\sqrt{3}}\,\overline{m}.\frac{a}{h}\right) \approx \left(1 + 0.45\,\overline{m}.\frac{a}{h}\right)$$

Stress heterogeneity / crack formation and opening

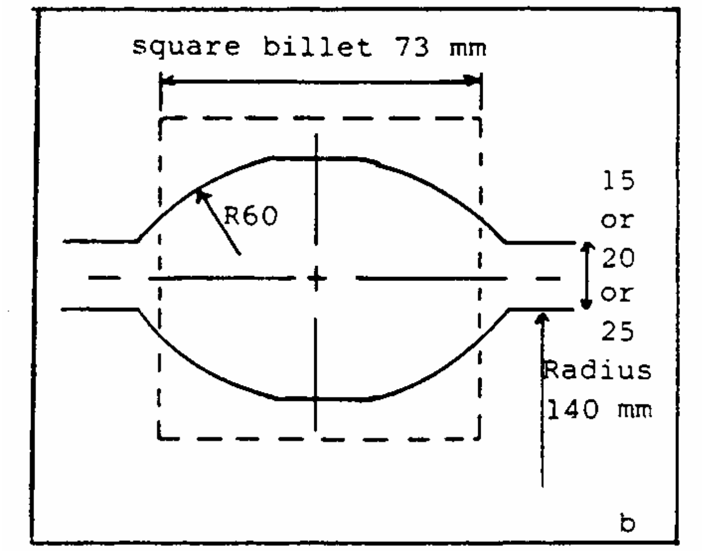
Large tensile stresses are often present at both ends of the bite



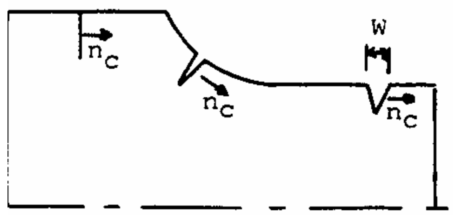
Crack width / damage criterion correlation



An experimental study by physical simulation (plasticine)



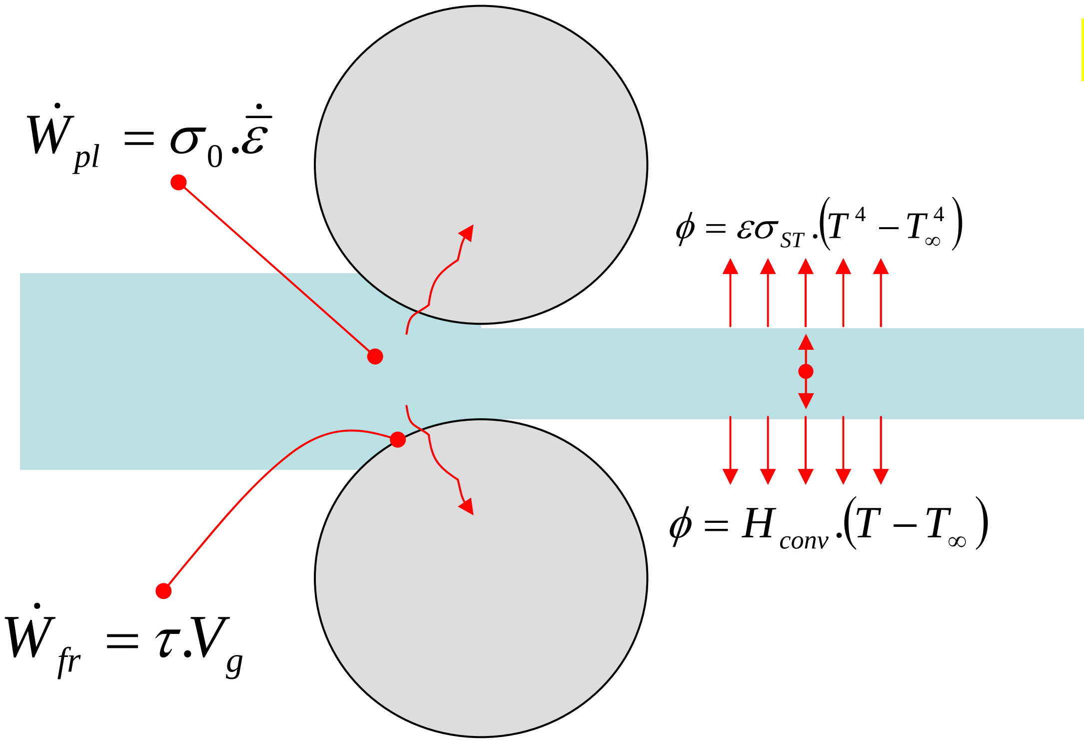
Cutting of transverse cracks and observation of their behaviour



$$C = \int_0^t Max\left[\left(n_c.\sigma.n_c\right),0\right].d\bar{\varepsilon}$$

Oriented Latham & Cockroft damage criterion

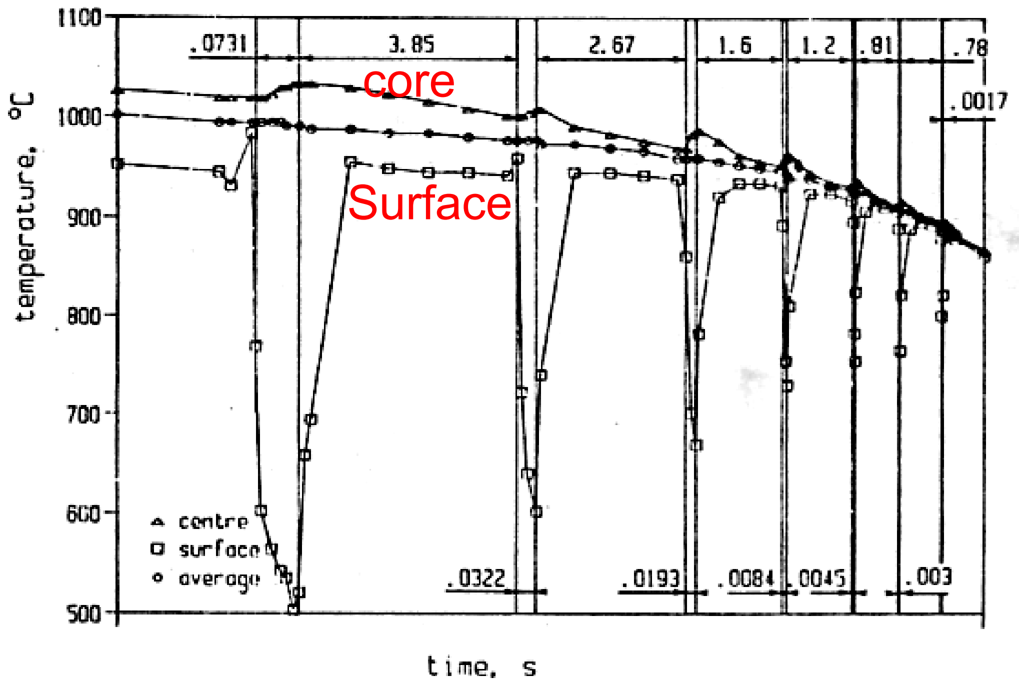
Heat Transfer and temperature field



Heat Transfer Equation

$$\rho C . \frac{dT}{dt} = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \dot{W}_{pl}(x,y,z)$$

$$\rho C . \left(\frac{\partial T}{\partial t} + V_x . \frac{\partial T}{\partial x} + V_y . \frac{\partial T}{\partial y} + V_z . \frac{\partial T}{\partial z} \right) = k \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \dot{W}_{pl}(x,y,z)$$



Adiabatic approximation (centre)

$$\rho C . \frac{dT}{dt} = \dot{W}_{pl}(x,y,z) = \sigma_0 . \dot{\bar{\varepsilon}} \quad \rightarrow \quad \delta T = \frac{\sigma_0 . \bar{\varepsilon}}{\rho C}$$

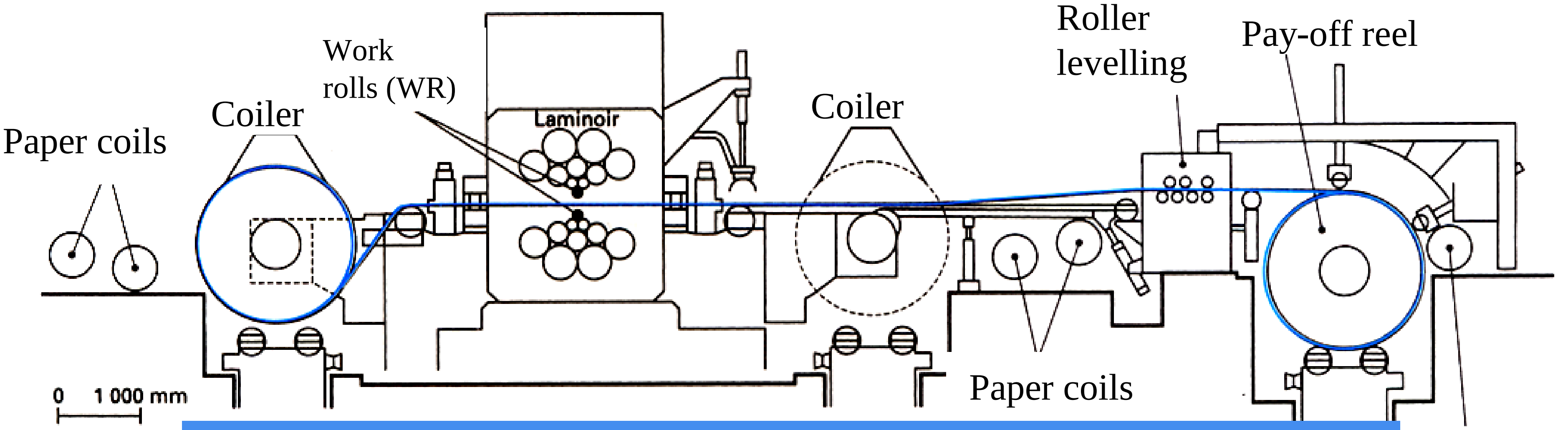
5 – 10°C per pass in hot rolling,
up to 100°C per pass in cold rolling

→ consequences on microstructures

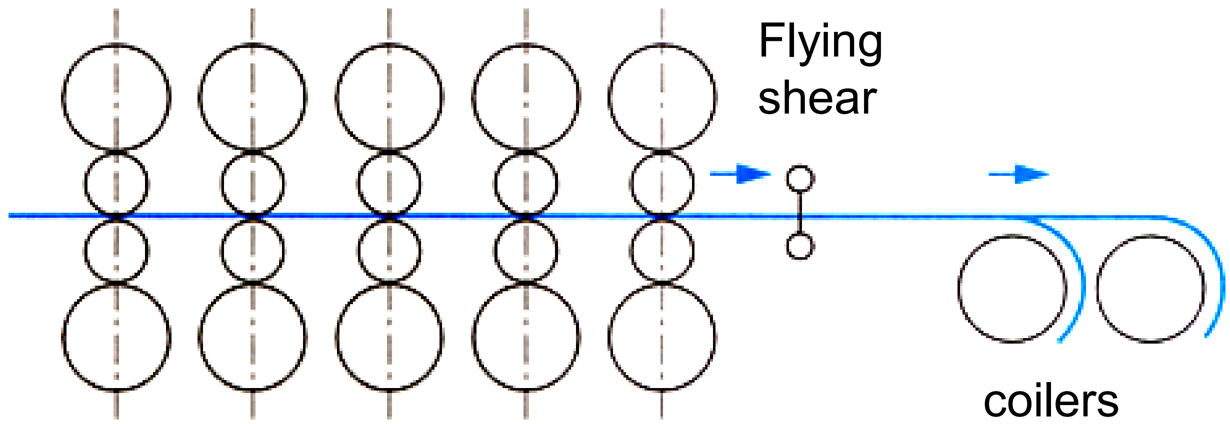
On cold rolling processes

Cold rolling mill : reversible ou multistand ?

Cluster mill (Sendzimir) for stainless steel rolling



Small work rolls → lower forces: excellent for hard, thin strip
But work rolls must be strongly supported in both x and z directions → complex roll set



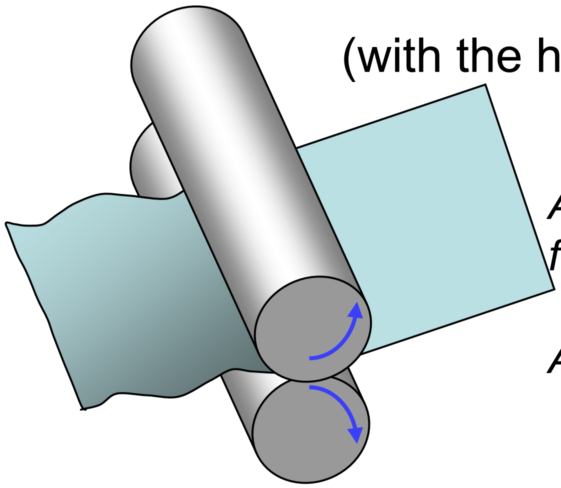
Tandem mill with 5 4-high stands

Large productivity due to high speed (up to 50 m/s !) – complexity due to stand interactions (tension regulation, chatter…)

« skin pass » (temper rolling)

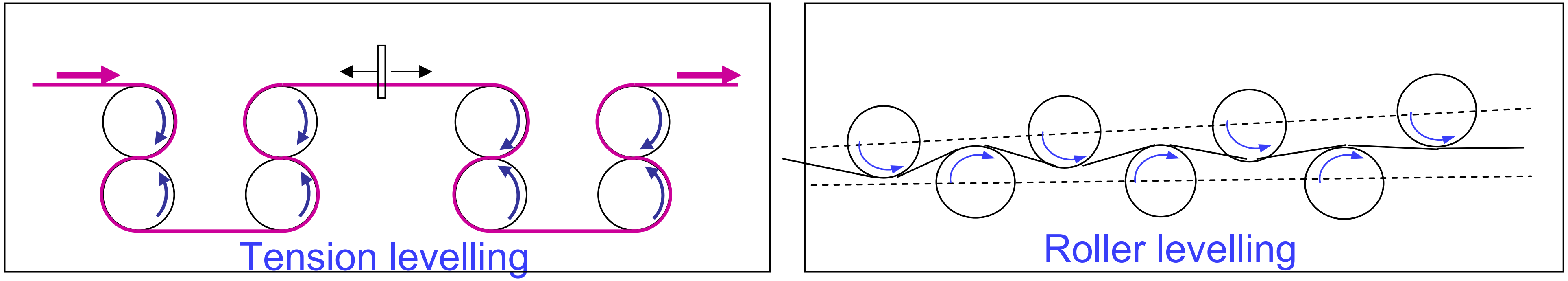
A rolling operation, 0.5 to 2.5% in reduction → carbon steels, Cu alloys.
3 goals:

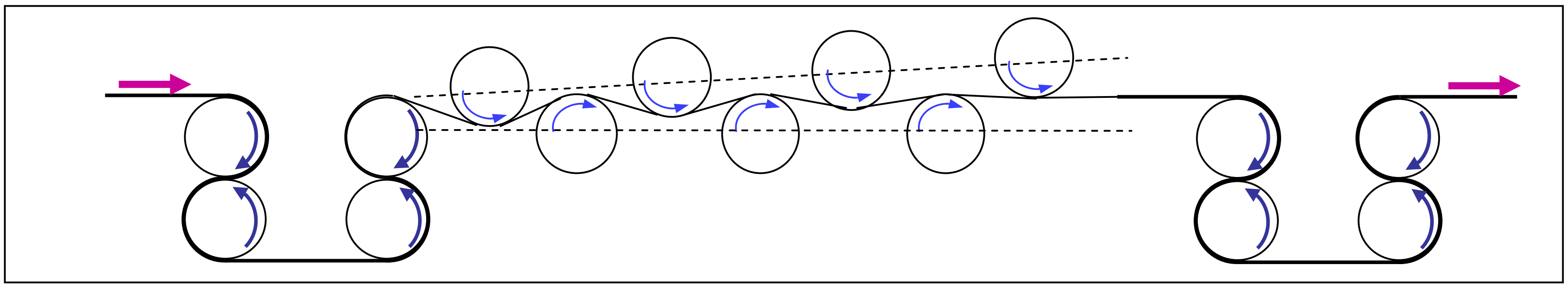
- Improve flatness (with the help of a leveller)



A small elongation compensates for heterogeneous « metal fibres » length,

A small plastic deformation, if homogeneous, eliminates residual stresses



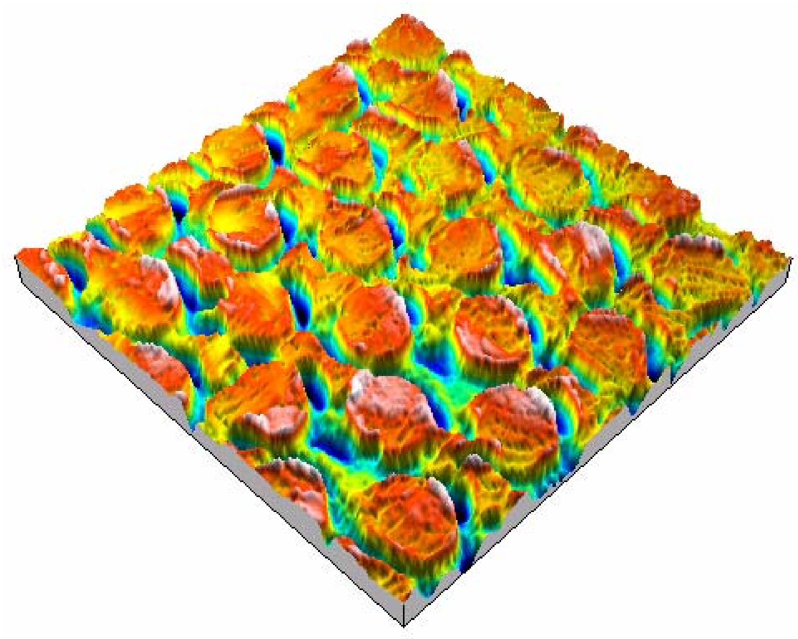


« skin pass » (temper rolling)

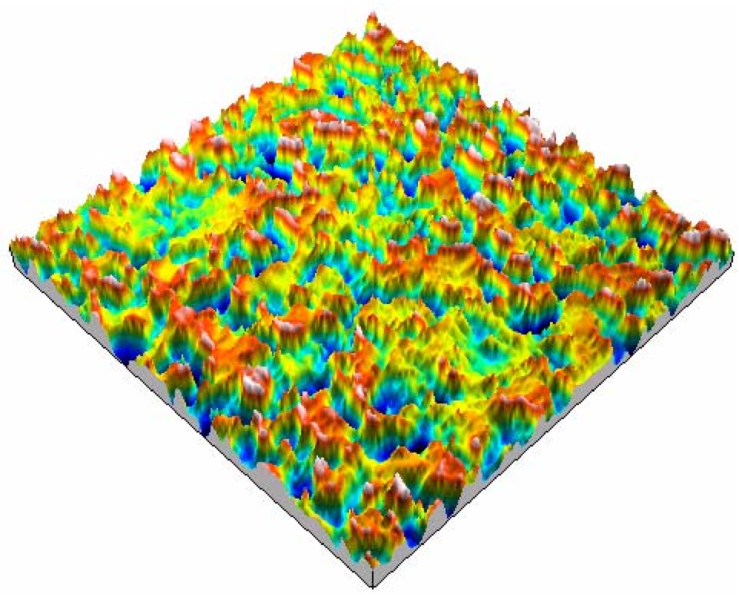
A rolling operation, 0.5 to 2.5% in reduction → carbon steels, Cu alloys.
3 goals:

- Improve flatness (with the help of a leveller)

- Give adequate surface texture (roughness) to ensure easier deep drawing



Electron Beam Texturing (EBT): periodic, deterministic roughness



Electro-Discharge Texturing (EDT) Random roughness

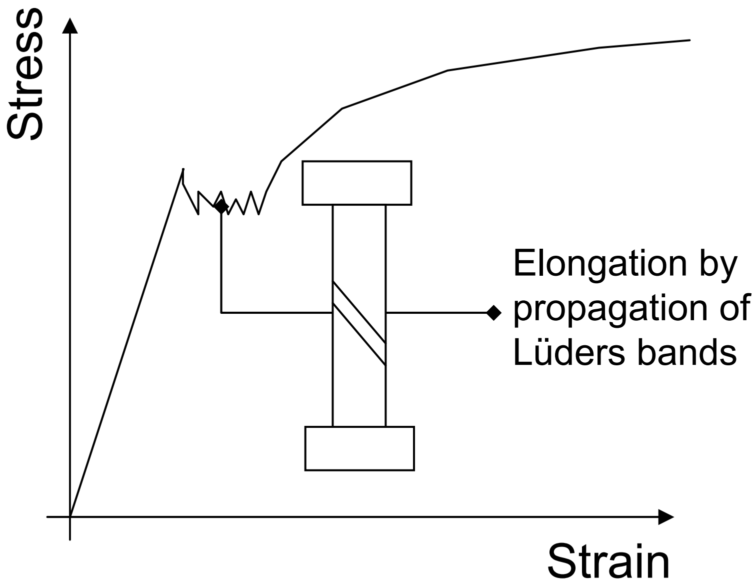
« skin pass » (temper rolling)

A rolling operation, 0.5 to 2.5% in reduction → carbon steels, Cu alloys.
3 goals:

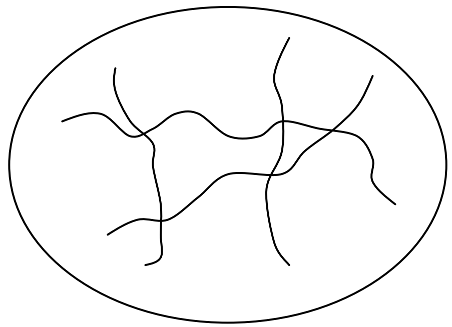
- Improve flatness (with the help of a leveller)

- Give adequate surface texture (roughness) to ensure easier deep drawing

- Go over the « tension hook », avoidinig Lüders bands.



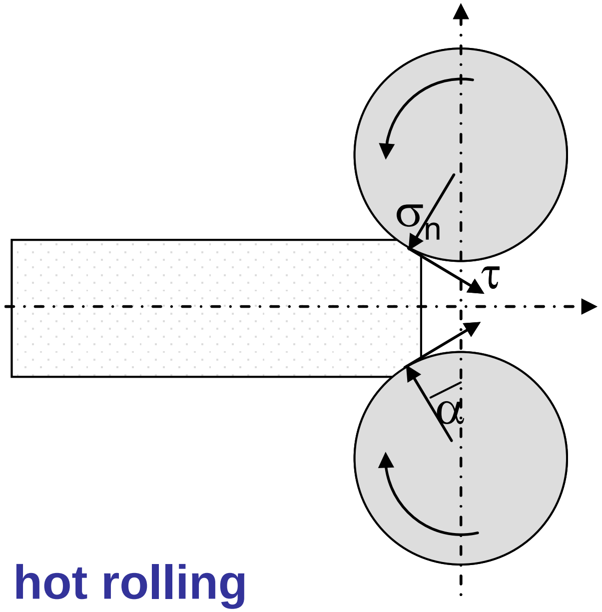
Network of lines during deep drawing



Croos the dangerous area by a rolling process, <u>with imposed thickness</u>, solves the problem

Some elements of mechanical analysis

Example of entrainment condition (linked with friction)



entrainment condition

$$\mu \geq \tan\alpha \approx \sqrt{\frac{\Delta h}{R}}$$

Steel ingot hot rolling

σ_0 = 100 MPa
R = 500 mm.
V = 2 m/s.
h = w = 400 mm
25% reduction → Δh = 100 mm :

$L_{contact} \approx$ 220 mm
F ≈ 8.8 10^6 N = 880 T.
P ≈ 10^7 W = 13000 HP.
Torque = P/ω ≈ 2,5 10^6 N.m

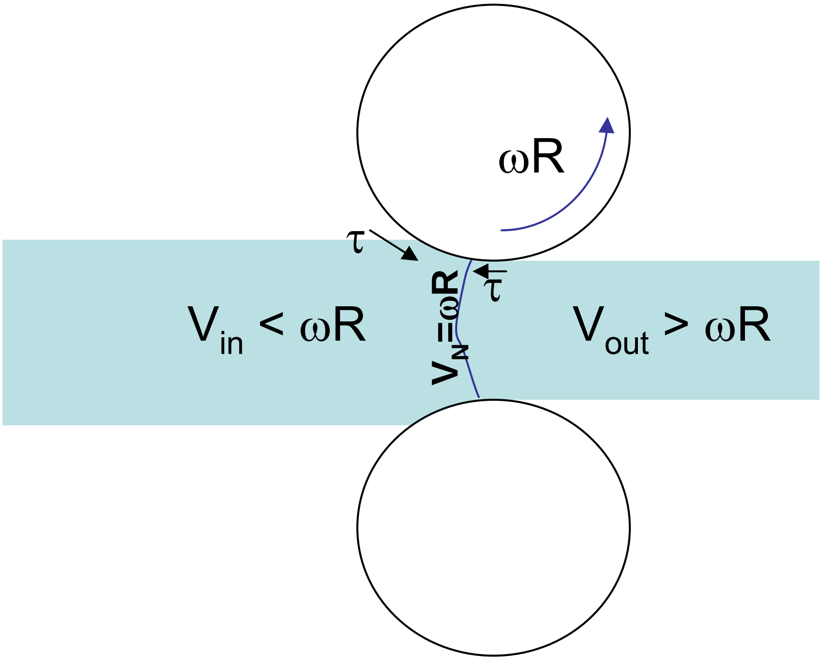
μ > 0.45

High friction is *necessary* → no lubrication* !
Only moderate reductions are possible at this stage → a number of passes

* But for Al hot rolling, lubrication is necessary to avoid welding of slab on rolls!

Neutral point and forward slip

Friction changes direction (sign) at the neutral point:
an essential feature of the mechanics of rolling processes



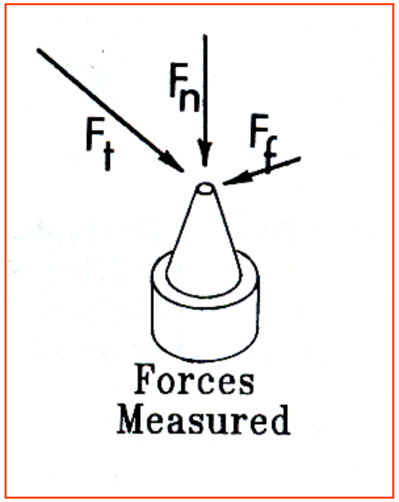
Under normal, stable conditions, the strip exit velocity is slightly larger than the roll velocity, whereas the entry velocity is smaller.

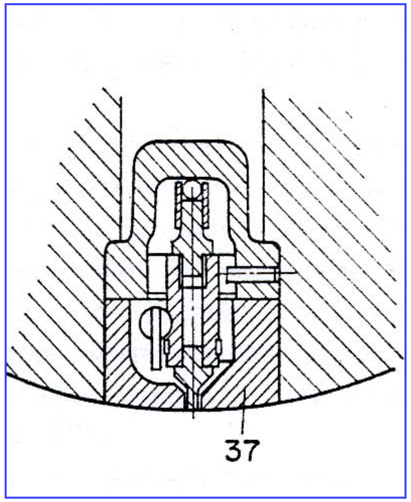
By continuity, $V_{strip} - V_{roll} = 0$ on a certain surface inside the bite. This defines the « neutral point », or « neutral plane », « neutral line »…

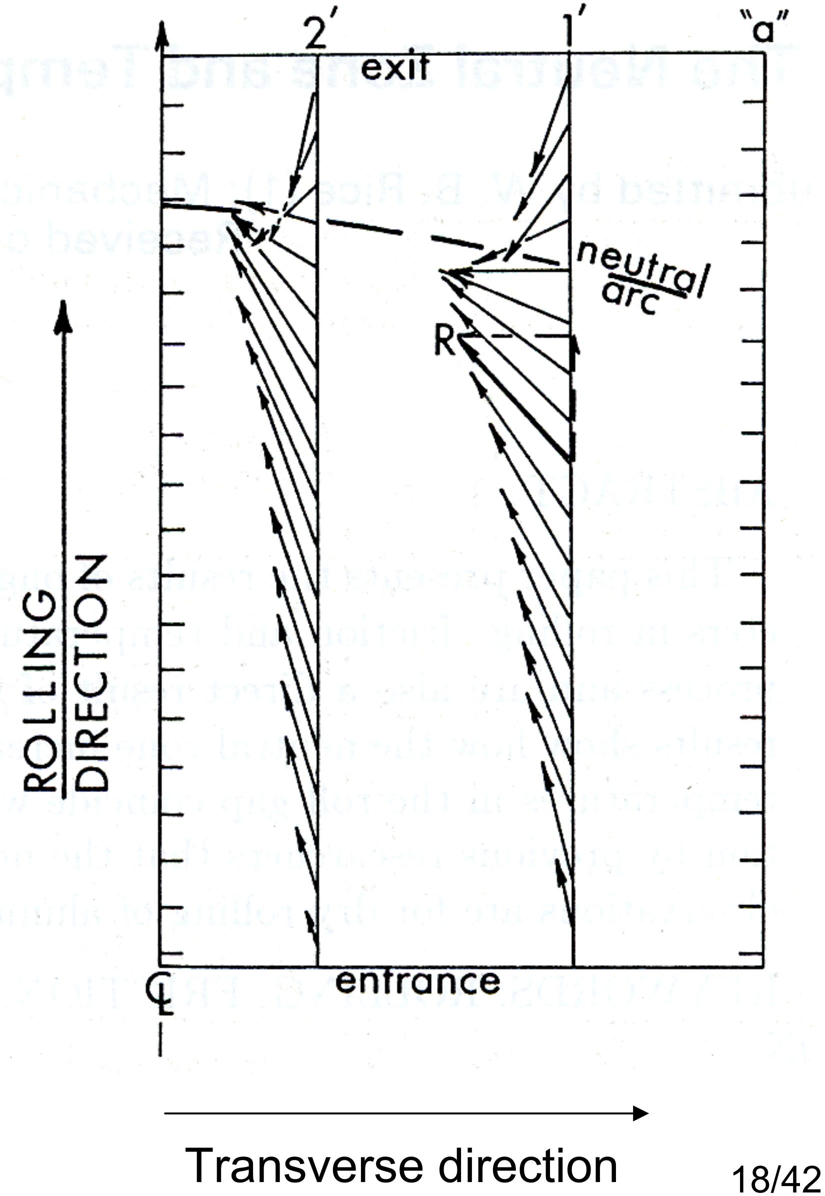
$$S_f = \frac{V_{out} - \omega R}{\omega R}$$

is the *forward slip*

The neutral line may be measured using embedded force transducers



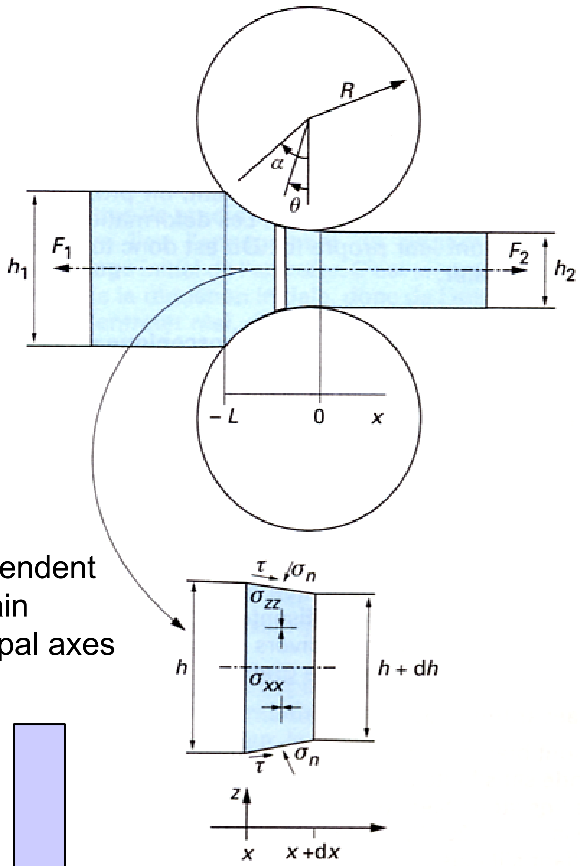




- The direction change of the stress vector is clear
- The transverse component is evidenced, it opposes spread

A simple, but seminal 1D model

Slab method, small angle



i.e.

- y- and z-independent stress and strain
- (x,y,z) = principal axes

Equilibium equation:

$$\frac{d(h\sigma_{xx})}{dx} = -2\left(\sigma_{xx} - \frac{2\sigma_0}{\sqrt{3}}\right)\frac{tg\theta \pm \mu}{1 \mp \mu . tg\theta}$$

Solution

$$\Sigma_{zz}^{-} = \frac{h(\theta)}{h_1}(1-T_1)\,.\,\exp\left[2\mu\sqrt{R/h_2}\left\{\mathrm{Arctg}\left(\alpha.\sqrt{R/h_2}\right) - \mathrm{Arctg}\left(\theta\sqrt{R/h_2}\right)\right\}\right]$$

$$\Sigma_{zz}^{+} = \frac{h(\theta)}{h_2}(1-T_2)\,.\,\exp\left\{2\mu\sqrt{R/h_2}\,.\mathrm{Arctg}\left(\theta.\sqrt{R/h_2}\right)\right\}$$

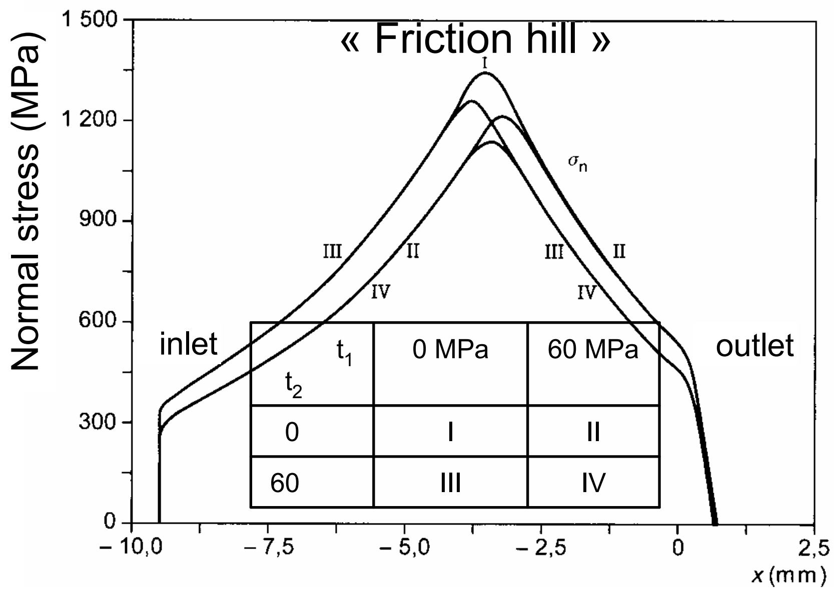
$$\Sigma_{zz} = -\sigma_{zz}/\sigma_0', \sigma_0' = 2\sigma_0/\sqrt{3}$$

$$T_1 = \frac{t_1}{\sigma_0'} \quad , \quad T_2 = \frac{t_2}{\sigma_0'} \quad , \quad t_1 = \frac{F_1}{h_1} \quad , \quad t_2 = \frac{F_2}{h_2}$$

Neutral point, forward slip

$$\Sigma_{zz}^{+} = \Sigma_{zz}^{-} \quad \Rightarrow \quad \theta_N = \sqrt{\frac{h_2}{R}}.\tan\left(\frac{1}{2}\mathrm{Arctg}\left(\alpha.\sqrt{\frac{R}{h_2}}\right) + \frac{1}{4\mu}\sqrt{\frac{h_2}{R}}.\mathrm{Ln}\left(\frac{h_2}{h_1}.\frac{1-T_1}{1-T_2}\right)\right)$$

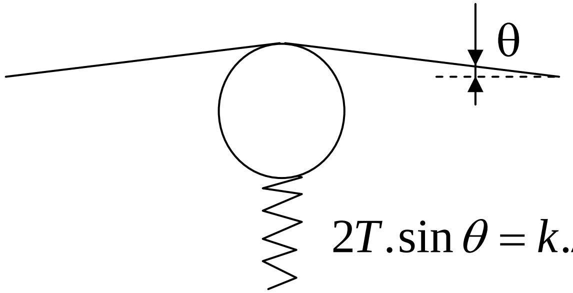
$$S_f = \tan^2\left(\frac{1}{2}\mathrm{Arctg}\left(\sqrt{\frac{\Delta h}{h_2}}\right) + \frac{1}{4\mu}\sqrt{\frac{h_2}{R}}.\mathrm{Ln}\left(\frac{h_2}{h_1}.\frac{1-T_1}{1-T_2}\right)\right)$$



t_2 \ t_1	0 MPa	60 MPa
0	I	II
60	III	IV

Strip tensions

- Tensions are therefore used to decrease the contact stresses (see previous slide), the roll force, and consequently the roll deformation.
- They also help keep the strip in line and centered
- They keep the strip flat during rolling

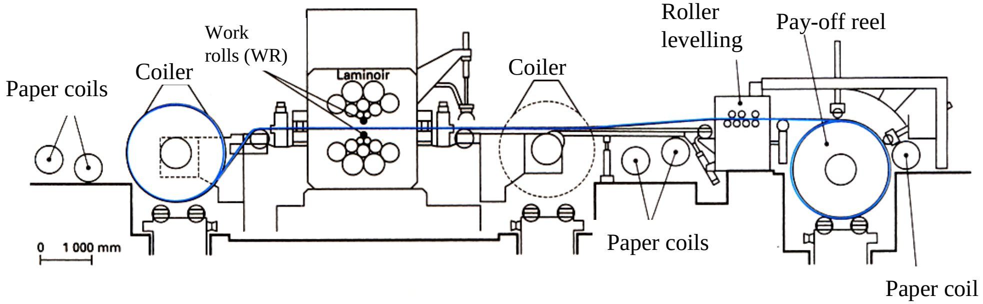


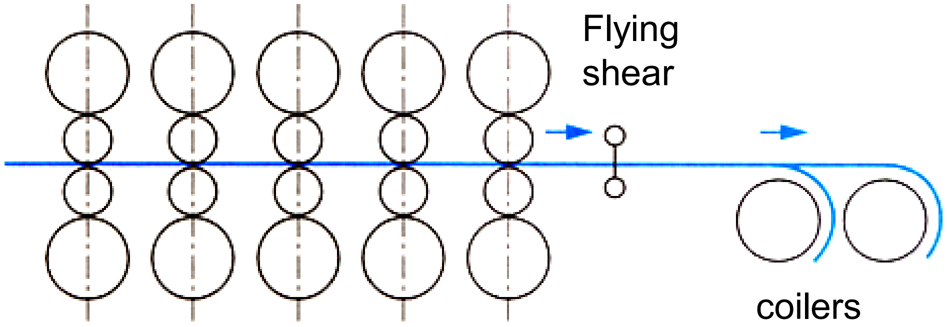
$$2T.\sin\theta = k.\Delta z$$

Note: on the wire rod mills, tensions are used also to control spread

Tension in the range 0.1 – 0.2 x σ_0 are most common. The regulation is based on tension loops.

Tensions are applied either by pay-off reel / coiler (single stand reversing mills),

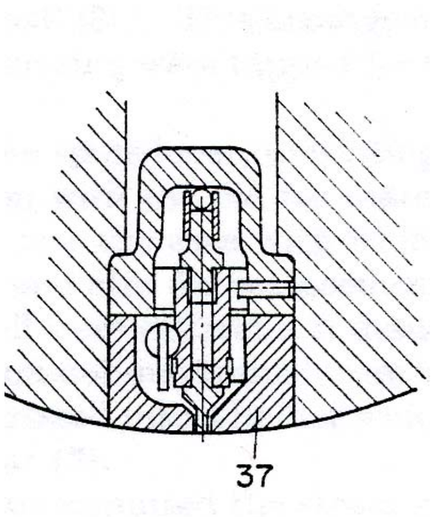




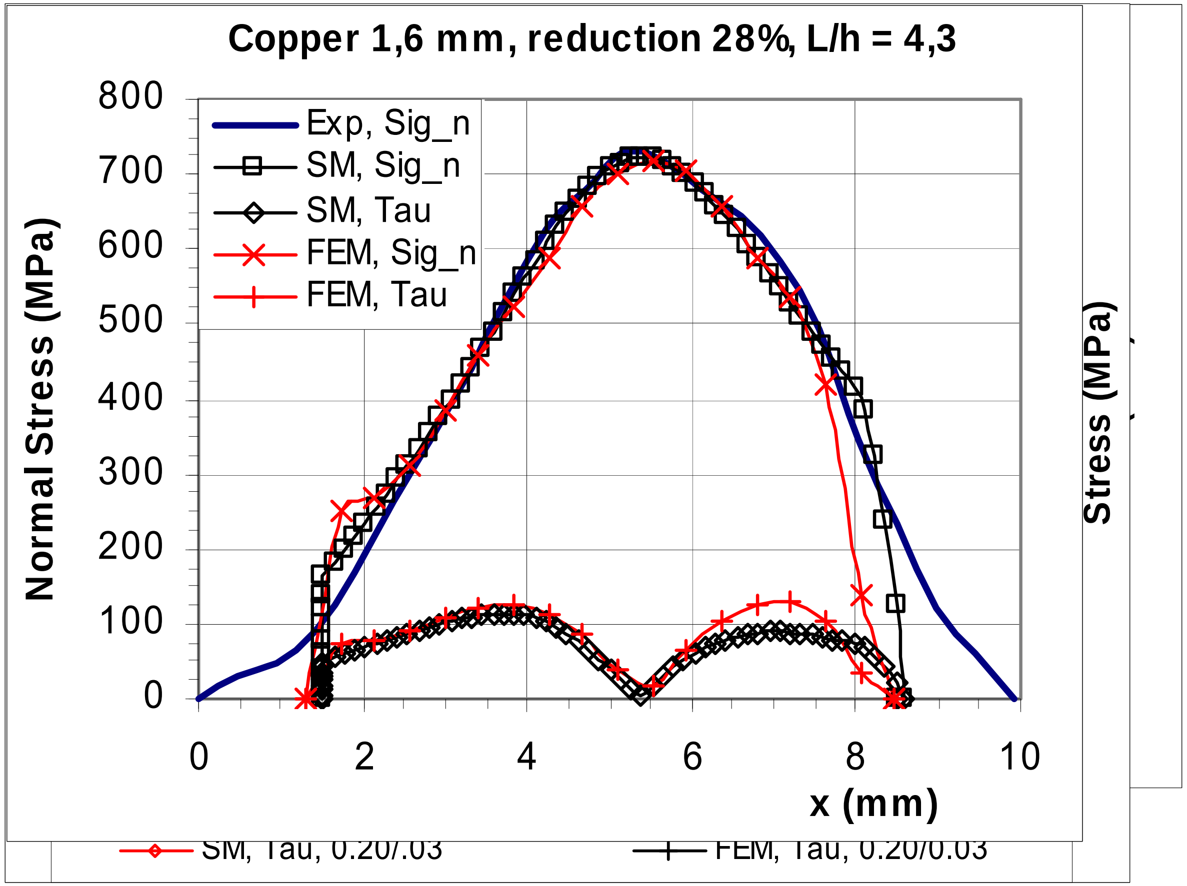
or by the velocity sequence on tandem mills ($V_{i+1} > V_i.h_i/h_{i+1}$)

Criticism and limits of the 1D model

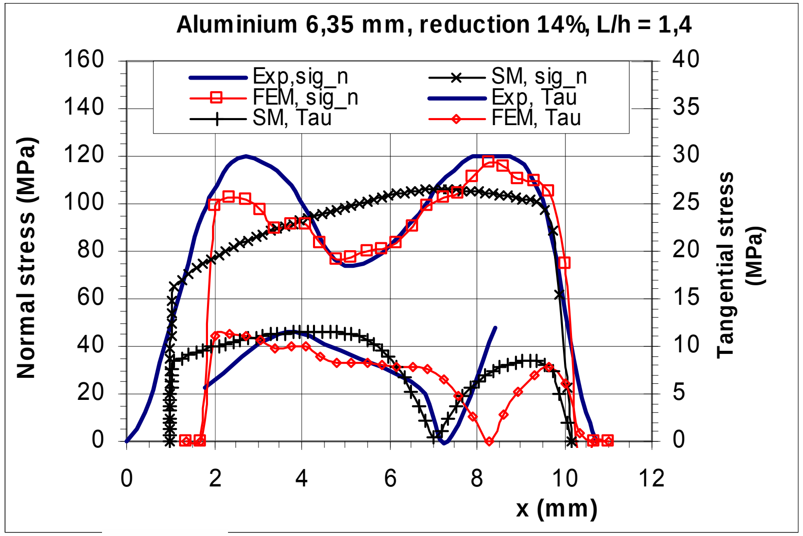
1 – 2D vision: neglected shear strain & stress, z-heterogeneity

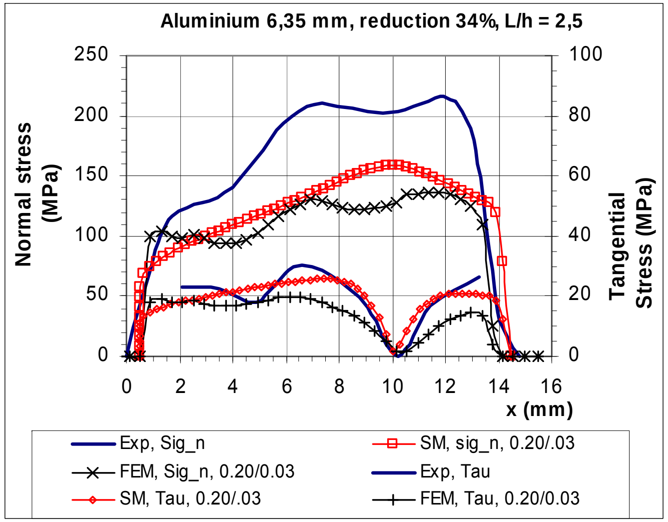


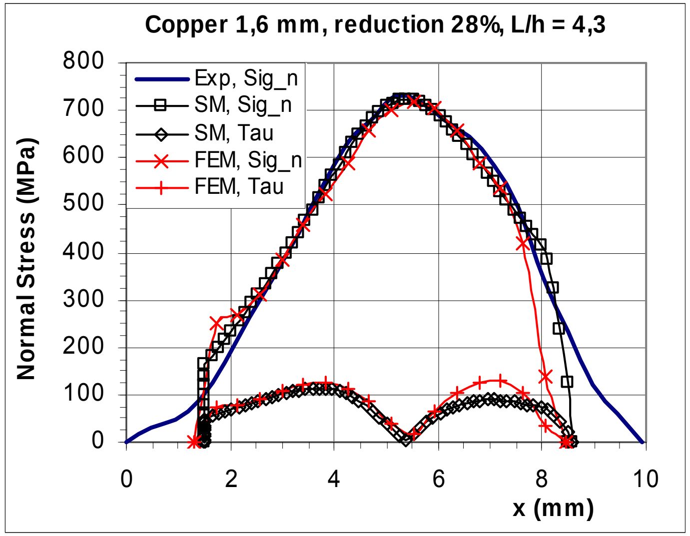
Measurement
of normal and tangential stresses,
comparison with the slab method
and with the FEM

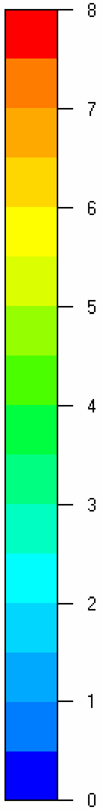


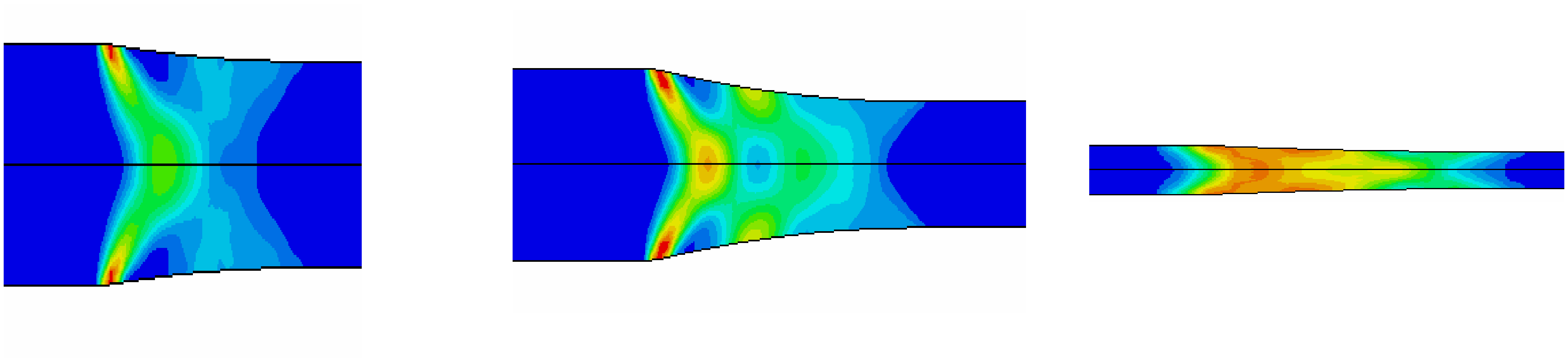
The validity of the 1D model scales with the value of L/h







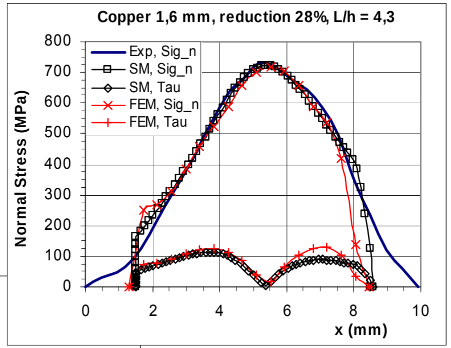


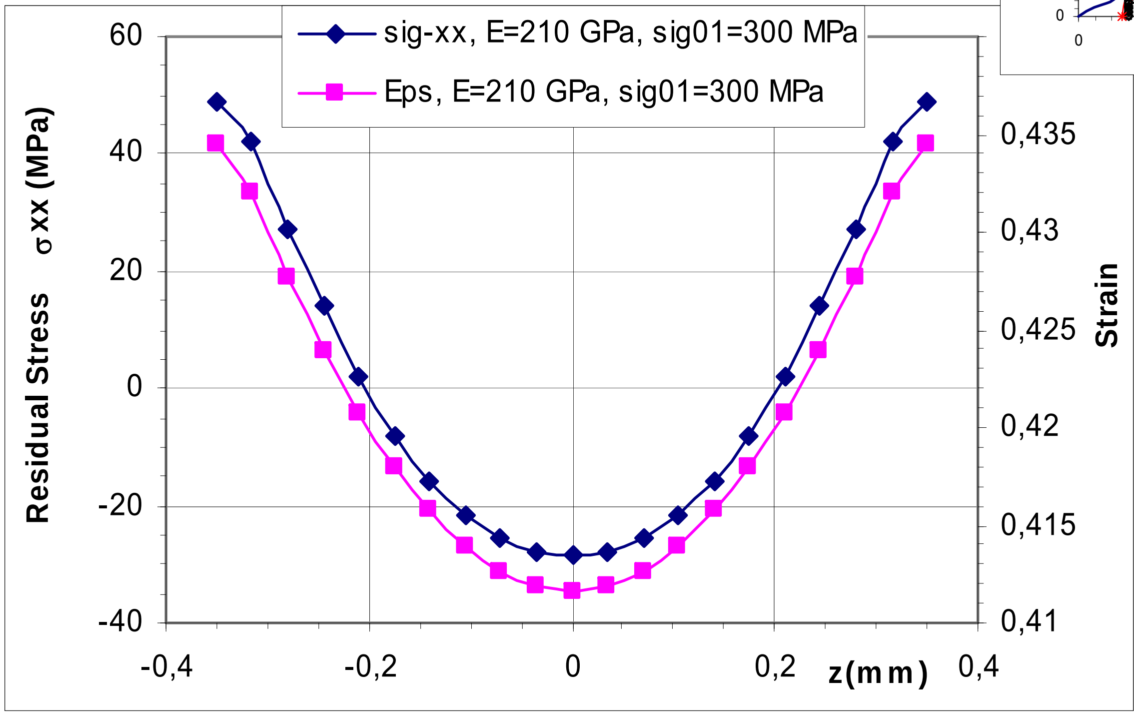


Where shear bands are dominant, the 1D model fails because it neglects shear components

Heterogeneity is governed by a geometric ratio: bite length / average thickness: $L / \overline{h}$

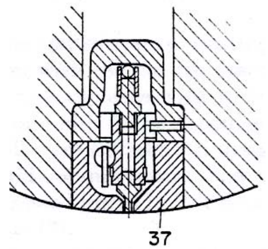
From strain-rate to strain to residual stress



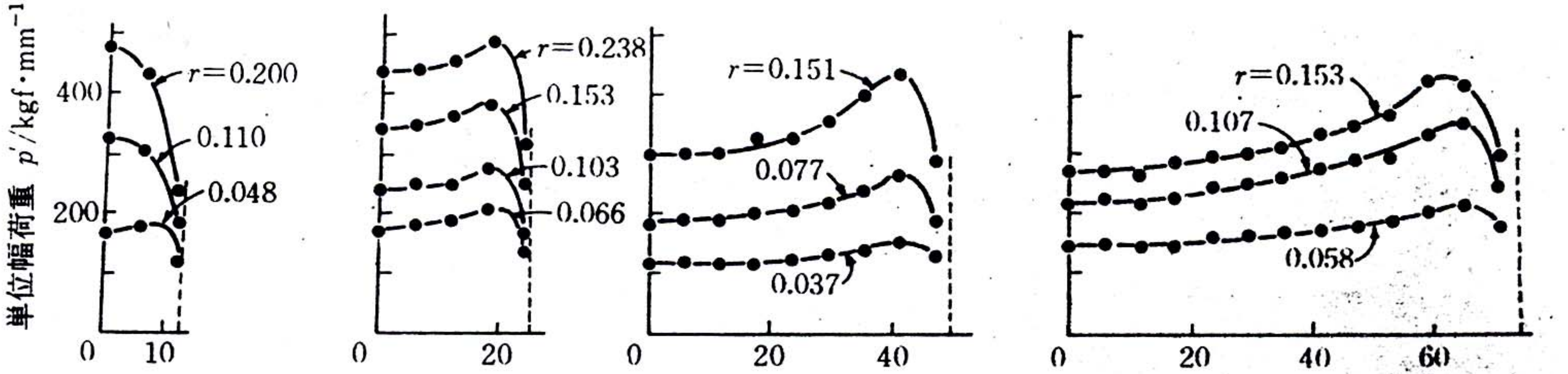


- The strain is always larger near the surface due to the strain rate concentration at the entry point
- the difference increases when L/h decreases
- $\sigma_{xx}(z)$ residual stress heterogeneity is connected with the strain gradient

2 – Plane strain vs 3D



The stress transducer is located successively at different positions along Oy

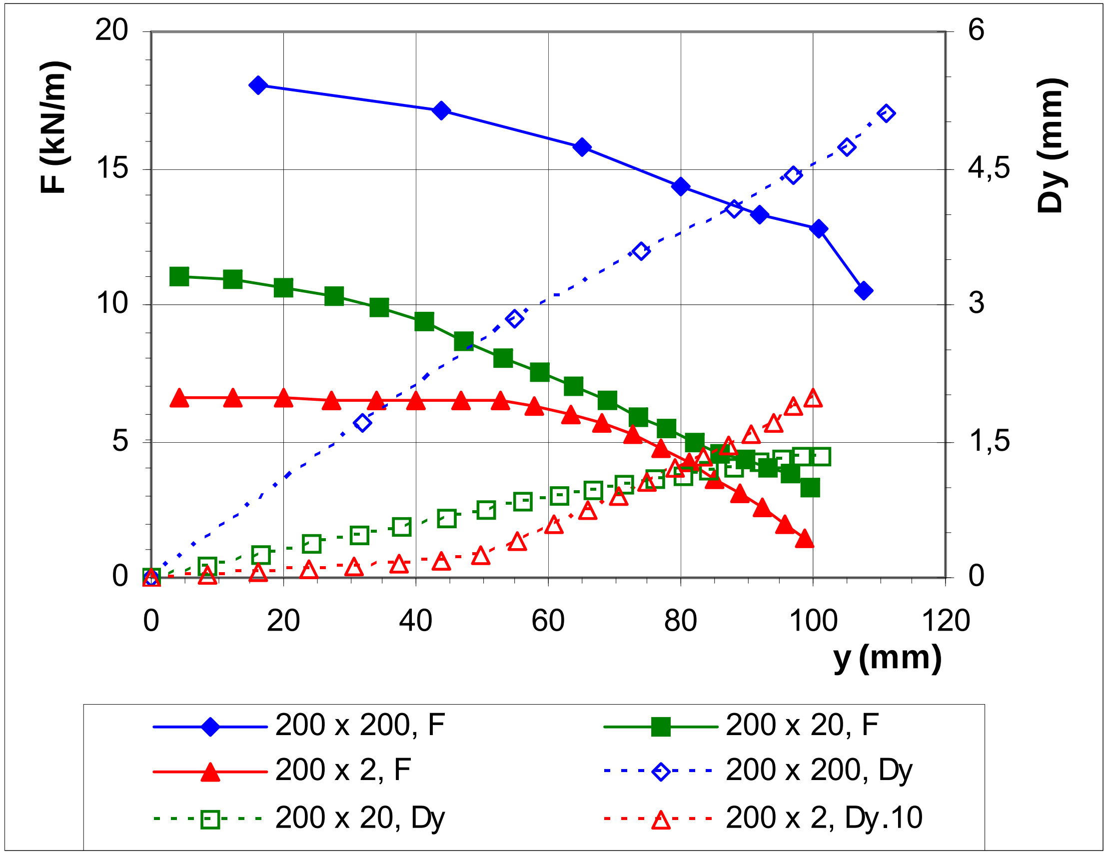


y (= width)

p'(y) (Tons / meter) = rolling load profile
Initial thickness h1 = 2 mm; Roll radius R ≈ 250 mm. L/h ≈ 4.

- Edges introduce 3D effects (edge = free surface → decreased p hence σ_n)
- But most of the profile comes from roll deformation (bending + flattening) resulting in (slightly) y-dependent reduction

Influence of width on edge effects (FEM, rigid rolls)



- When W/H ≈ 1 (long products), edge effects extend on the whole width:
  - * σ_n decreases consistantly from centre to edge,
  - * transverse flow starts from the centreline (V_y quasi-linear)

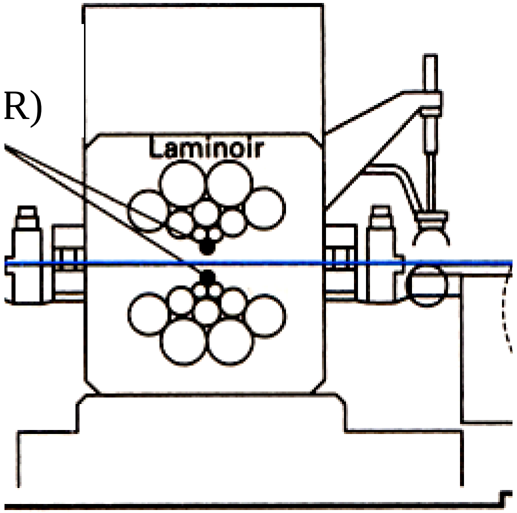
- When W/H >> 1, edge effects extend on near-edge area only (more or less, depending on friction)
  - * σ_n is constant on the central part ($V_y \approx 0$), then decreases towards the edge,
  - * transverse flow is restricted to the edge area

On roll deformation: profile and flatness actuators

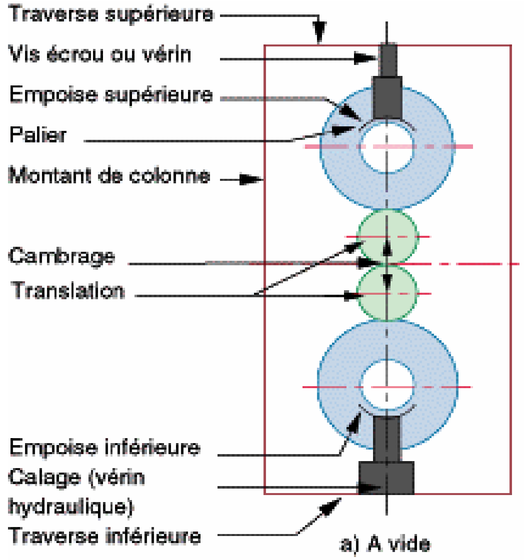
Profile and flatness actuators are many, with different complexity

Non-adaptative actuators (1)

- Against roll *bending* : complex styands with back-up rolls

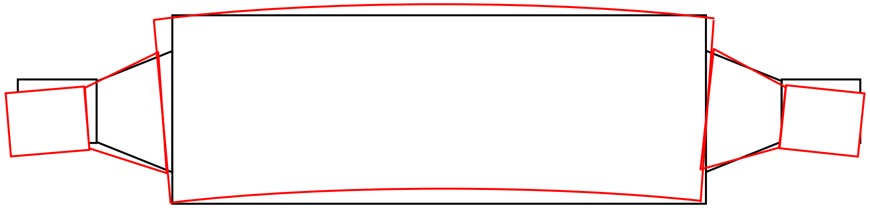


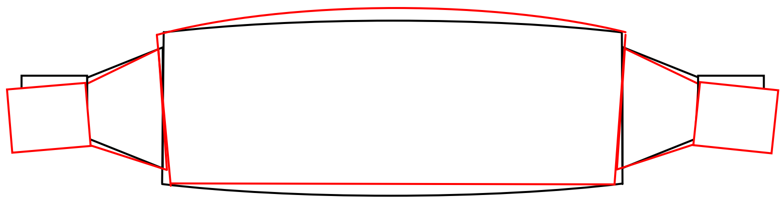
20-roll Sendzimir stand



4-high stand

- Against roll *bending* : grinding crown





Profile and flatness actuators are many, with different complexity

Non-adaptative actuators (2)

- Against thermal crown (differential dilatation) and its time evolution:
  pre-heating of rolls to avoid excessive variations along one roll mounting

- Against wear profile : the « rolling cone » :
  less and less wide strips are rolled

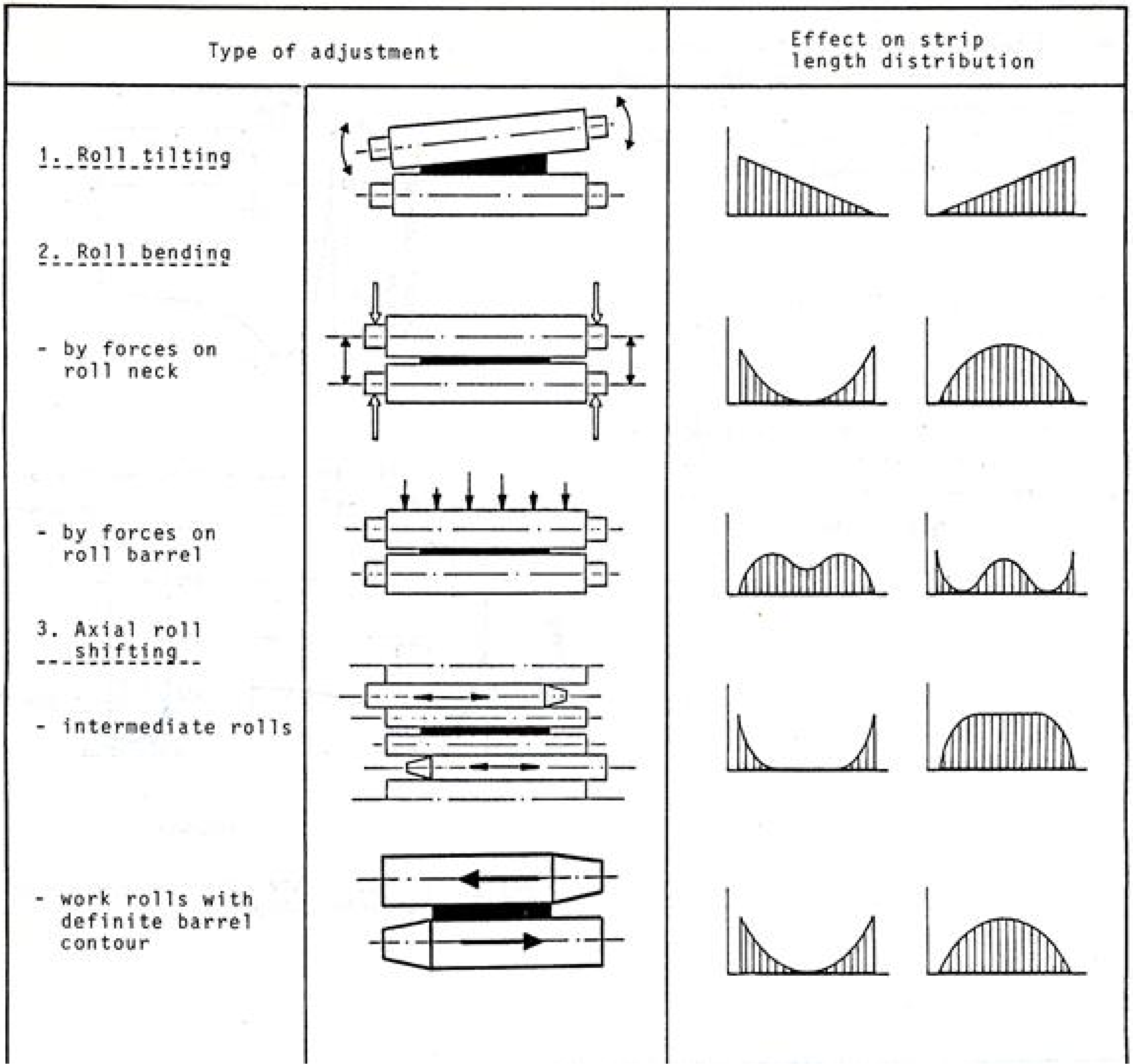
  Note: to counter wear (by abrasion, fatigue), rolls are changed regularly.
  Frequency depends on load severity, requested surface quality
  (each new shift for carbon steel, each new coil for stainless steel, each new day for light alloys…)

Profile and flatness actuators are many, with different complexity

Adaptative actuators (1)

Roll (counter)bending is present on most stands of most rolling mills (light alloys and steel)

Efficient to correct near-edge defects



Profile and flatness actuators are many, with different complexity

Adaptative actuators (2)

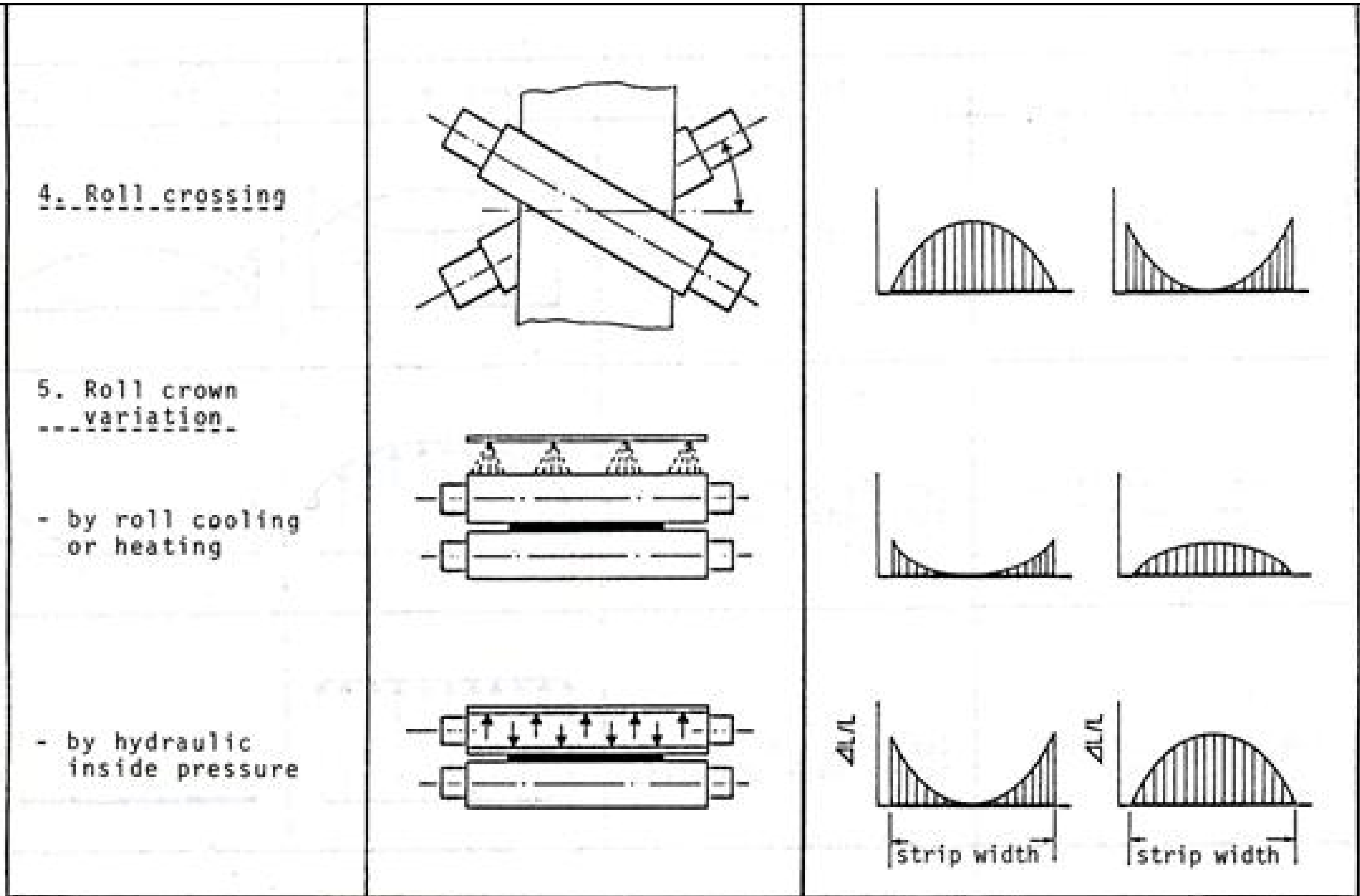


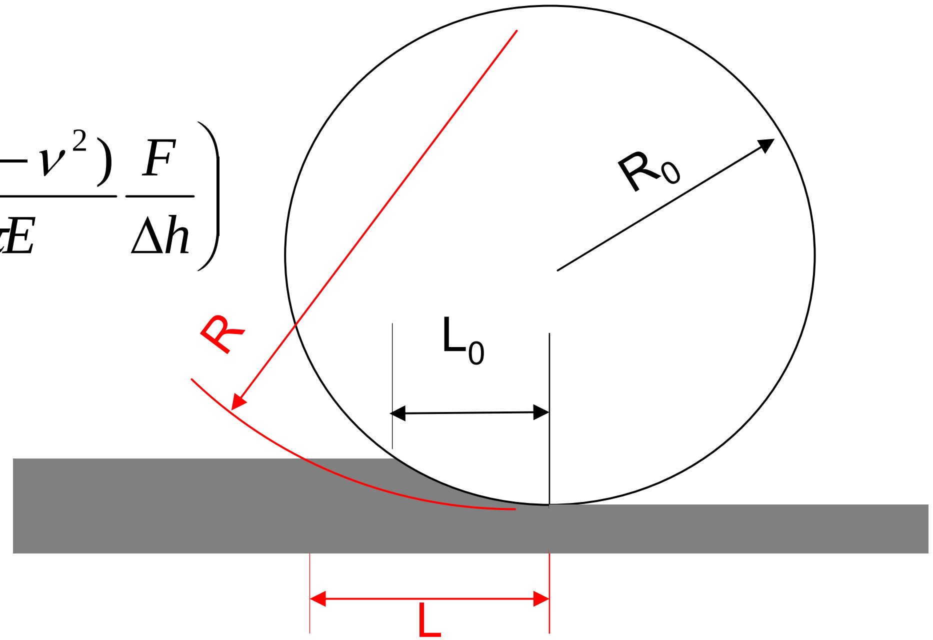
FIGURE 3: MEANS OF CONTROLLING STRIP SHAPE

On roll deformation: roll deformation models (2D approach)

Analytical estimate of roll flattening
Hitchcock's formula (1935)

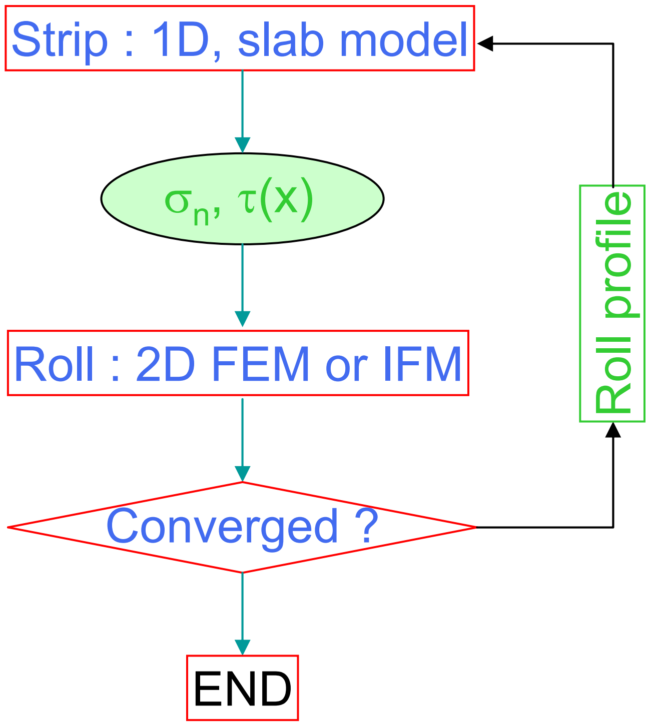
Based on Hertz's elastic contact theory, it assumes a circular deformed roll profile

$$\mathrm{R} = \mathrm{R}_0 \left(1 + \frac{16(1-\nu^2)}{\pi E} \frac{F}{\Delta h} \right)$$



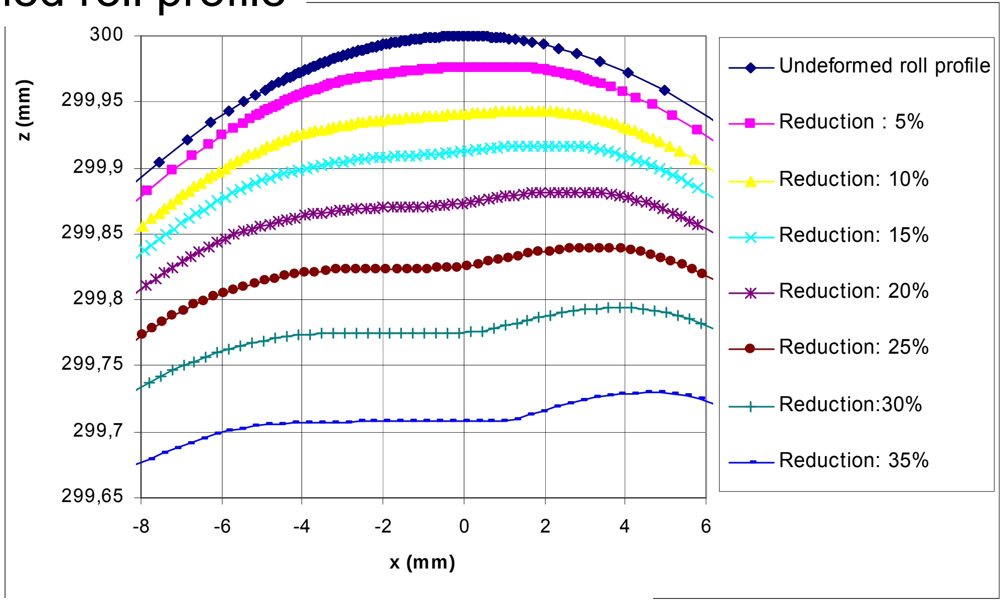
This approximation may be grossly erroneous if $R/R_0 > 2$

Coupled roll / strip modelling

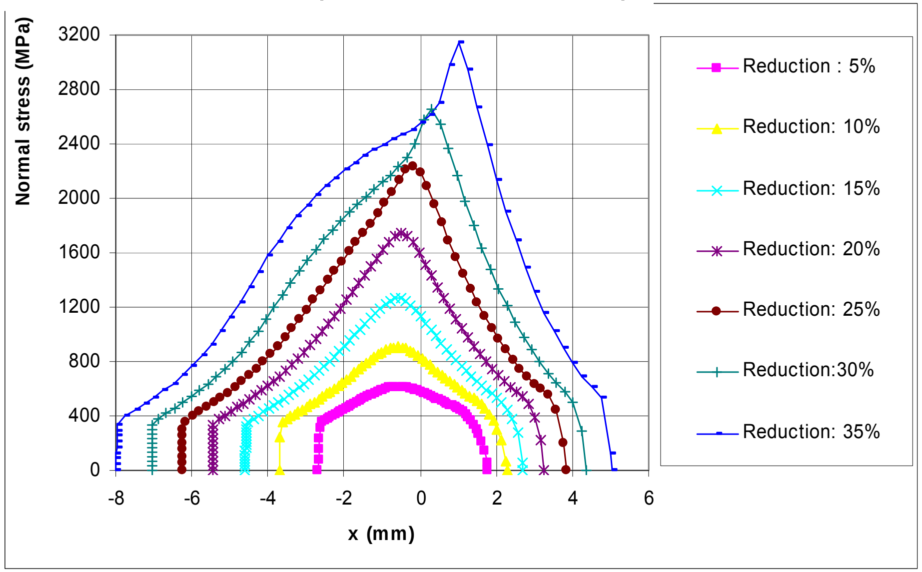


IFM = Influence Function Method

Deformed roll profile

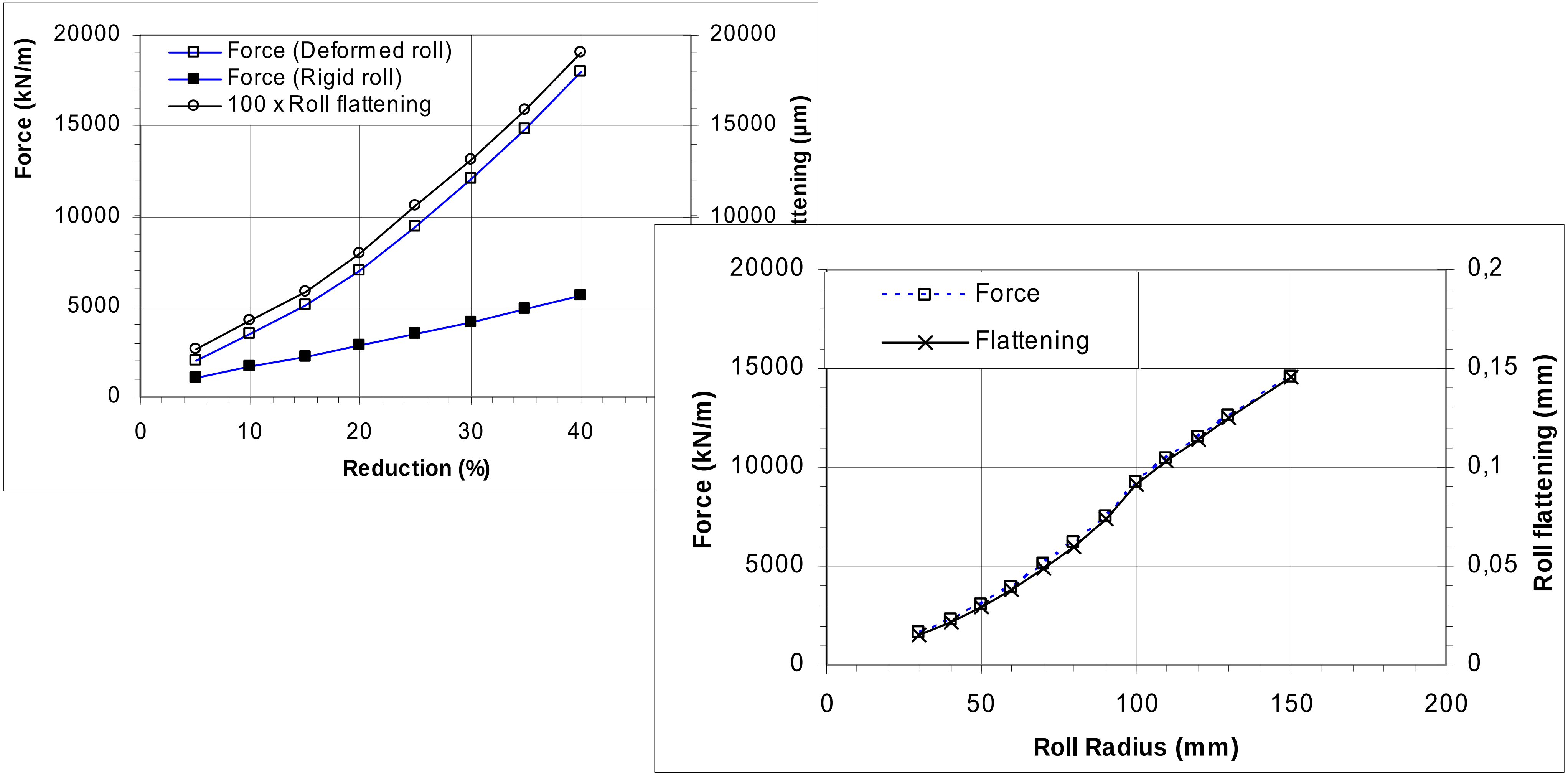


Normal stress profile (« friction hill »)



h_1 = 0.3 mm, R = 300 mm, variable reduction.
Steel strip, $\sigma_0 = 300(1+50.\bar{\varepsilon})^{0.1}$,
Friction coefficient μ = 0.05

Influence of roll deformation on roll load (through contact length)

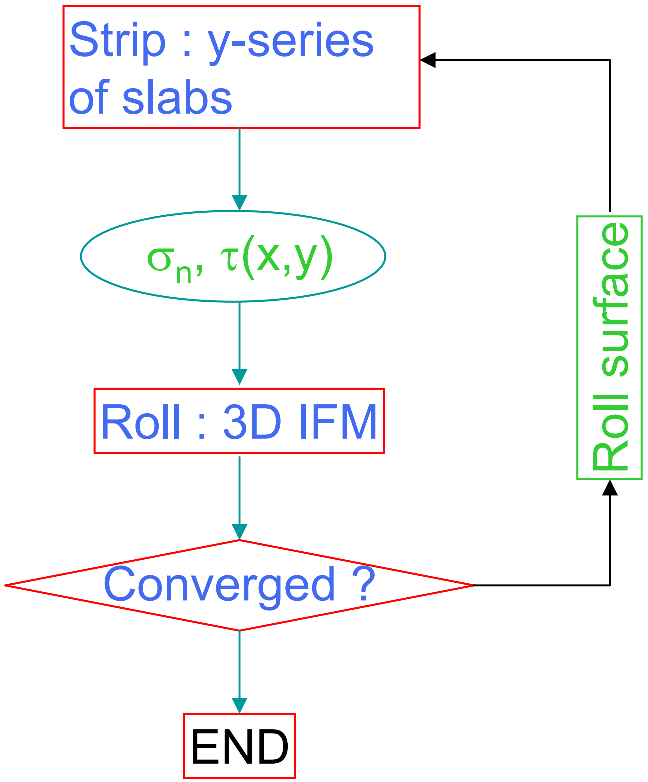


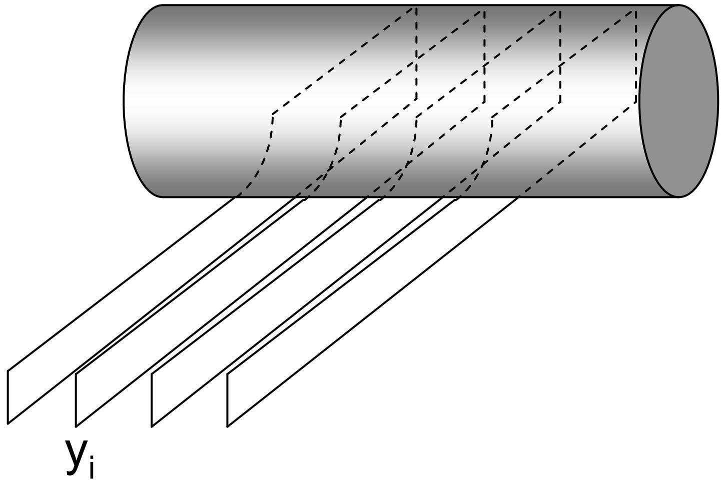
Small rolls give less flattening and lower edge-drop defect

Roll flattening (local decrease of the radius) is roughly proportional to the load and to the radius

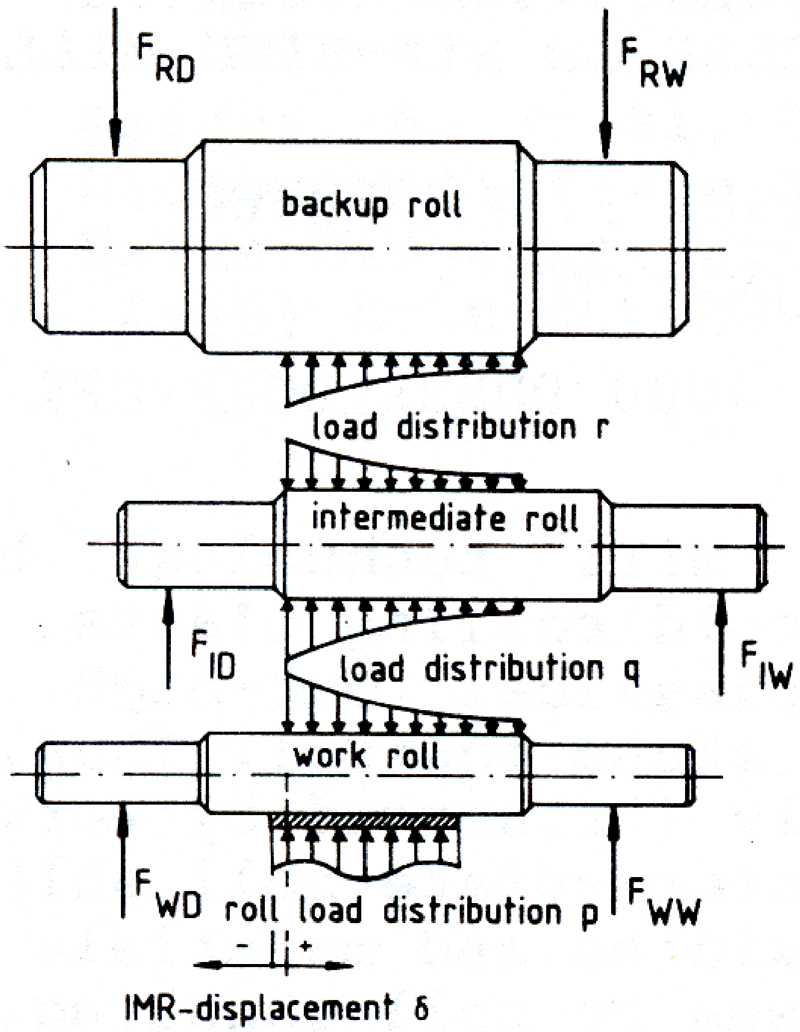
On roll deformation:
roll deformation models
(3D approach)

3D approach #1:
iterative modeling of roll flattening and roll bending



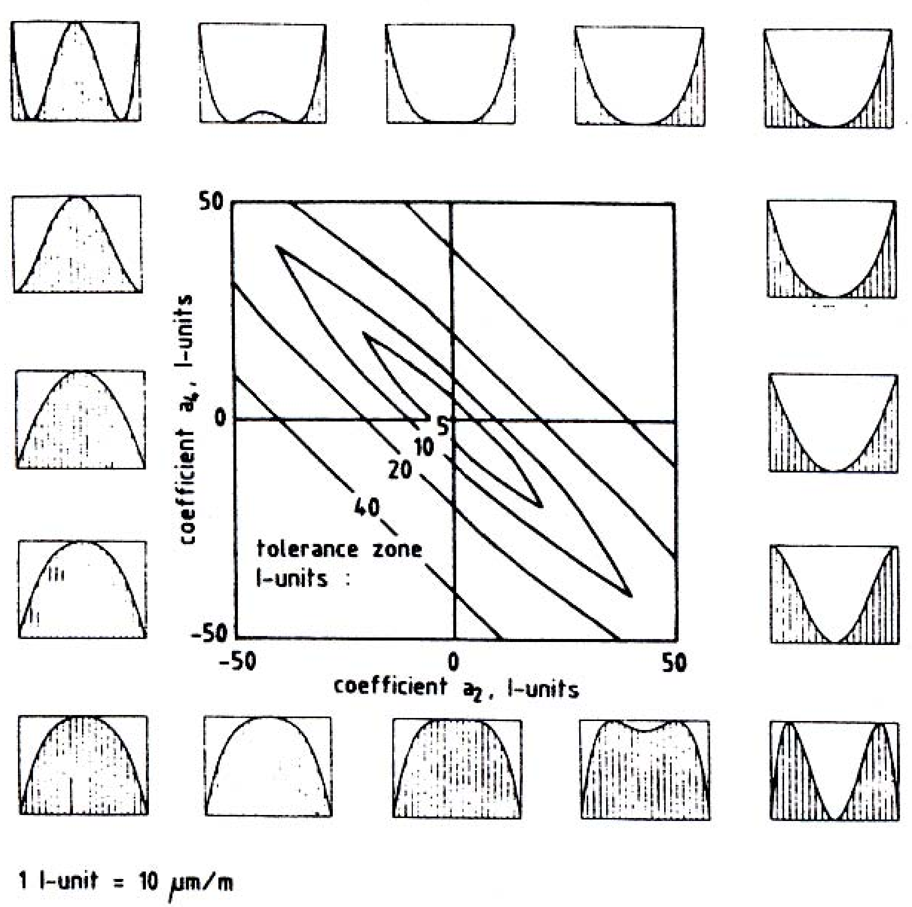


An application: understanding the 6-high mill



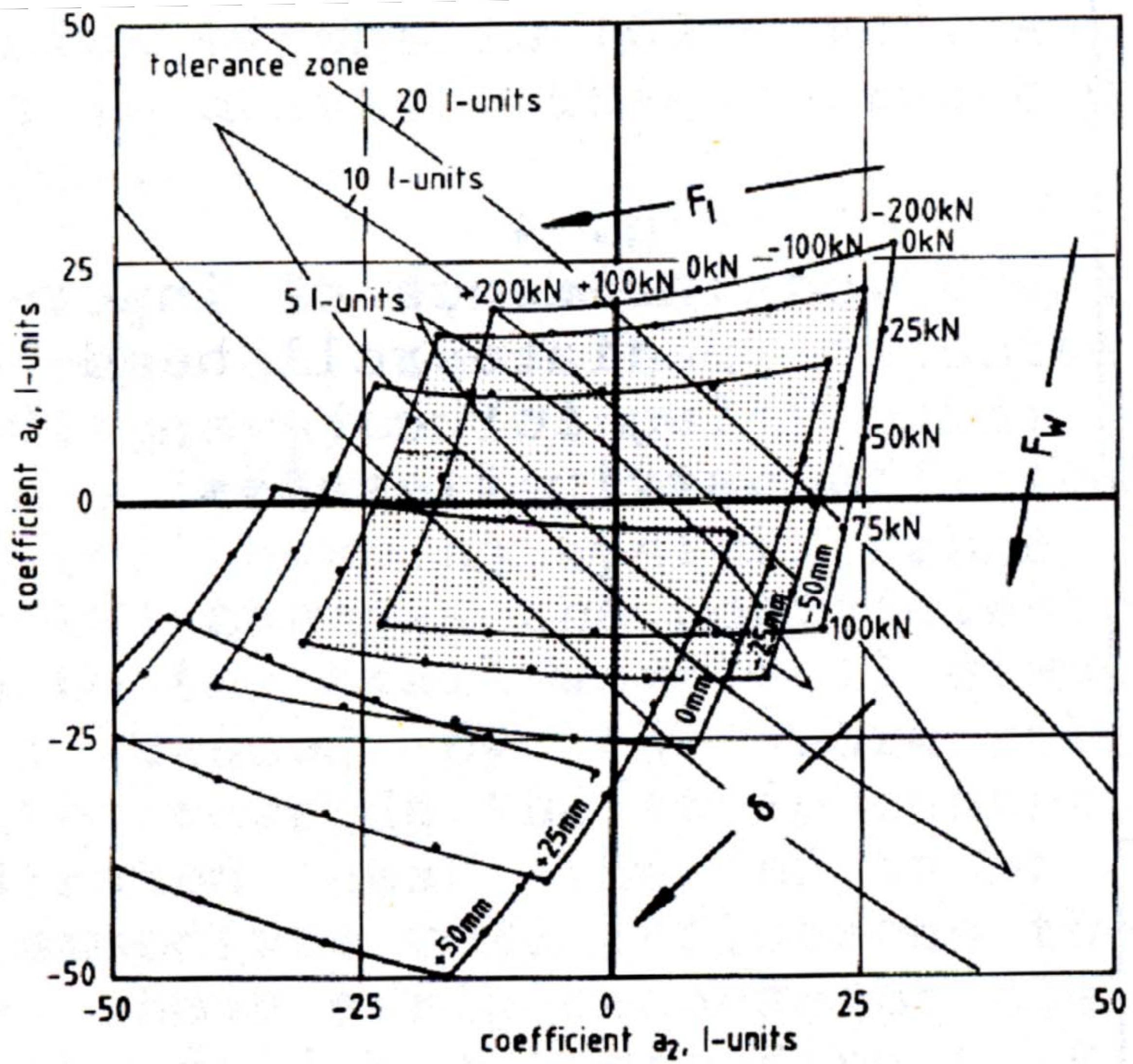
Relative differential elongation

$$\frac{\Delta\Lambda}{\Lambda}(y) = a_2\left(\frac{y}{w/2}\right)^2 + a_4\left(\frac{y}{w/2}\right)^4 - A\exp\left(-\frac{w/2-|y|}{B}\right)$$



Description of strip profile by a 4th-order polynomial (1 I-unit (IU) = 10^{-5})

Effect of the WR and IR bending forces on reduction profile and strip flatness



- F_i is found to influence mainly a_2
- F_w changes firstly a_4

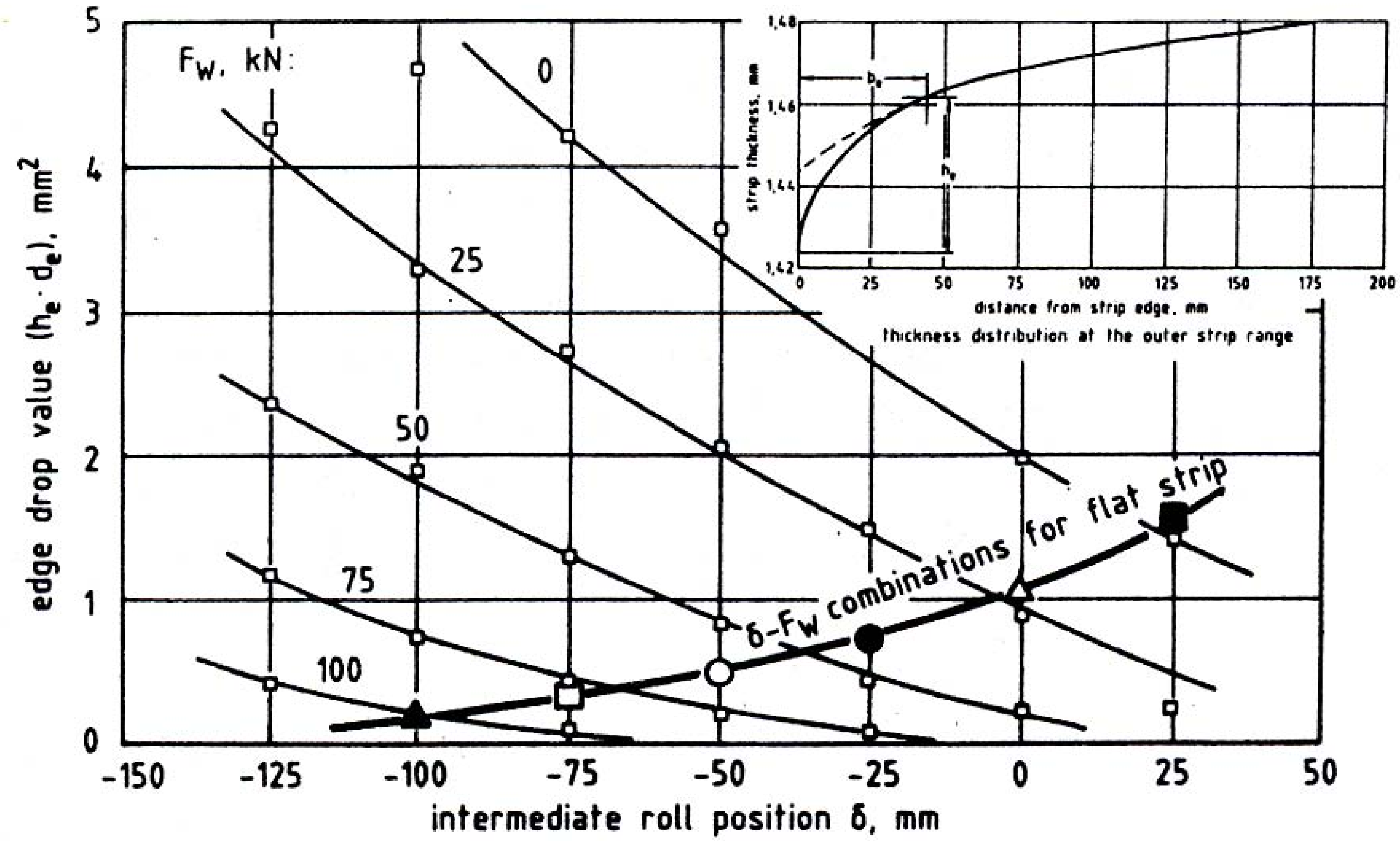
Changing F_i and F_w builds a quadrilateral, the centre of which should be close to $a_2 = a_4 = 0$ for optimal performance

Roll shifting δ can be used for this:

- $\delta < 0$ (outside strip edge) has little effect
- $\delta > 0$ (inside strip edge) is more effective

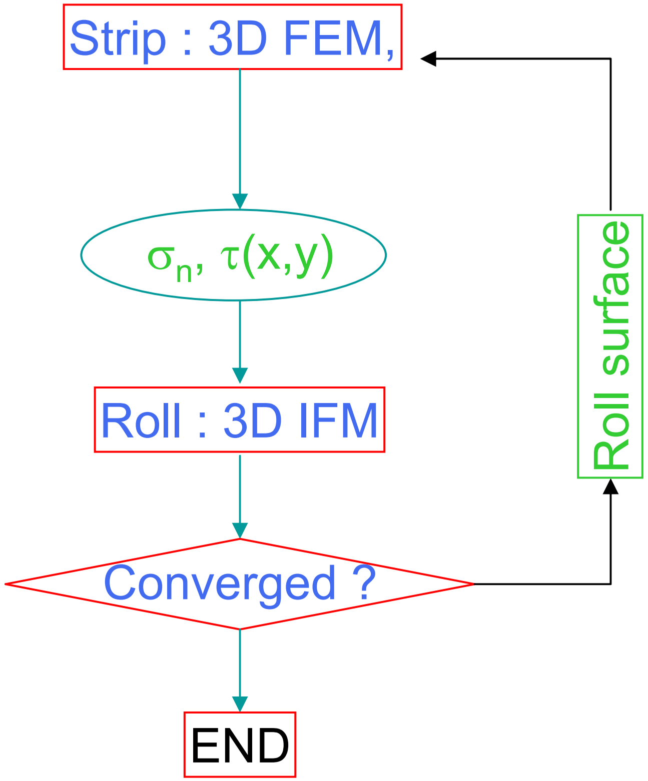
And what about edge-drop ?

- Edge drop is mostly sensitive to F_w and δ.
- Thanks to the redundancy of these 2 parameters, a combination can be selected which gives
  - (1) a flat strip (a_2 and a_4 small)
  - (2) a moderate edge-drop

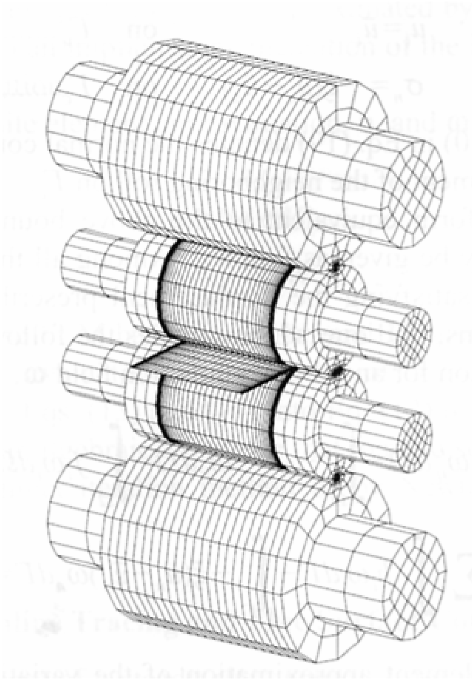


3D approach #2: FEM

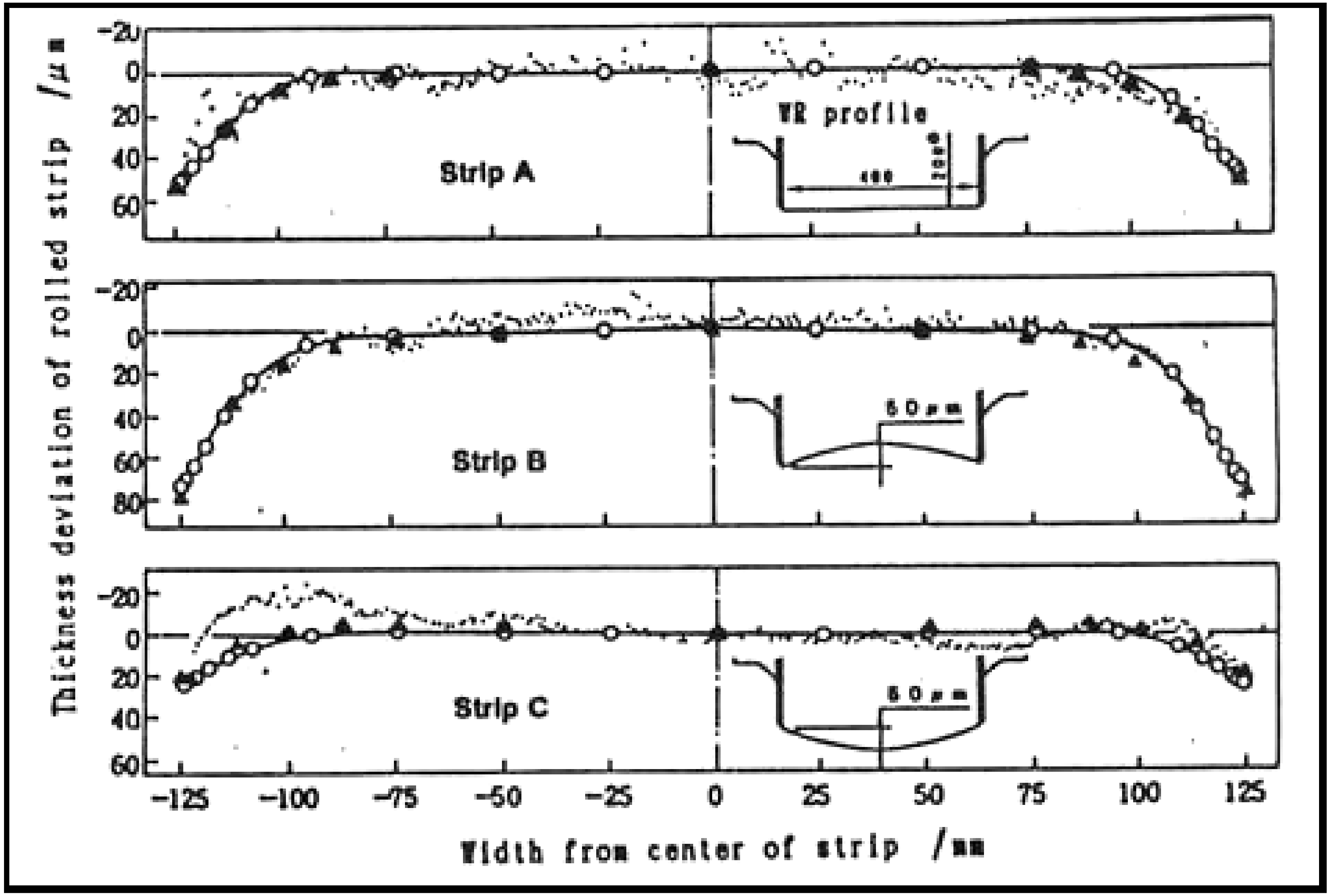
FEM / IFM



All FEM



Application: effect of roll grinding crown on strip profile



Small dots = measurements ;
Empty circles = strip FEM / roll flattening FEM + roll bending IFM
Full triangles = strip FEM / IFM (with end effect corrections)

3 references

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(Metal rolling : thermomechanical analyses