

# Forming

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Materials Engineering  
BMEGEMTBGF1  
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*Ideal lattice:* no defects

*Real lattice:* defects

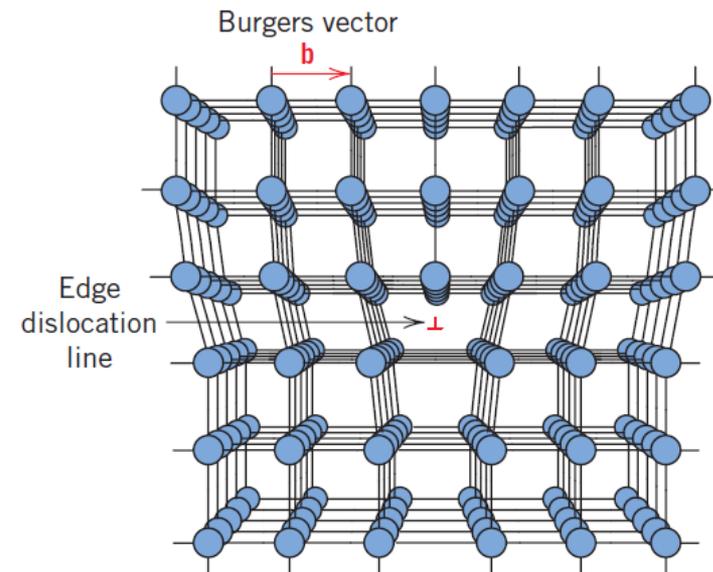
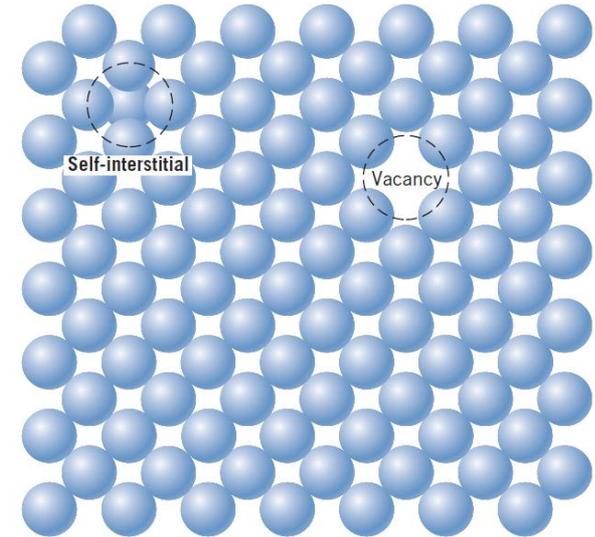
- Vacancy, interstitial atom
- Dislocation
- Grain boundaries
- Precipitations

0D

1D

2D

3D





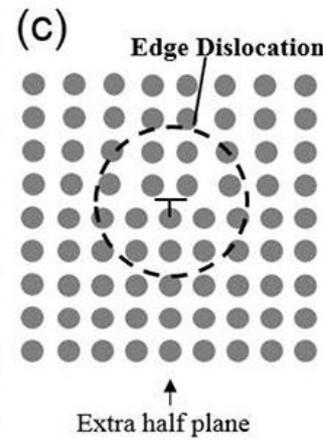
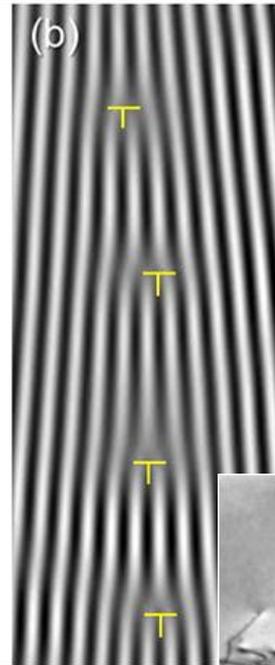
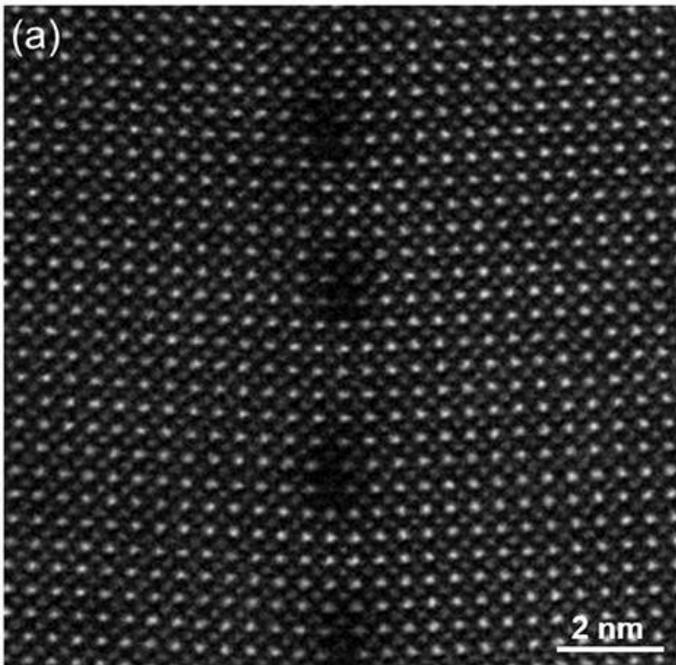
## Plastic deformation

Mechanical properties  $\sim$  plastic deformation

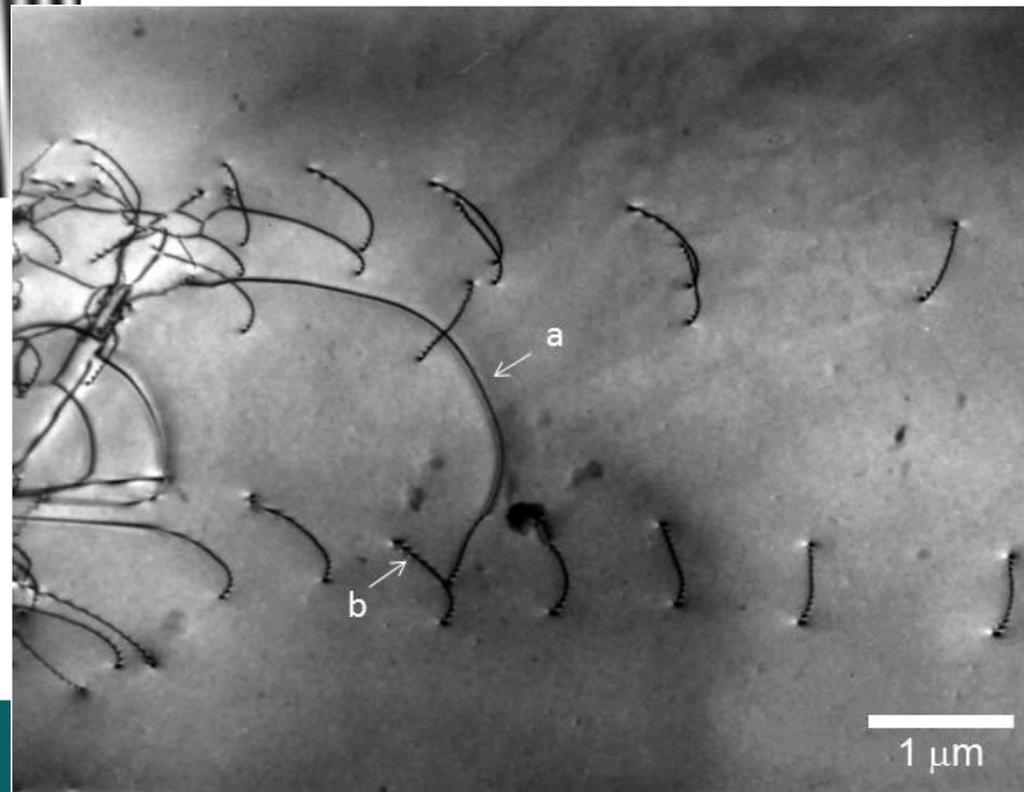
- hardness, toughness, yield stress
- formability

Mechanism of the plastic deformation:

- slip of the dislocation  
(*slip plain and slip direction*)



A linear crystallographic defect or irregularity within a crystal structure that contains an abrupt change in the arrangement of atoms. A dislocation defines the boundary between slipped and unslipped regions.



Bright-field image of dislocations in a silicon crystal taken at an accelerating voltage of 200 kV. (a) A black line (indicated by arrow "a") shows a dislocation line running parallel to the specimen surface.

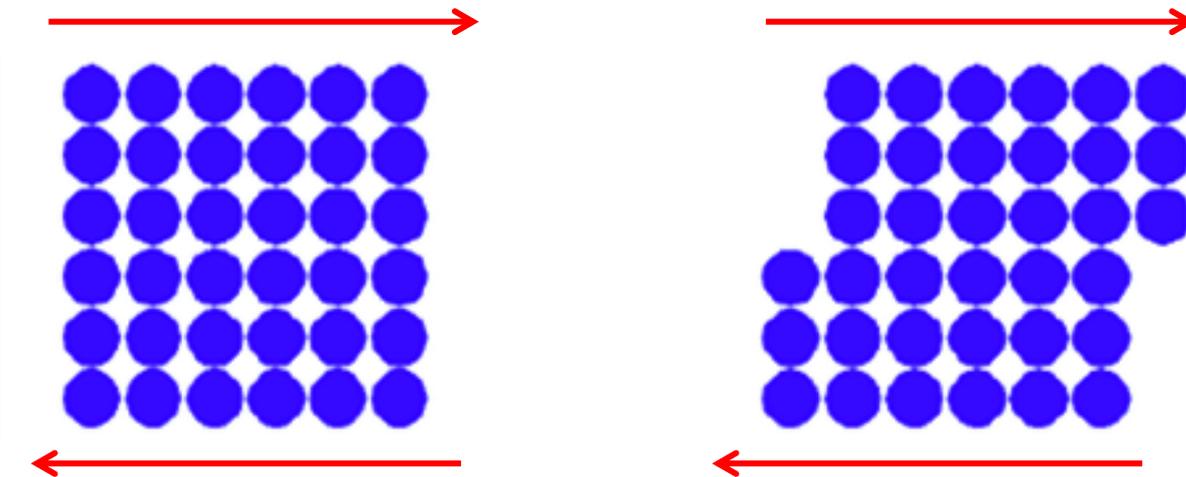
(b) A black zigzag line (indicated by arrow "b") exhibits a dislocation running oblique to the specimen surface. The zigzag contrast is created by a dynamical diffraction effect.

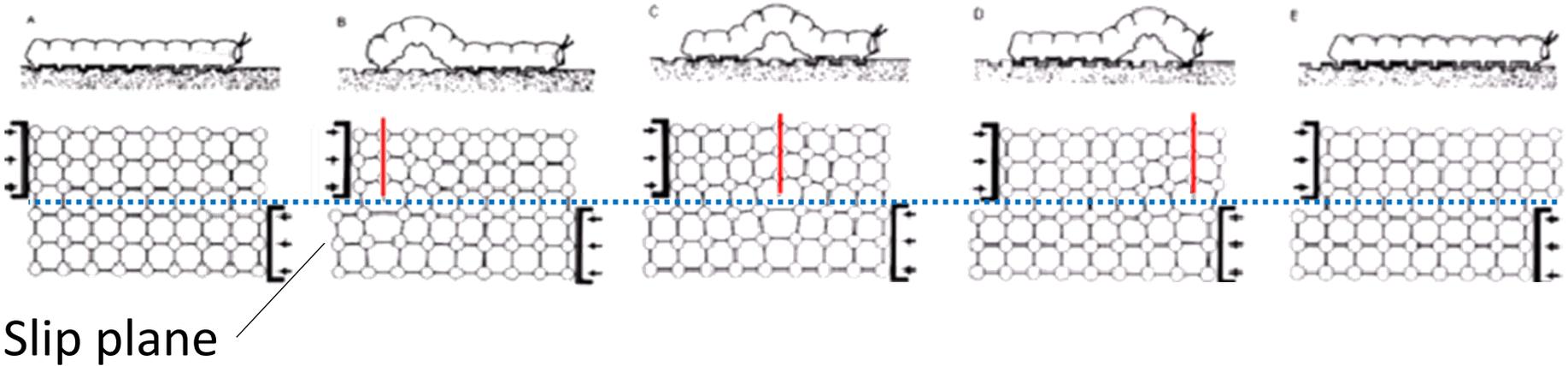
## Elastic deformation

- after the load is removed, no deformation remains
- no rearrangements in the atomic order

## Plastic deformation

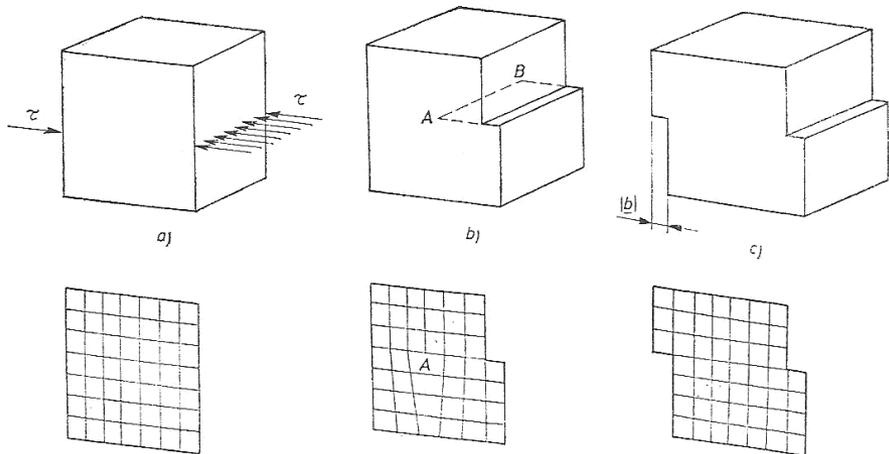
- deformation which remains after load is removed
- atomic rearrangements (change of neighbours)



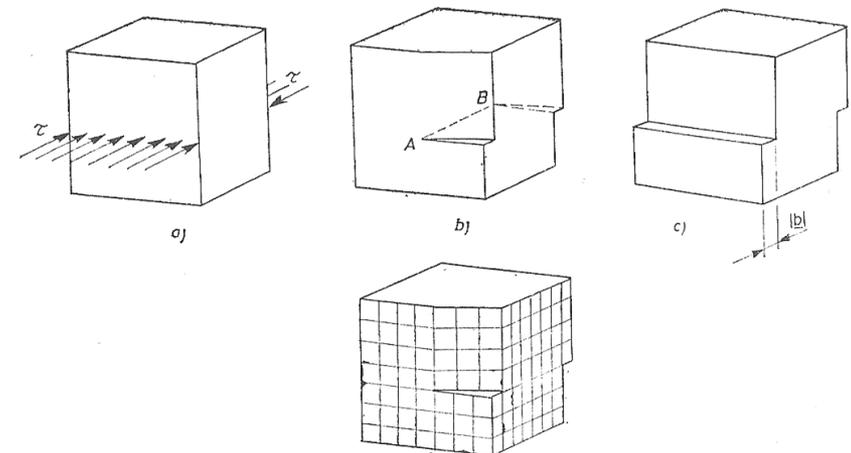


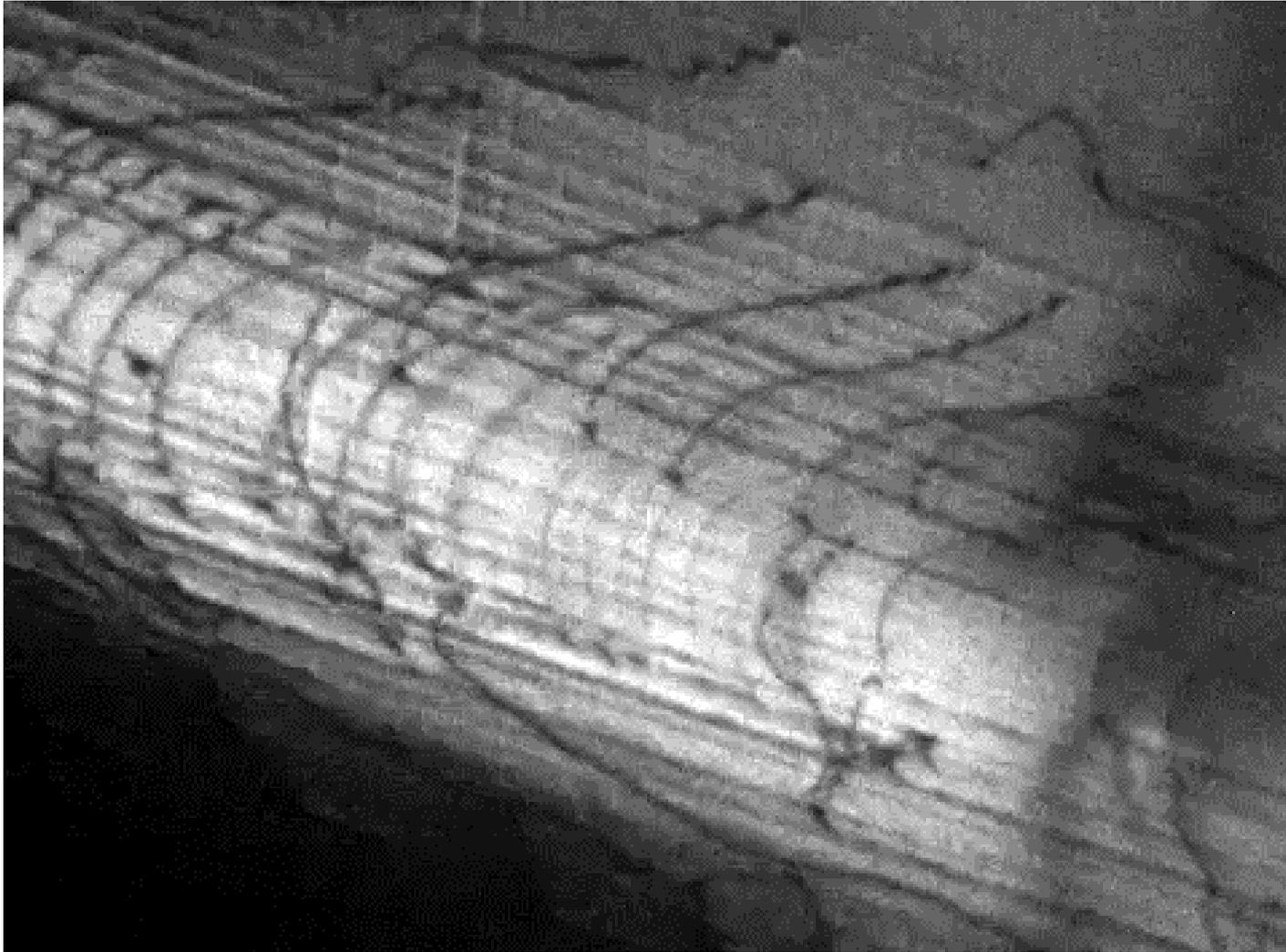
Deformation of crystals occurs by slip of lattice planes, motion of dislocations

## Edge dislocation



## Screw dislocation





Dislocation glide during in situ TEM straining at 400 °C of 304 stainless steel. Video speed is increased 5x.

Stress (pressure)  $\sigma = \frac{F}{A}$

## Driving force for slip:

Tensile stress leads to *resolved shear stress*  $\tau_r$  in slip system

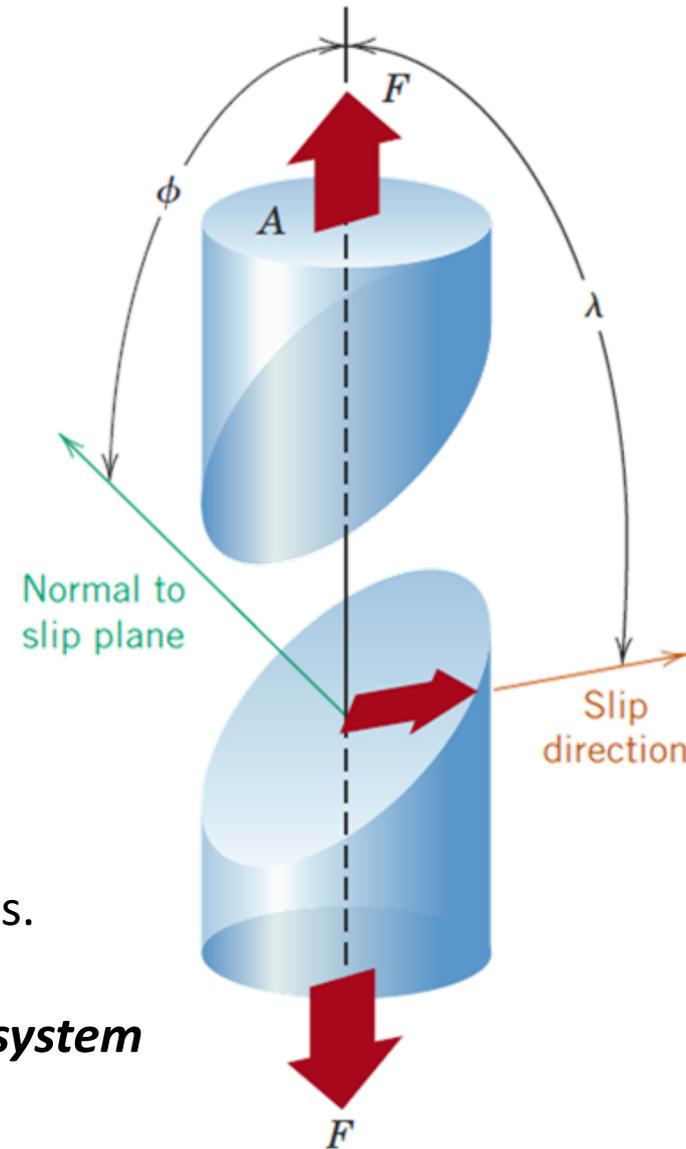
$$\tau_R = \sigma \cos \phi \cos \lambda$$

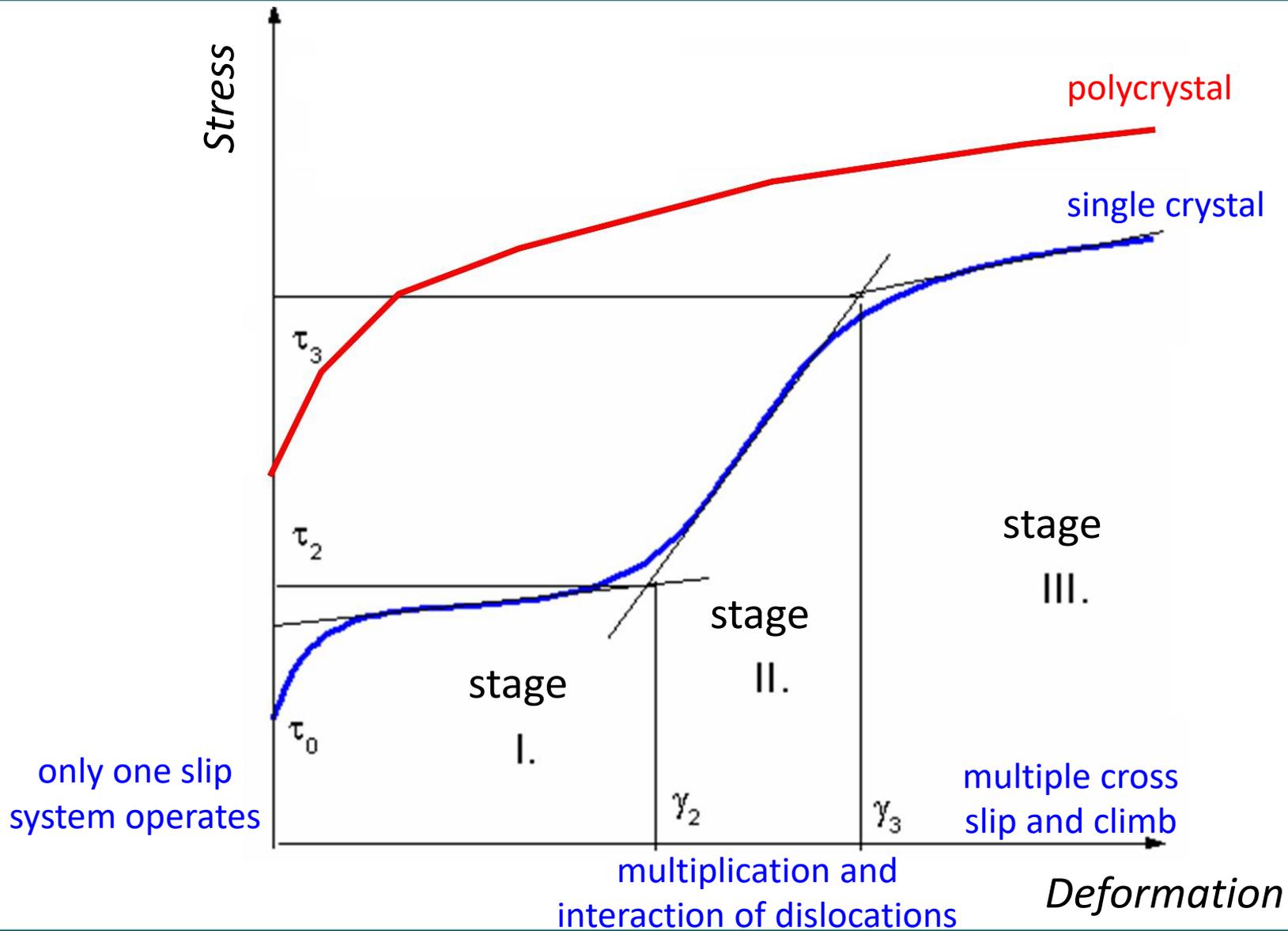
*No shear stress:* slip direction or slip plane normal are perpendicular to the tensile axis

*Maximum shear stress:* slip plane and slip direction are under  $45^\circ$  to the tensile axis.

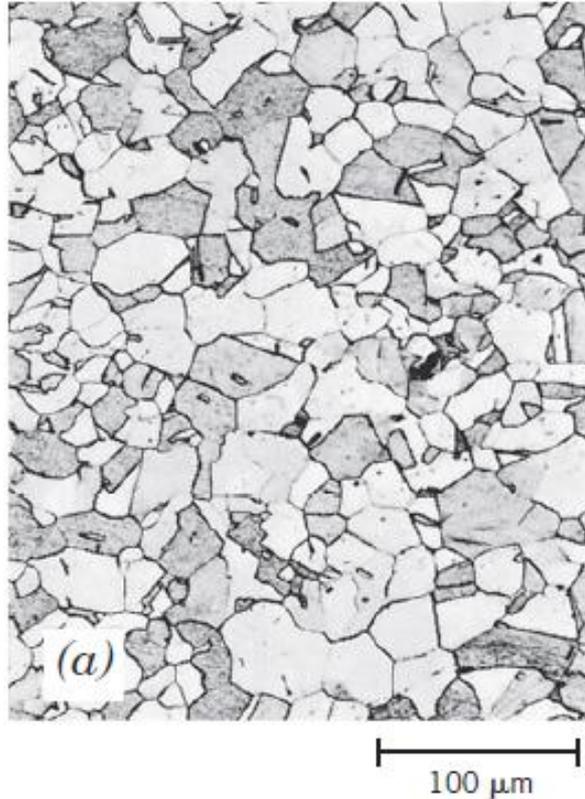
*In single crystals:*

Slip starts on slip system with highest  $\tau_r \rightarrow$  **active slip system**

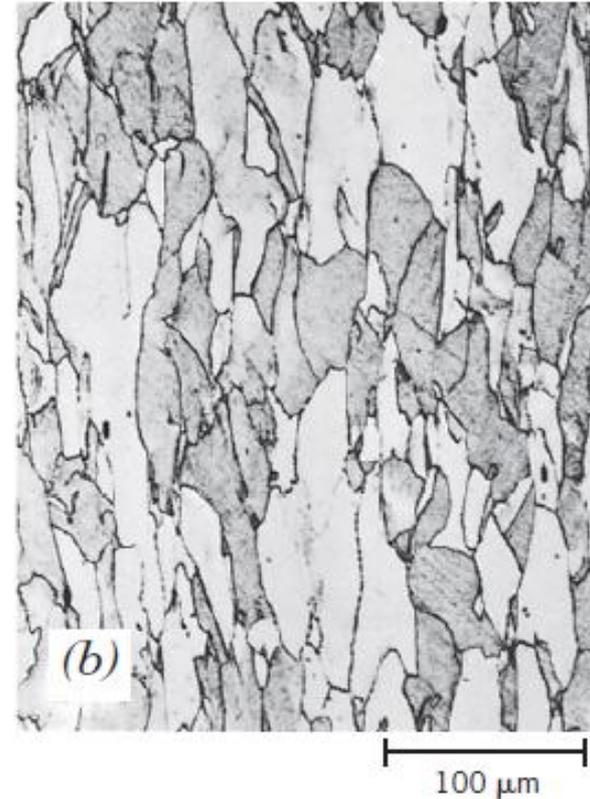




Alteration of the grain structure of a polycrystalline metal as a result of plastic deformation.



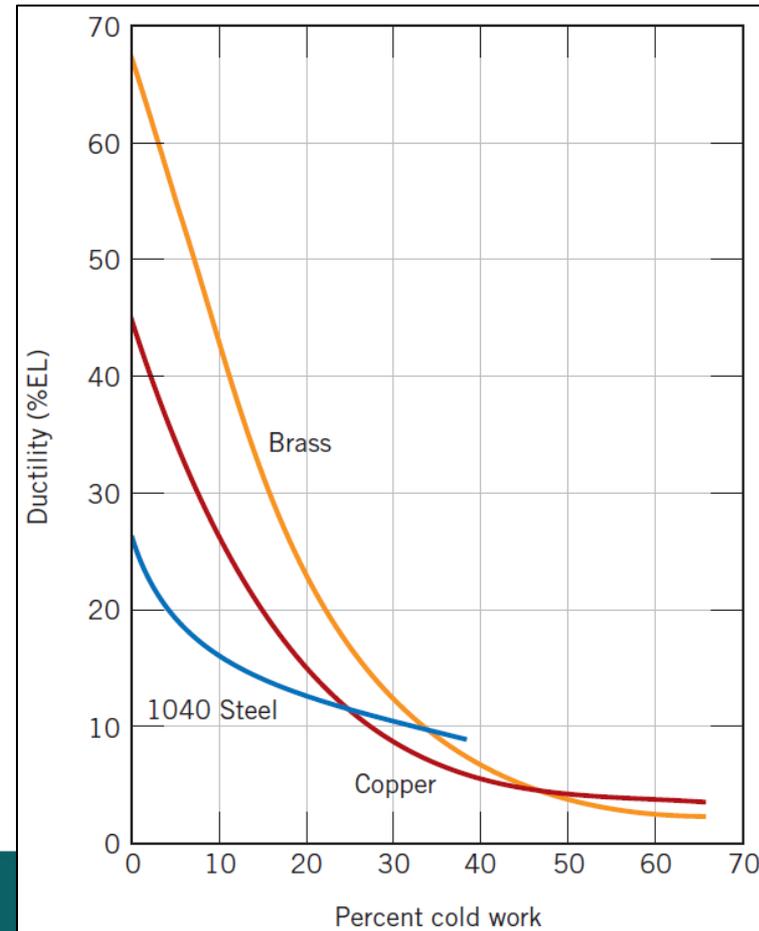
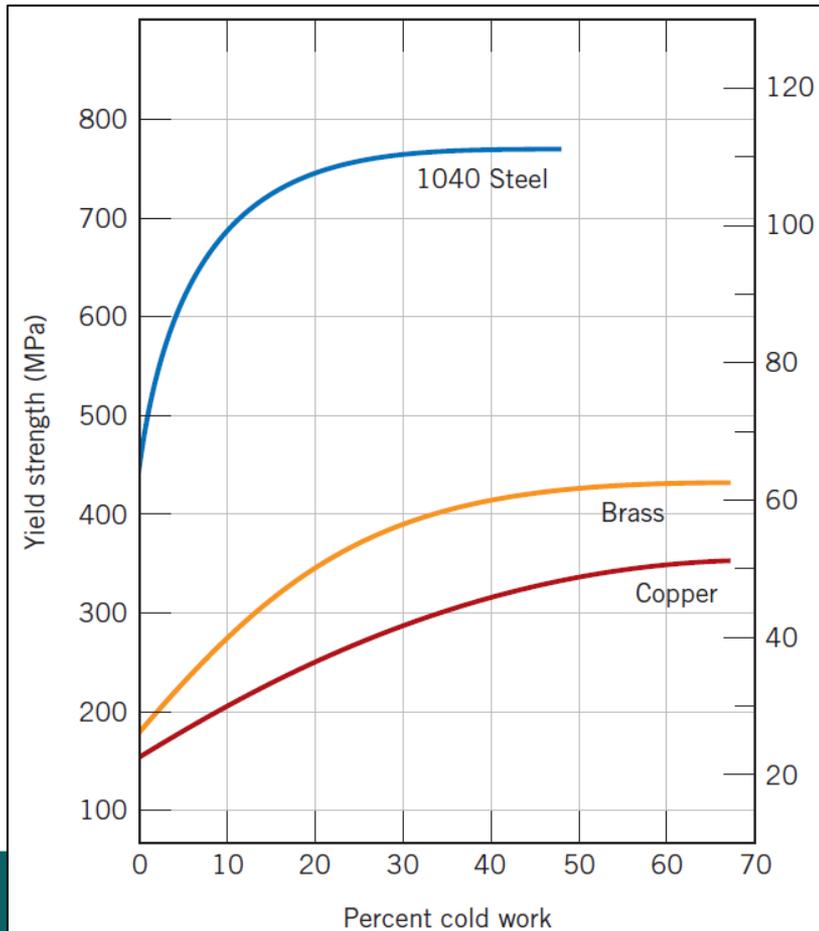
(a) Before deformation the grains are equiaxed.



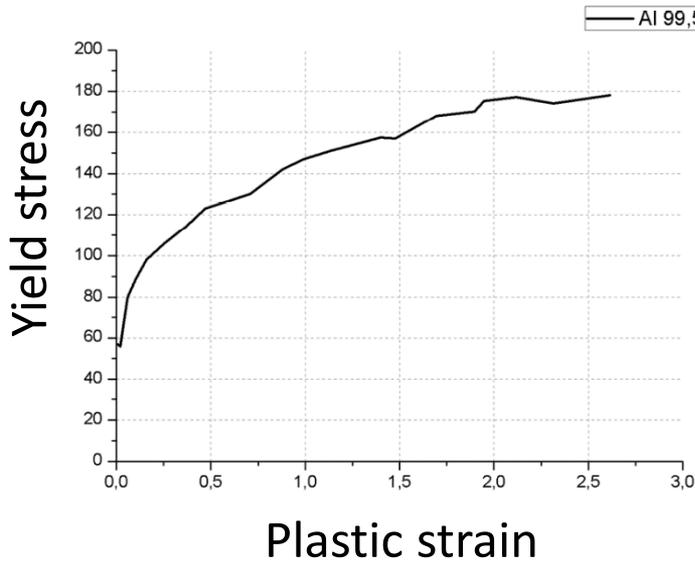
(b) The deformation has produced elongated grains.

The flow curve describes the stress-strain relationship in the region in which metal forming takes place. For most metals at room temperature, the stress-strain plot indicates that as the metal is deformed, its strength increases due to strain hardening. The stress required to continue deformation must be increased to match this increase in strength.

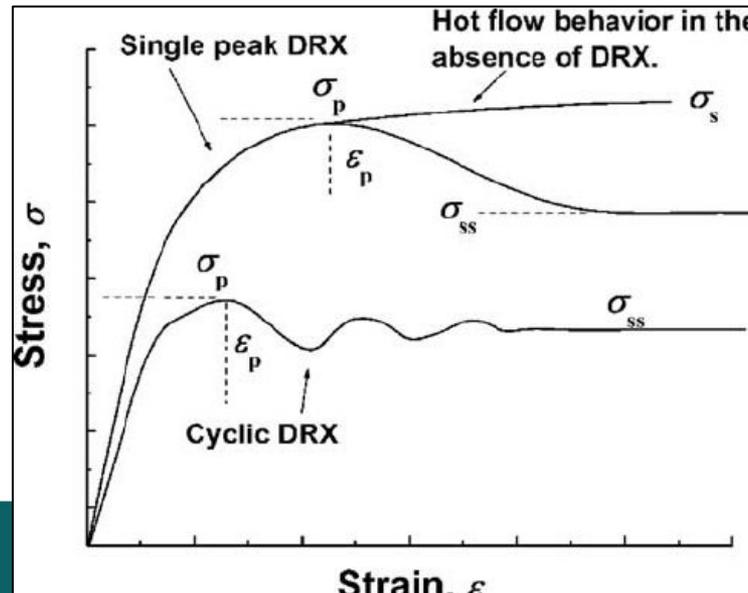
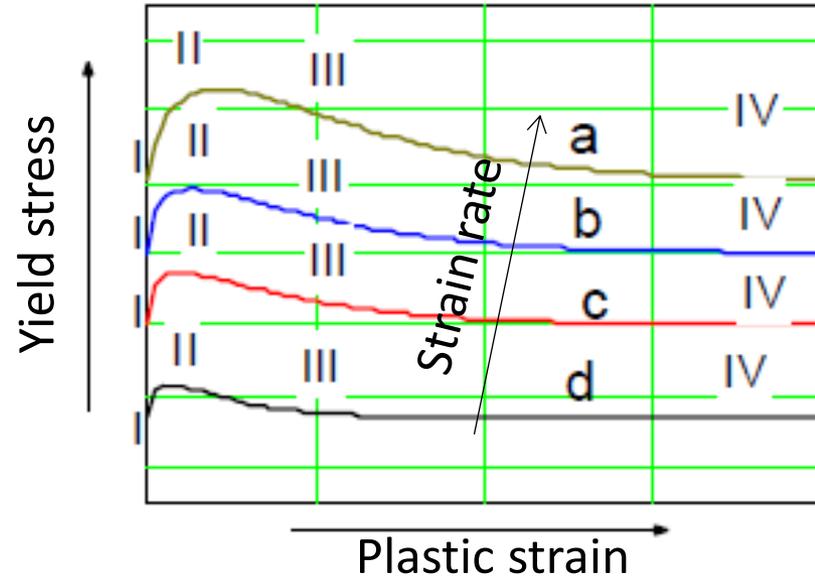
Callister: Materials Science and Engineering, 7th ed.



flow curves – cold deformation

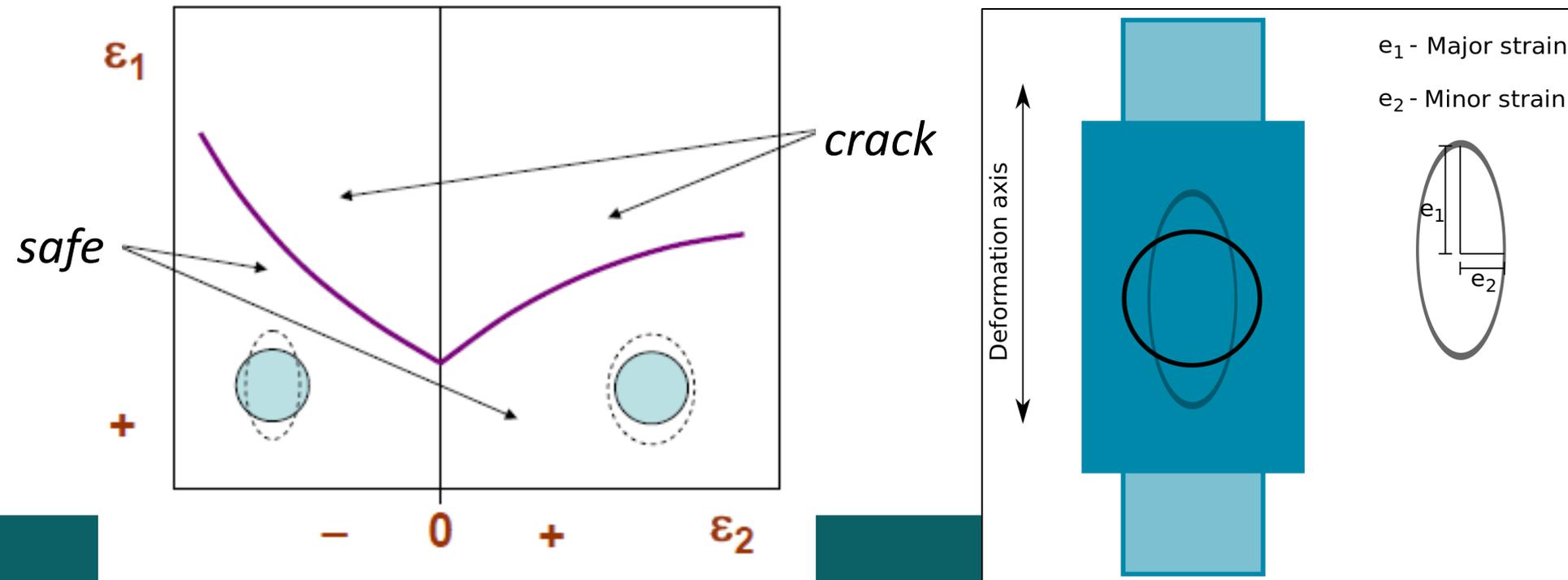


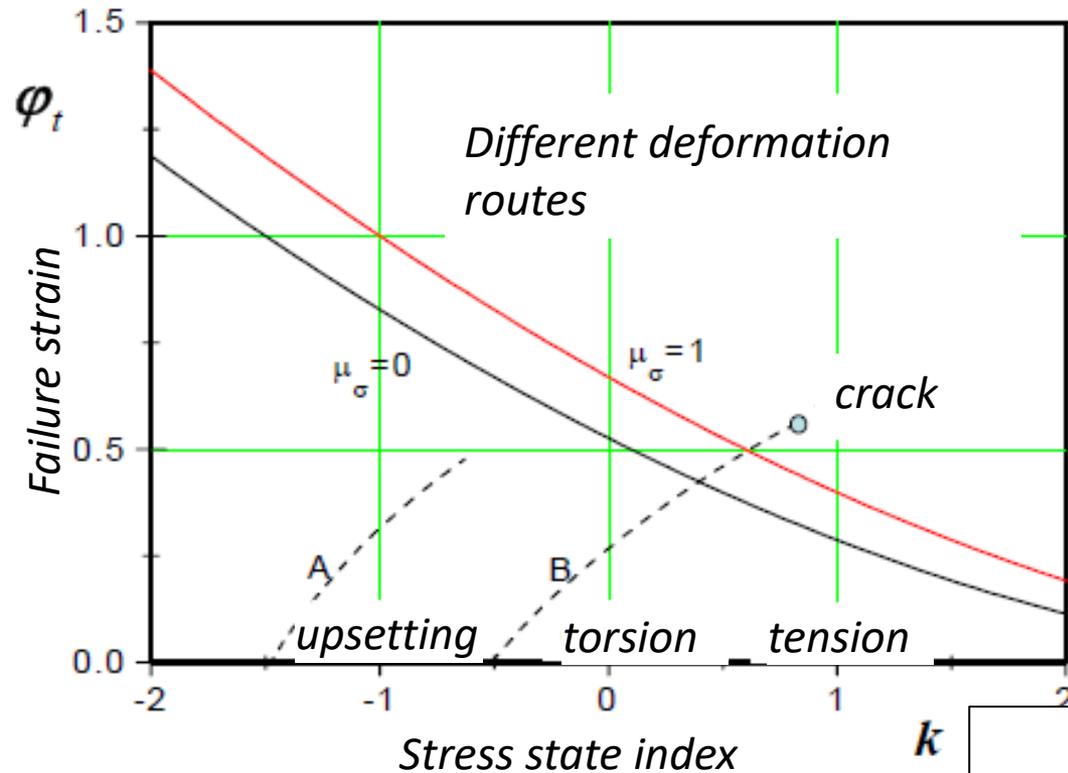
flow curves – hot deformation



[https://www.researchgate.net/publication/250196836\\_Modeling\\_of\\_the\\_hot\\_deformation\\_behavior\\_of\\_boron\\_microalloyed\\_steels\\_under\\_uniaxial\\_hot-compression\\_conditions/figures?lo=1](https://www.researchgate.net/publication/250196836_Modeling_of_the_hot_deformation_behavior_of_boron_microalloyed_steels_under_uniaxial_hot-compression_conditions/figures?lo=1)

- Used in sheet metal forming for predicting forming behavior of sheet metal.
- A minimum of the curve exists at the intercept with the major strain axis or close thereby, the plane strain forming limit.

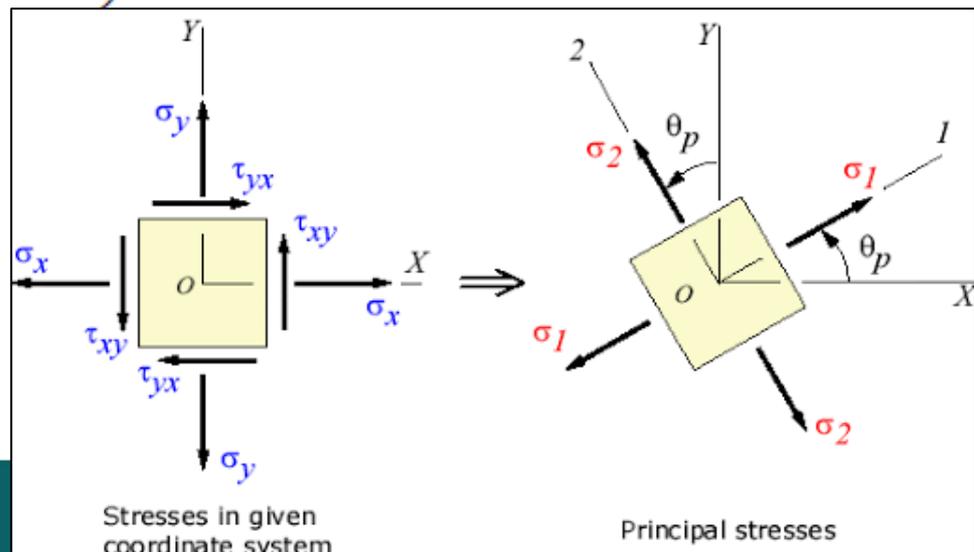




At every point in a stressed body there are at least three planes, called principal planes,  $n$ , called principal directions, where the corresponding stress vector is perpendicular to the plane, and where there are no normal shear stresses. The three stresses normal to these principal planes are called principal stresses.

$$\mu_\sigma = \frac{2\sigma_2 - \sigma_1 - \sigma_3}{\sigma_1 - \sigma_3}$$

$$k = \frac{\sigma_1 + \sigma_2 + \sigma_3}{\bar{\sigma}}$$



## Cold working

- Temperature  $< 0.3 * \text{melting point in deg. K}$
- In practice for most engineering metal this means *room temperature*
- *Work hardening* is dominant

## Hot working

- Above the *recrystallization* temperature
- Temperature  $> 0.5$  (or  $0.6$ ) \* melting point in deg. K
- *Strain rate sensitivity* more important

## Warm working

- Temperature between  $0.3$  and  $0.5$  of melting point
- Flow stresses somewhat less than cold working

## Sheet metal forming

- Input material: sheet form
- Thickness changes very small
- Stresses:        tensile

## Bulk forming

- Input material in the form of bars, billets, etc.
- Thickness of material usually substantially reduced
- Stresses:        compressive

## **Primary forming processes**

- Processes predominantly for producing materials for further processing
- Examples are rolling, drawing, extrusion, etc.

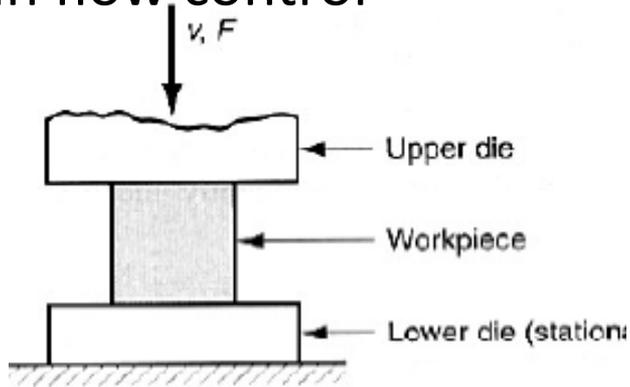
## **Component producing processes**

- Processes for producing component parts
- Input materials produced by primary processes
- Examples are forging, deep drawing, stretch forming, etc.

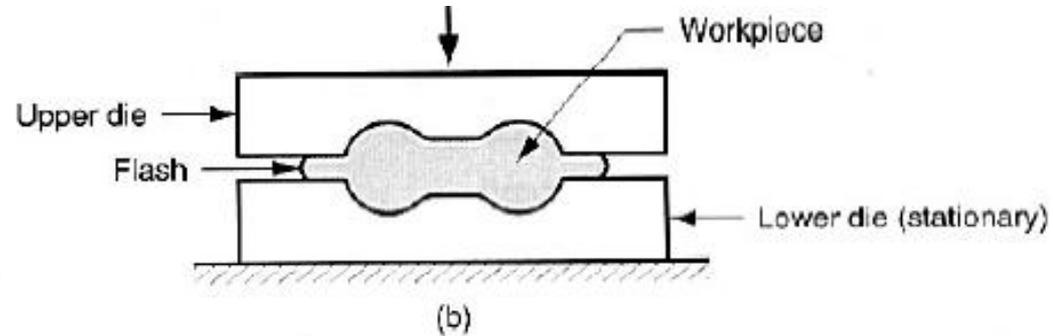
- **Free forming**
  - Tool does not contain the desired shape
- **Two dimensional forming**
  - Point contact between tool and work material
  - Two relative motions required to produce geometry
  - Incremental forming processes
- **One dimensional forming**
  - Line or surface contact with work material
  - Only one relative motion required to produce geometry
- **Total forming**
  - Tool contains the desired geometry
- **Process kinematics within each group differentiates the different processes**

Cold warm and hot forging depending on the temperature

Grain flow control



**Open die**



**Closed die**

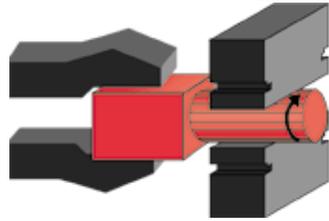
- + Simple and inexpensive dies
- + Small quantity

- Limited to simple shapes
- Low production rate
- High degree of skill required

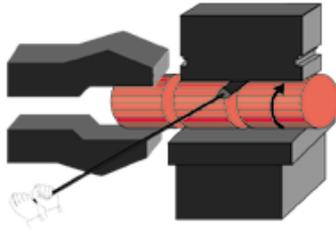
- + Relatively good utilization of material
- + Better properties than open-die forgings

- + Dimensional accuracy
- + High production rates
- + Good reproducibility

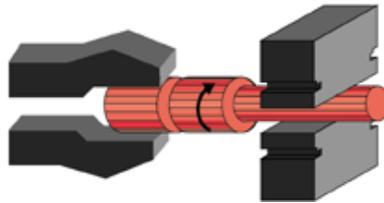
- High die cost
- Not economical for small quantities



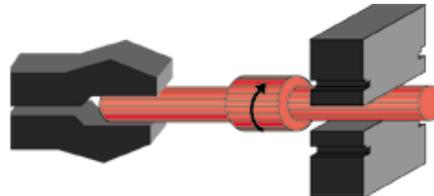
(a) forge hot billet to max diameter



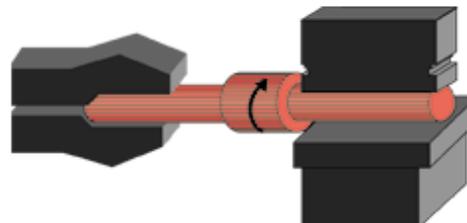
(b) fuller: tool to mark step-locations



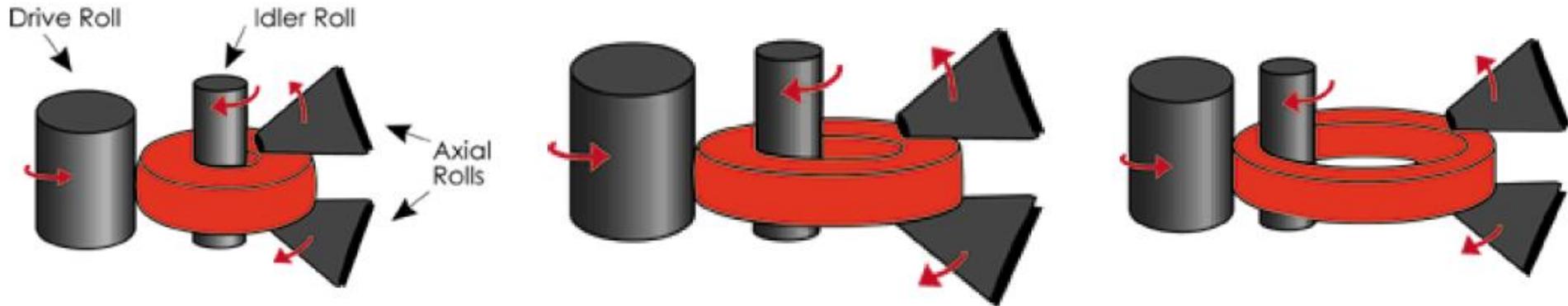
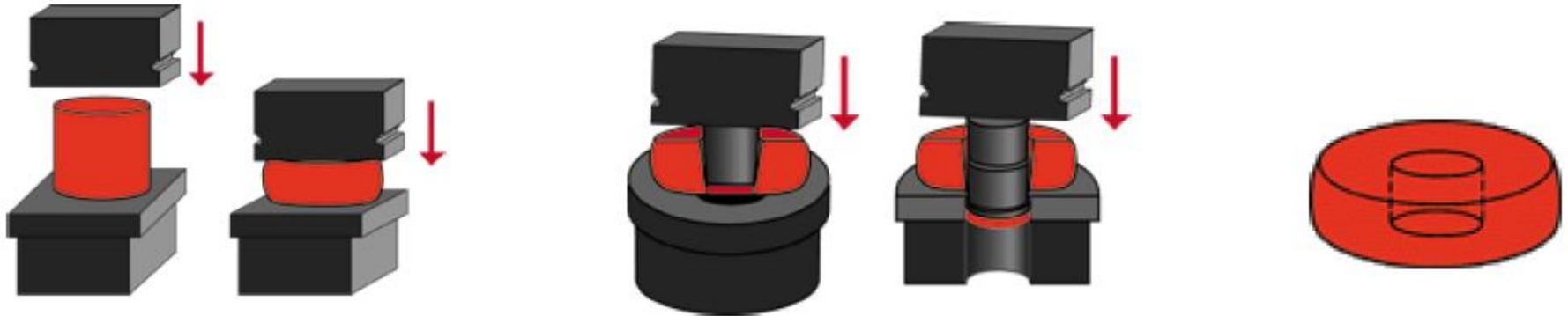
(c) forge right side



(d) reverse part, forge left side

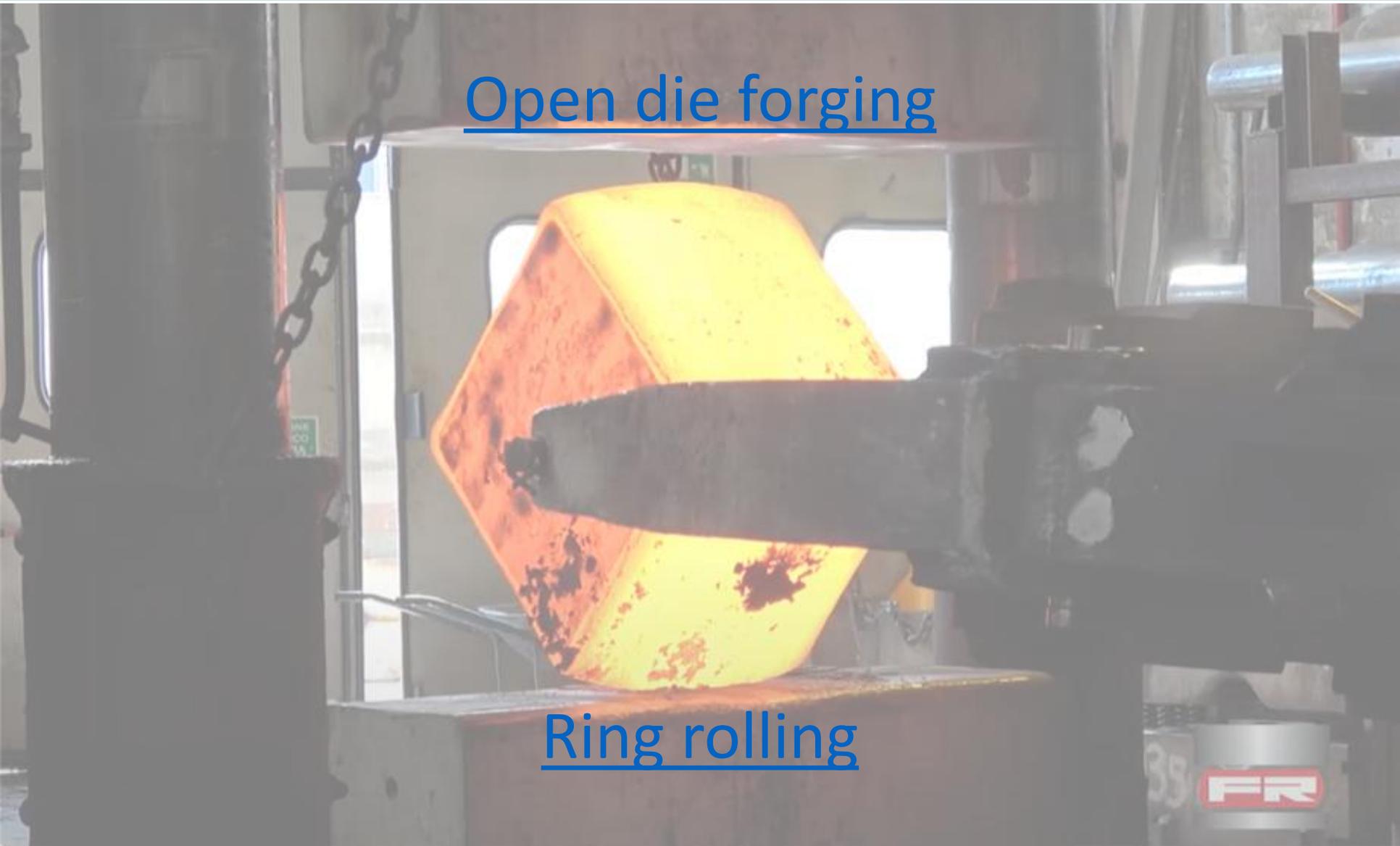


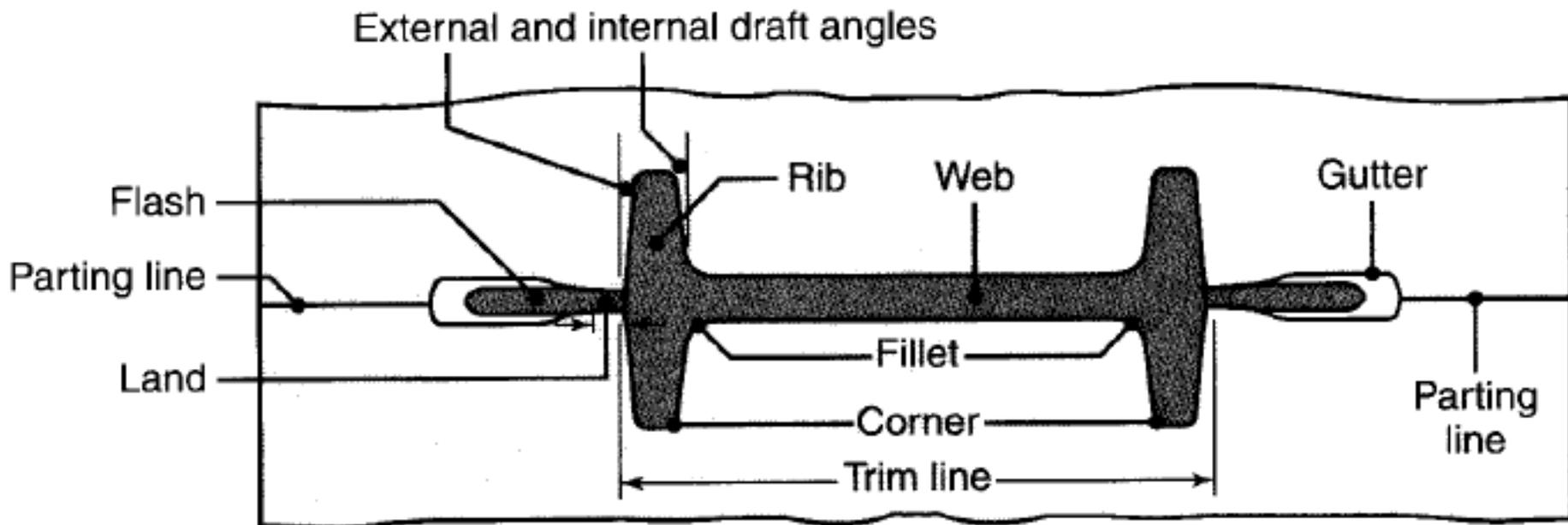
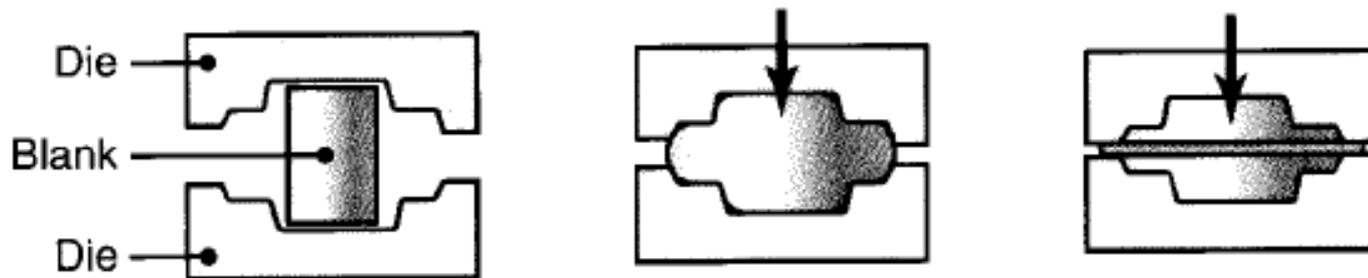
(e) finish (dimension control)

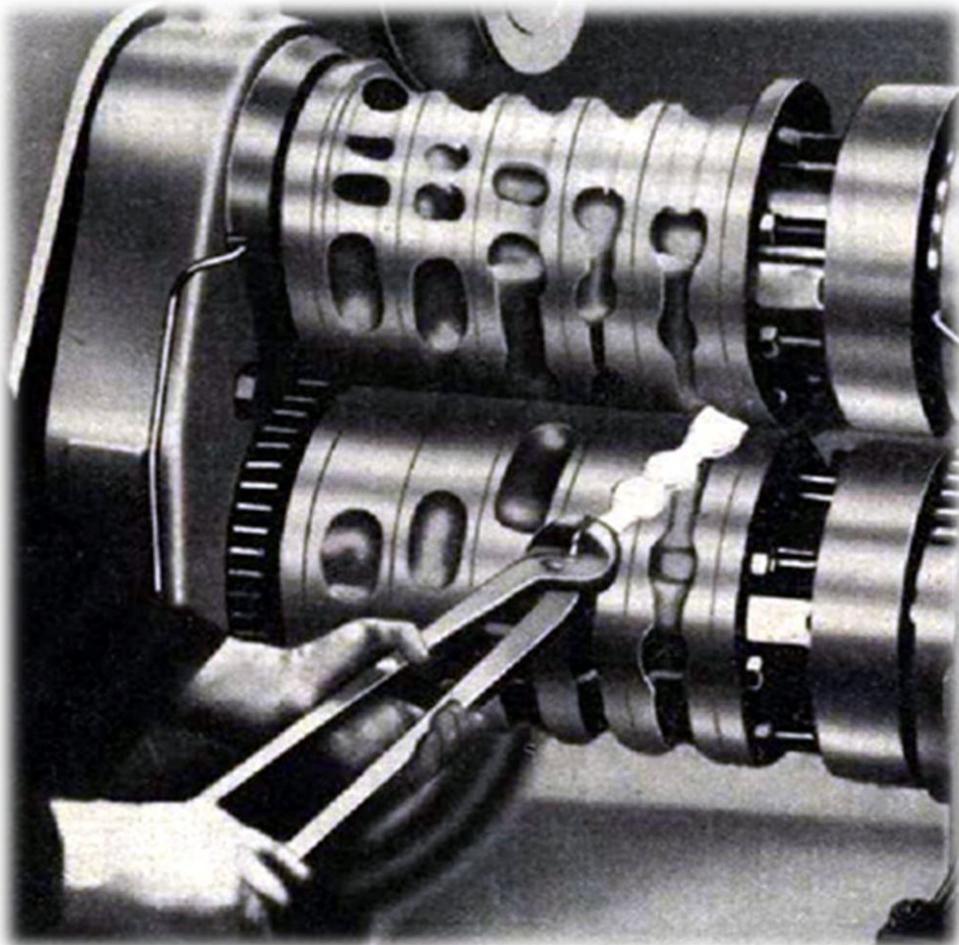


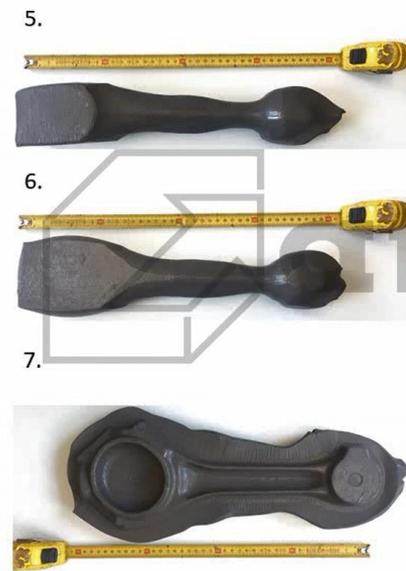
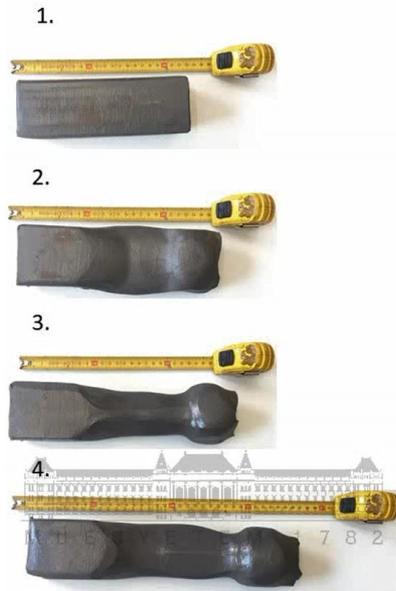
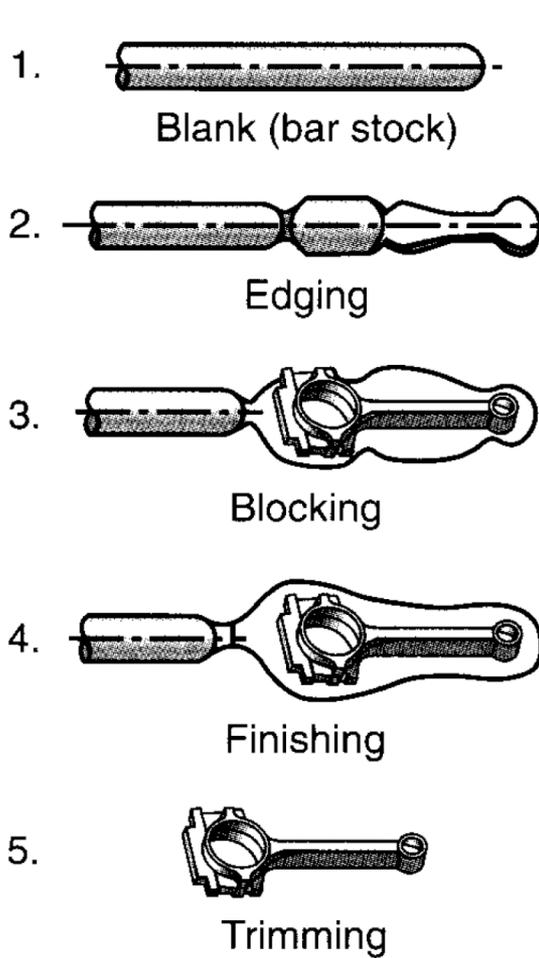
## Open die forging

## Ring rolling









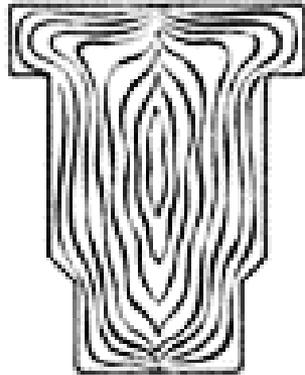
Forging steps of a connecting rod

1. Prepare a slug, billet, by shearing, sawing, or cutting.  
(clean surfaces e-g by shot blasting)
2. For hot forging, heat the workpiece in a furnace and then descale it (wire brush, water jet, or steam)
3. For hot forging: preheat and lubricate the dies  
For cold forging: lubricate the blank
4. Forge the billet in dies and in the proper sequence. (+ material removal (e.g. flash) by trimming, machining, or grinding.
5. Clean the forging and the dimensions
6. Additional operations: straightening, heat treating
7. Machining and grinding to final dimensions and specified tolerances.
8. Inspection: external and internal defects.

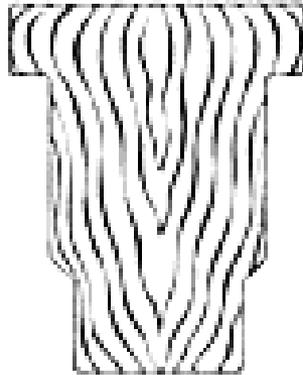
**COLD FORGING**

**HOT FORGING**

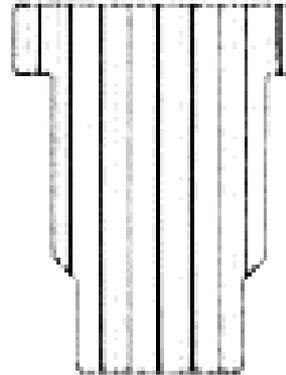
**MACHINING**



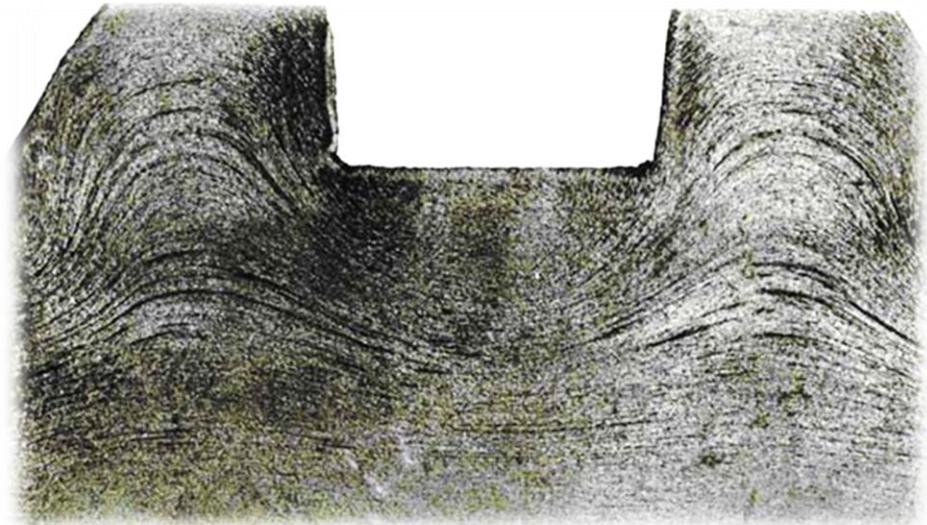
**MAXIMUM  
STRENGTH**



**HIGH  
STRENGTH**



**LOW  
STRENGTH**



## Quality of forged parts

Surface finish/Dimensional control: better than casting (typically)

Stronger/tougher than cast/machined parts of same material

## Closed die forging

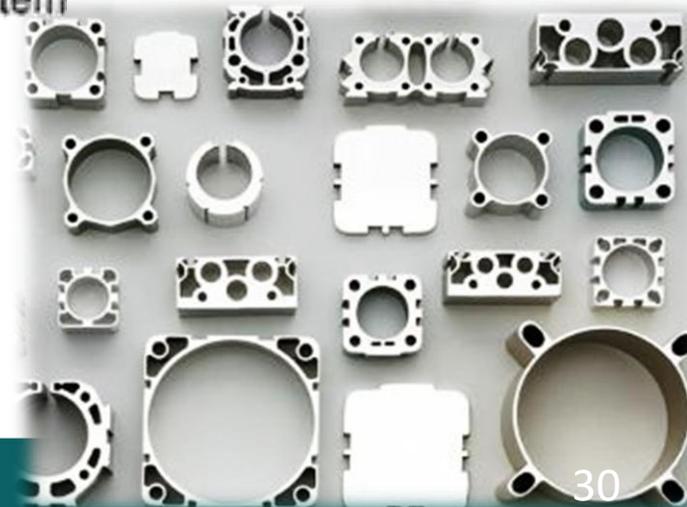
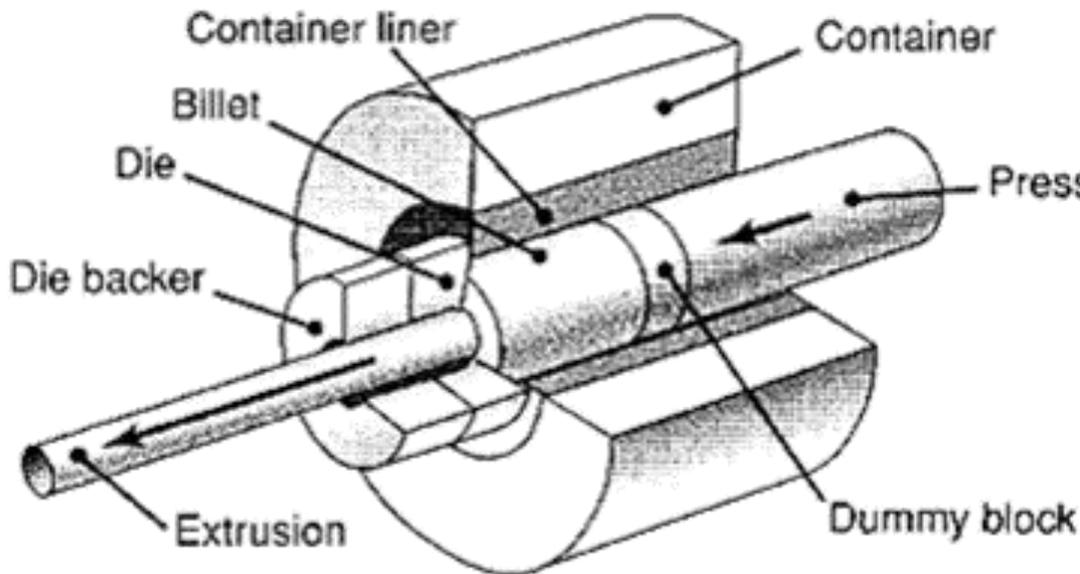


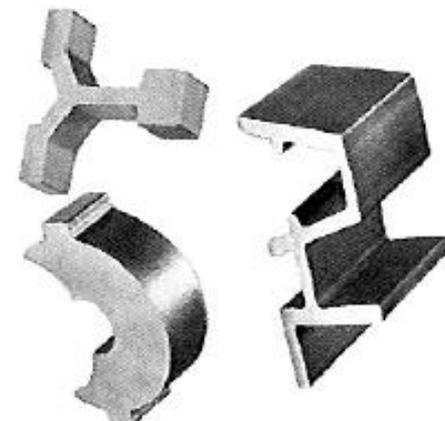
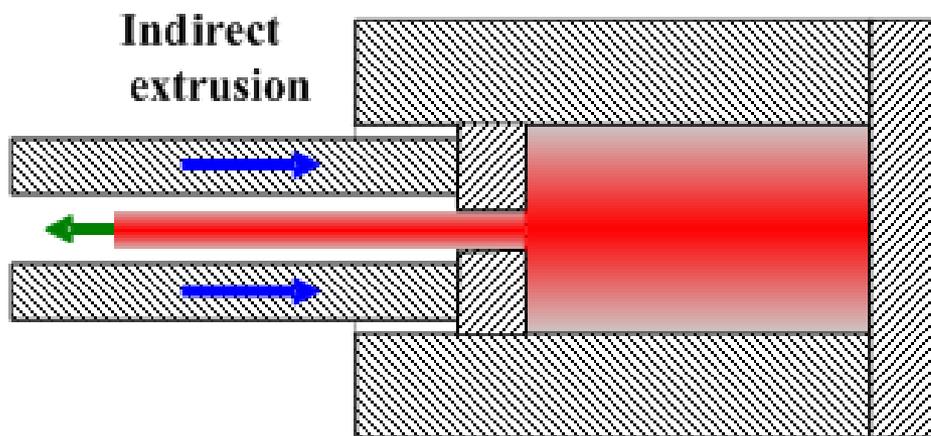
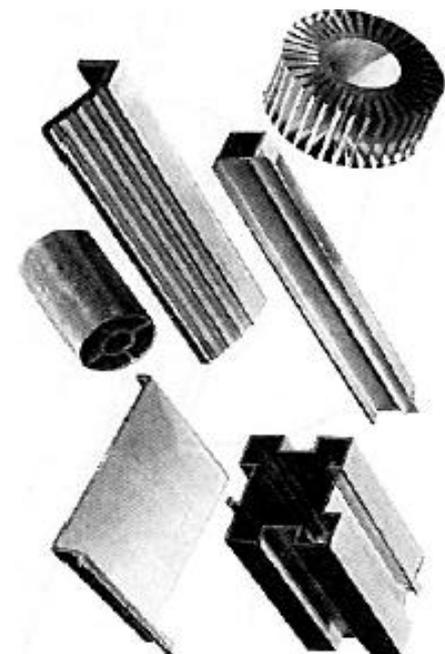
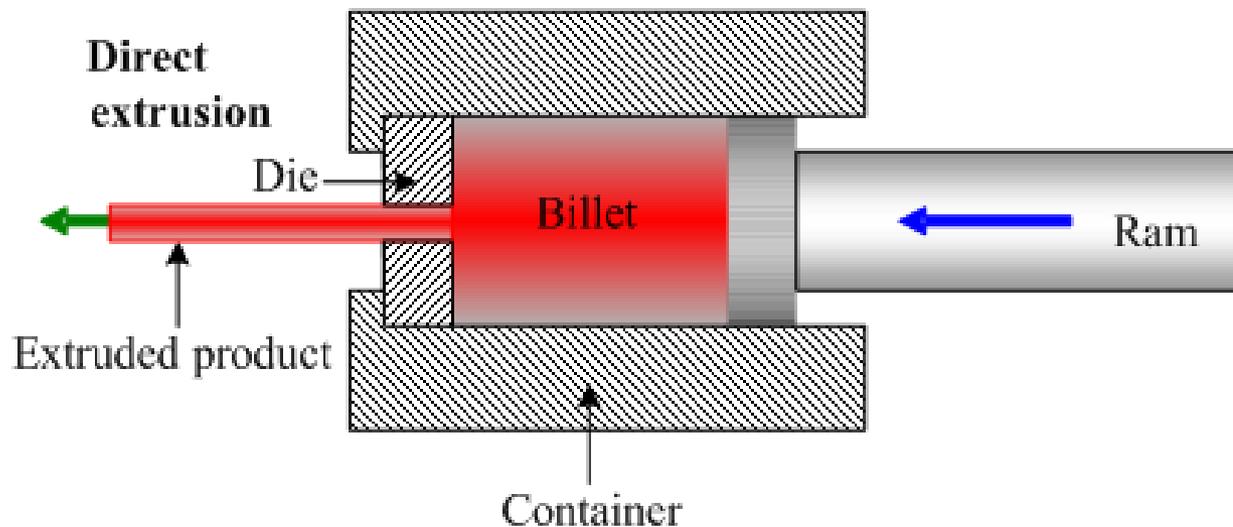
Hot and cold extrusion

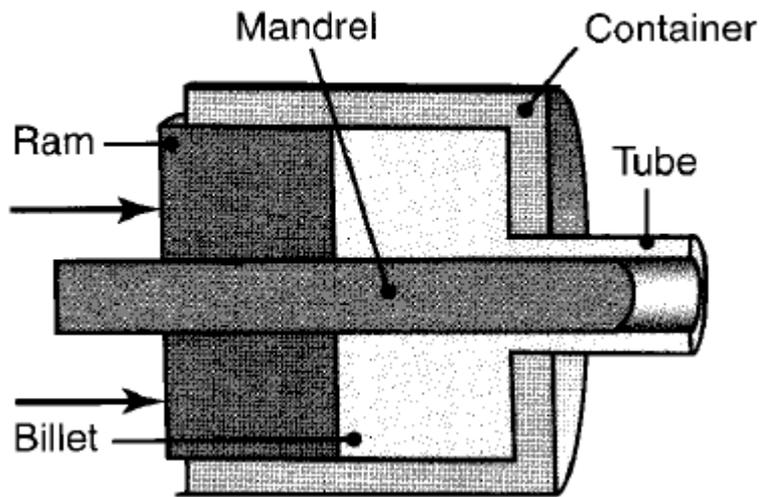
Forward and backward extrusion

Extrusion of other shapes

Drawing of rod and wire

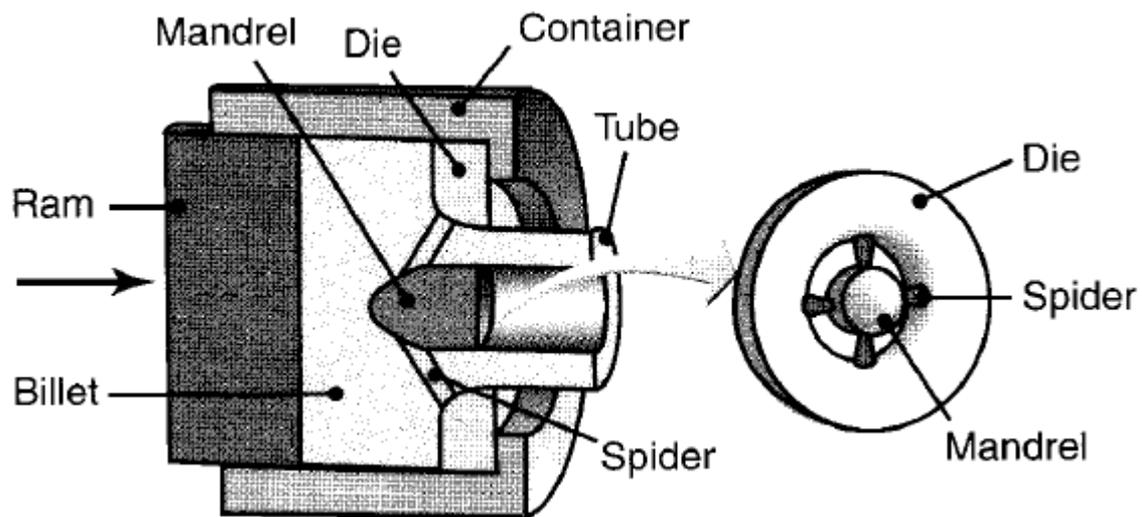






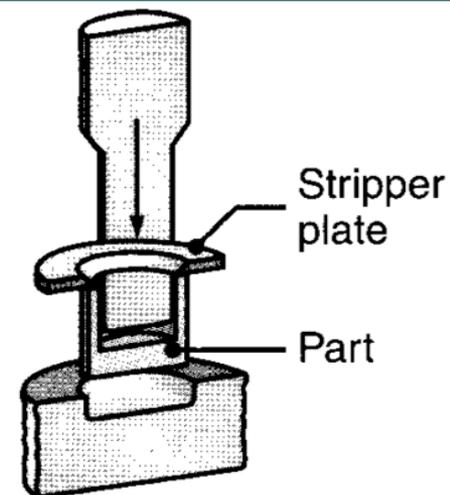
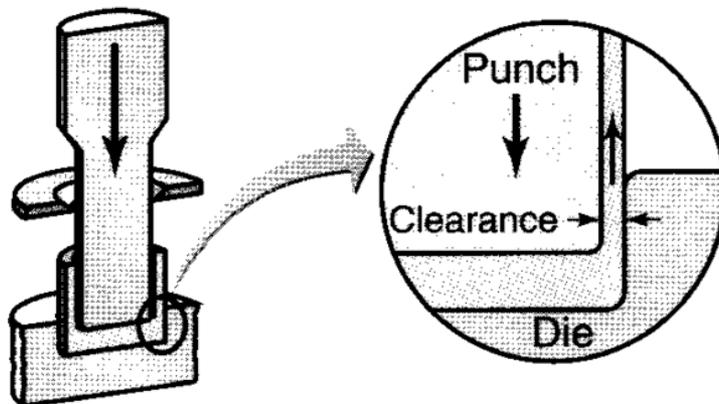
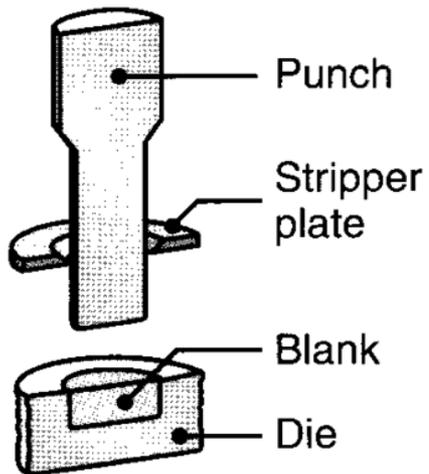
using an internal mandrel

using a spider die



## Aluminum extrusion



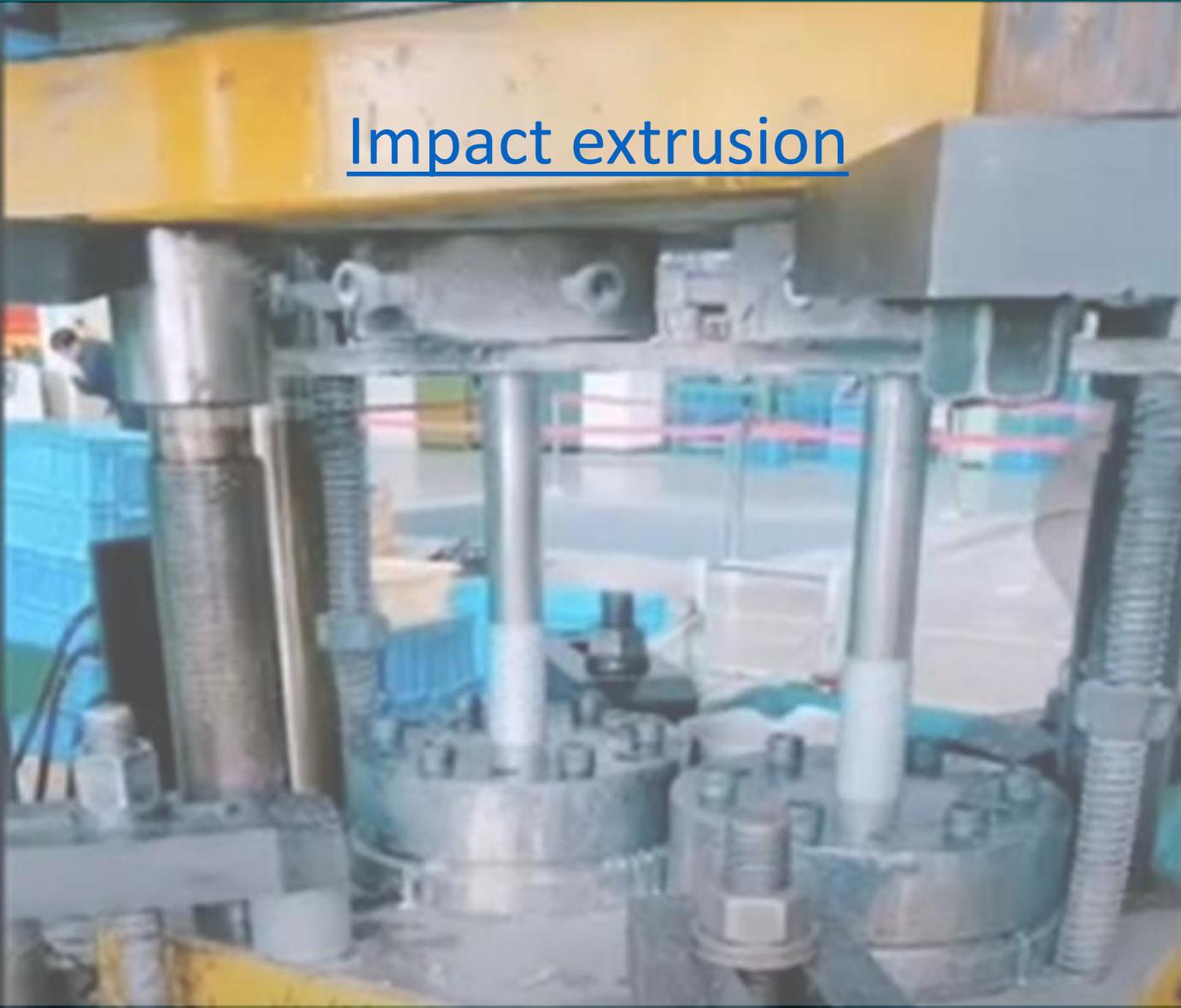


<https://www.plastprintpack.fairtrade-messe.com/en/Impact-Extrusion-our-core-expertise,p1546107>

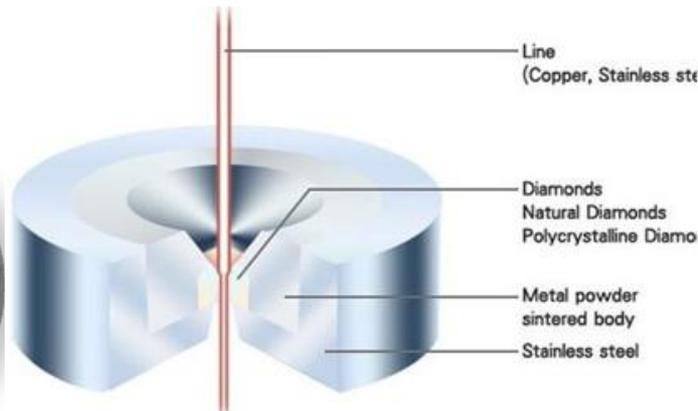
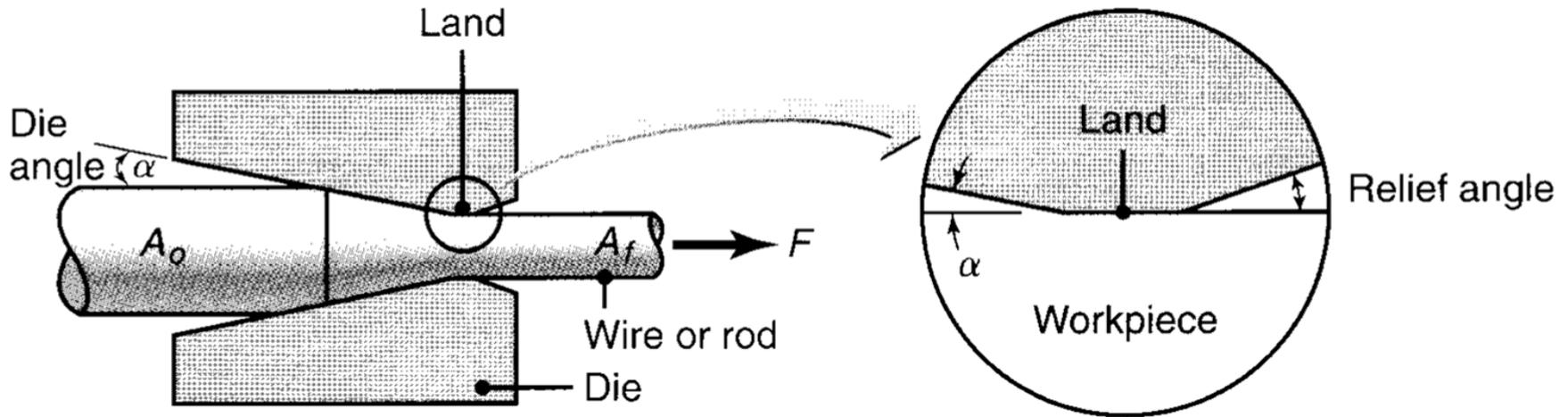


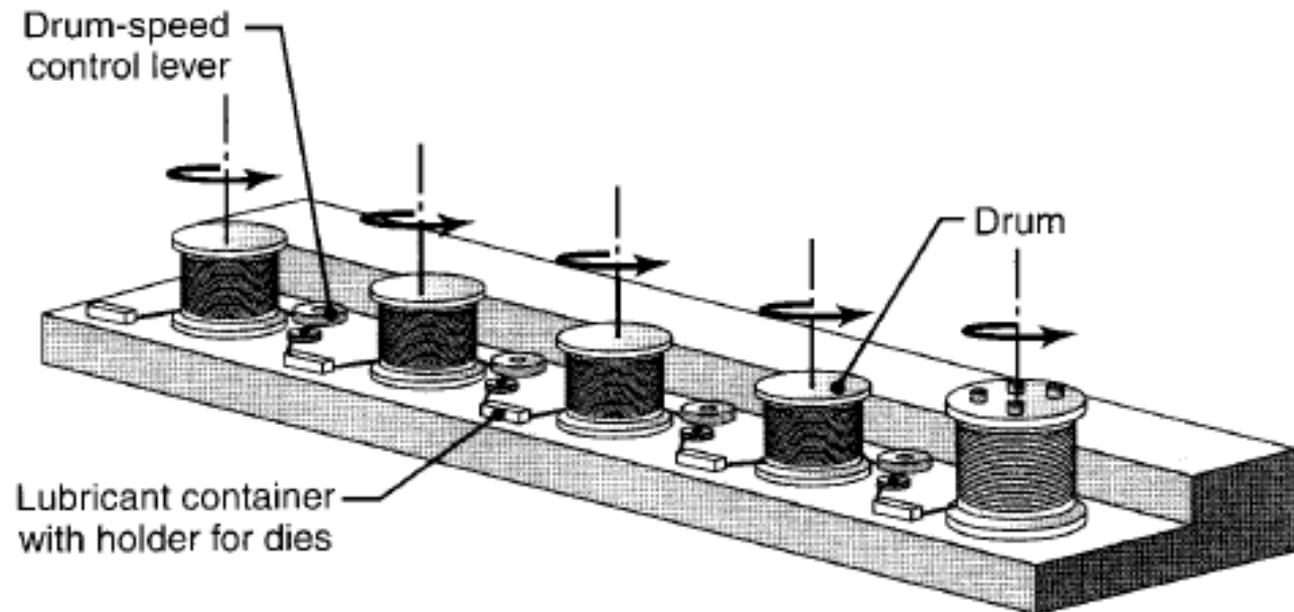
<http://www.ashfield-extrusion.co.uk/products/technical/>

## Impact extrusion



The cross section of a long rod or wire is reduced or changed by pulling it through a draw die.



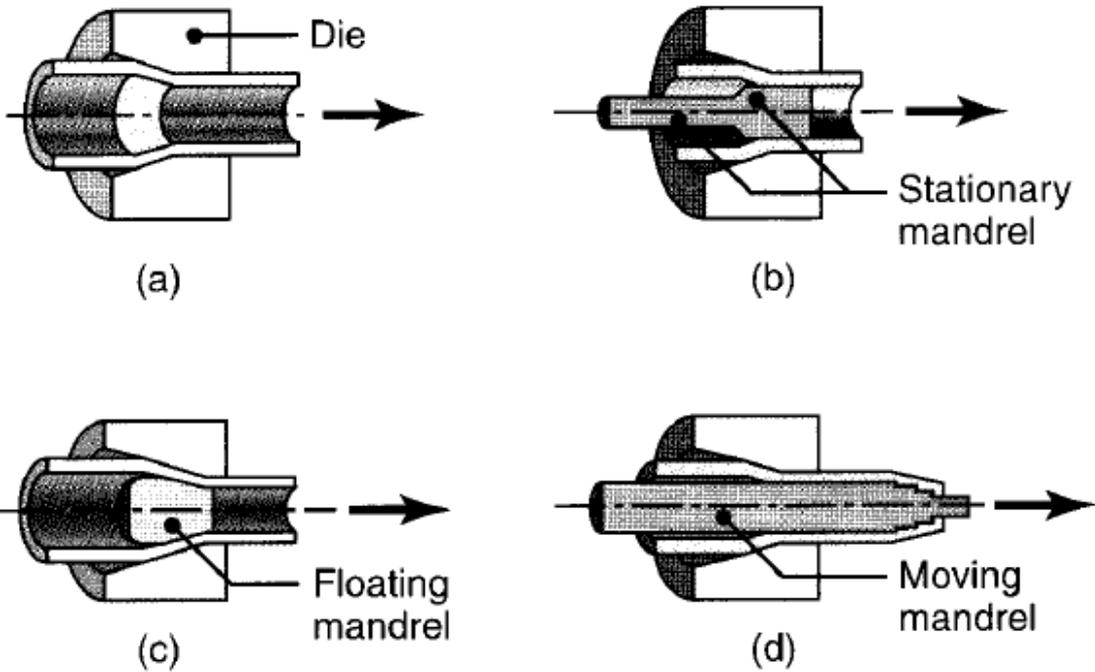


1. Descaling: machining, sand belt
2. Lubrication
3. WC wire drawing dies
4. 4.6 mm  $\rightarrow$  1.3 mm after 11 dies
5. Storing  $\rightarrow$  cooling (24 h)
6. Tensile, torsion test
7. Straightening
8. Spring making



## Wire drawing



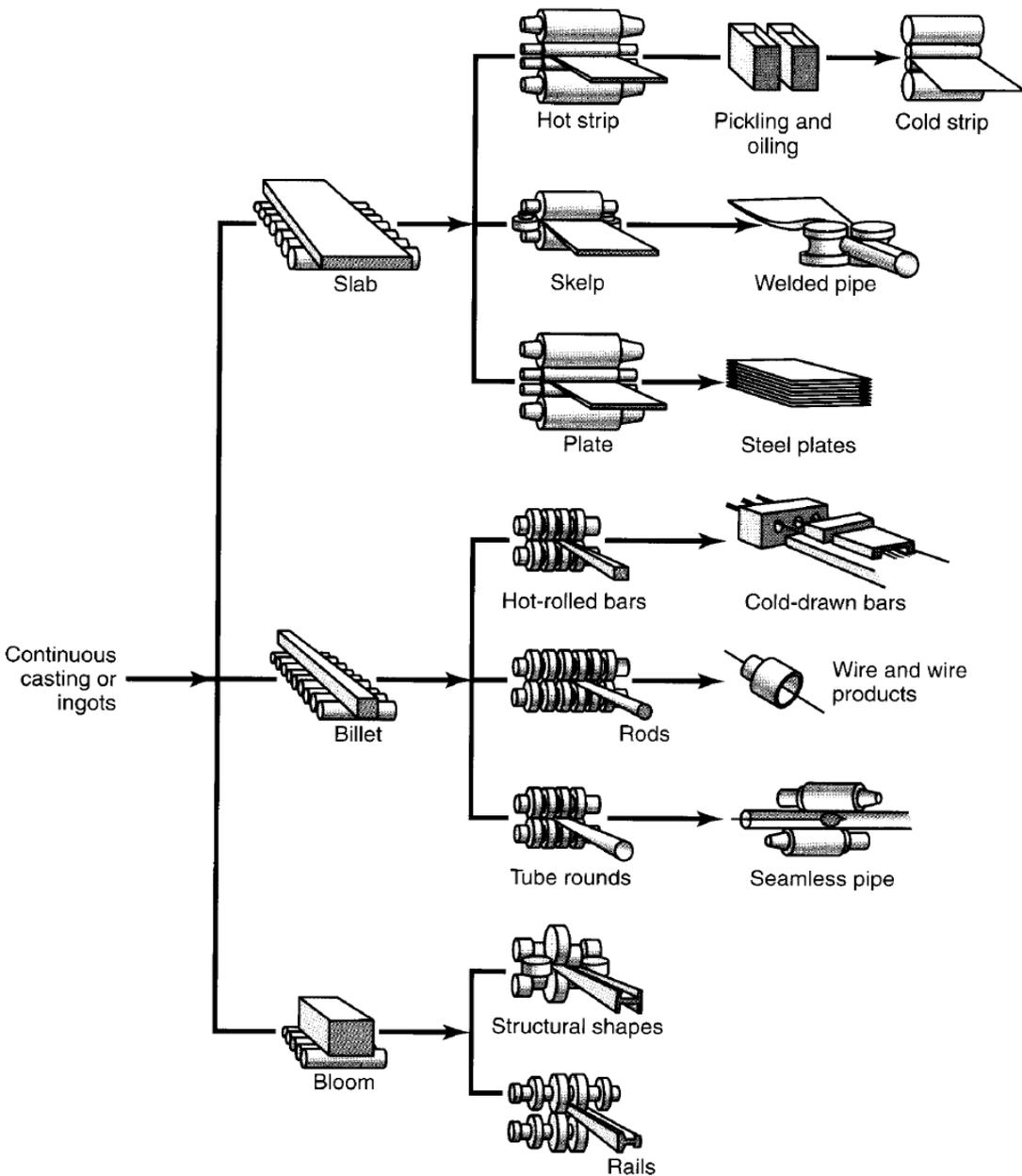


1. Annealing → softening
2. Pickling → cleaning, lubrication
3. Pointing → reducing diameter for drawing
4. Drawing
5. Annealing, repeating
6. Final annealing
7. Straightening
8. NDT: eddy current testing
9. Cutting
10. Final checking (dimensions, quality, etc.)
11. Shipping



## Tube drawing

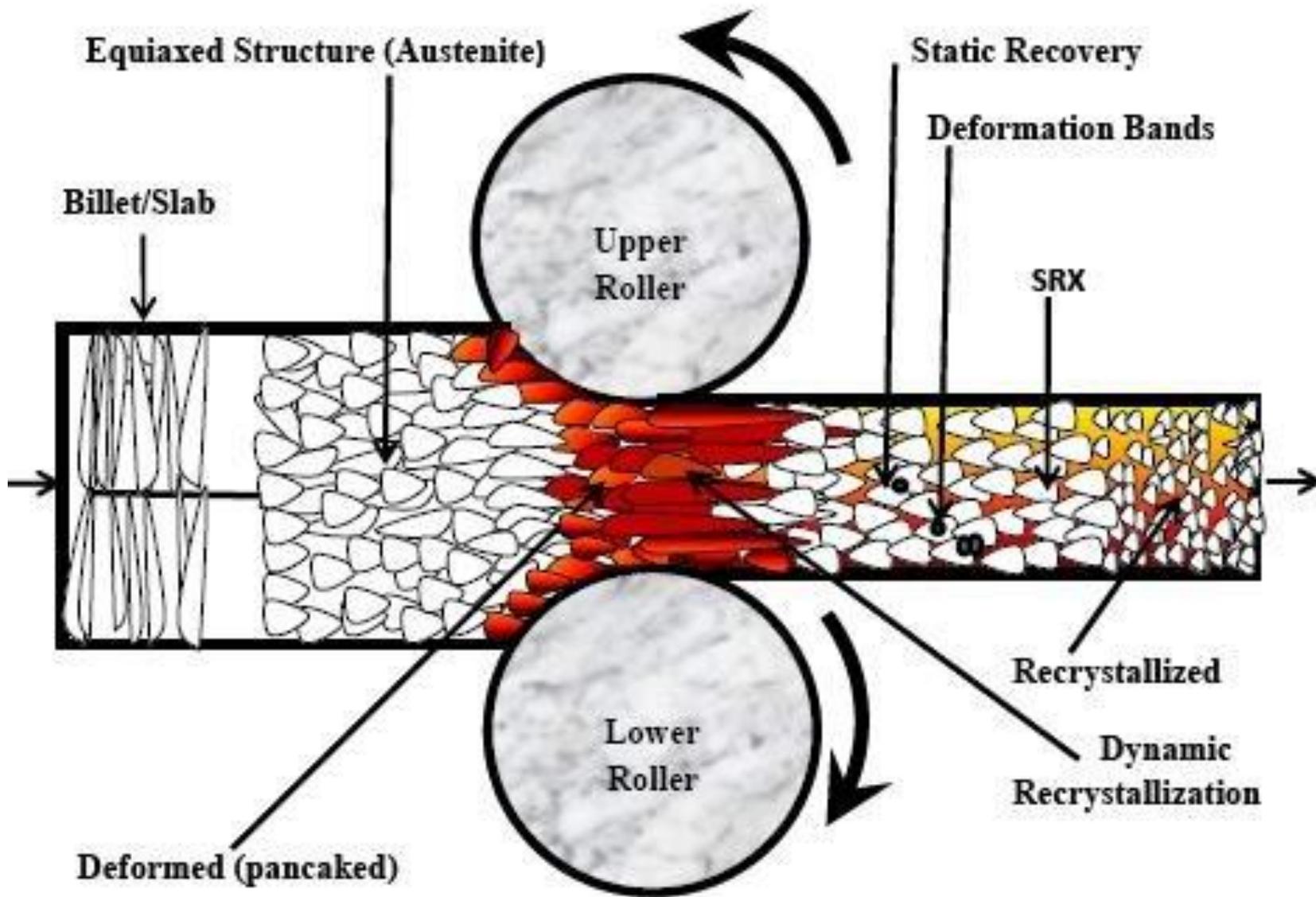




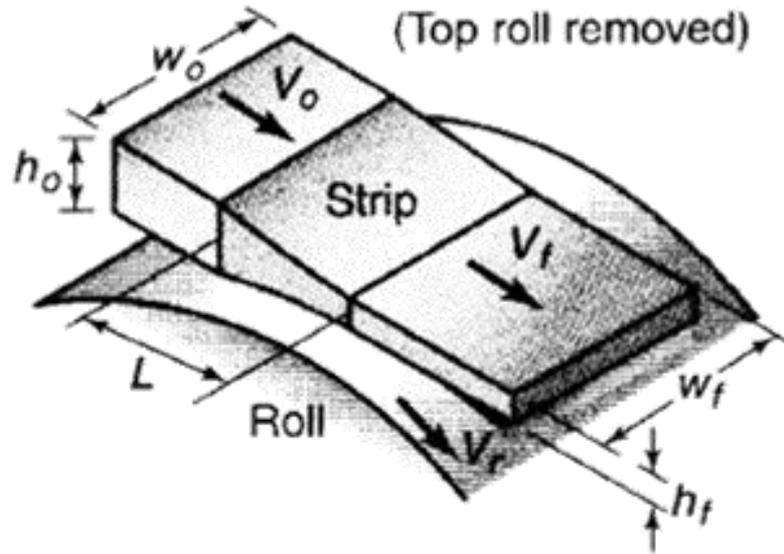
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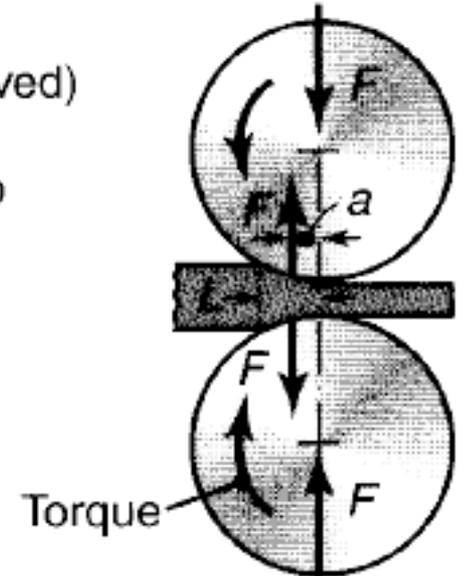
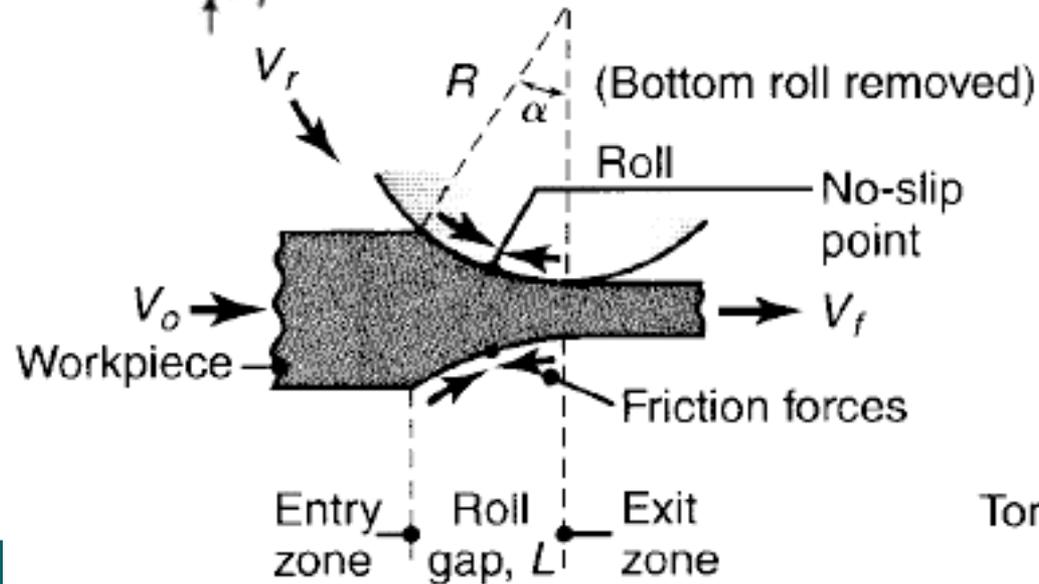
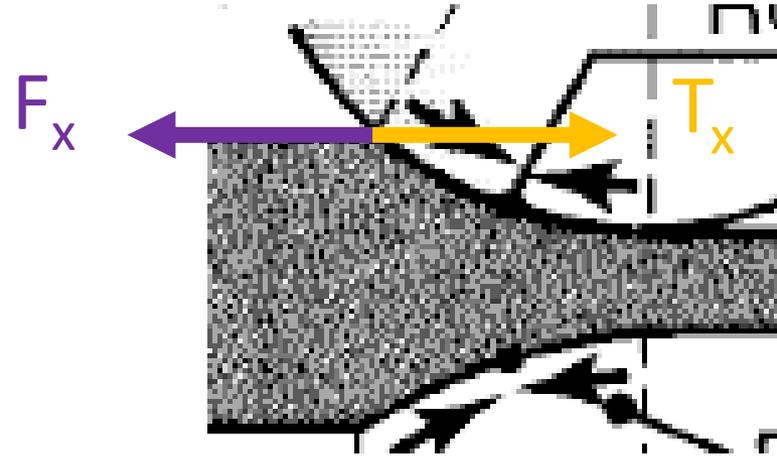
<https://www.sciencephoto.com/media/547084/view/rolling-a-rail-at-a-steel-mill>



## Material flow in the rolling gap

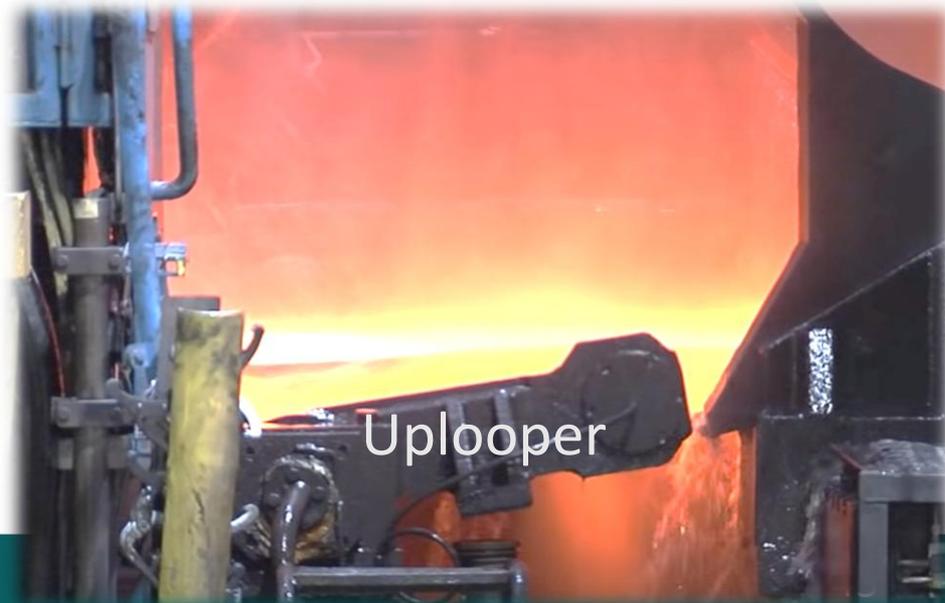


$$\text{tg}\alpha < \mu$$

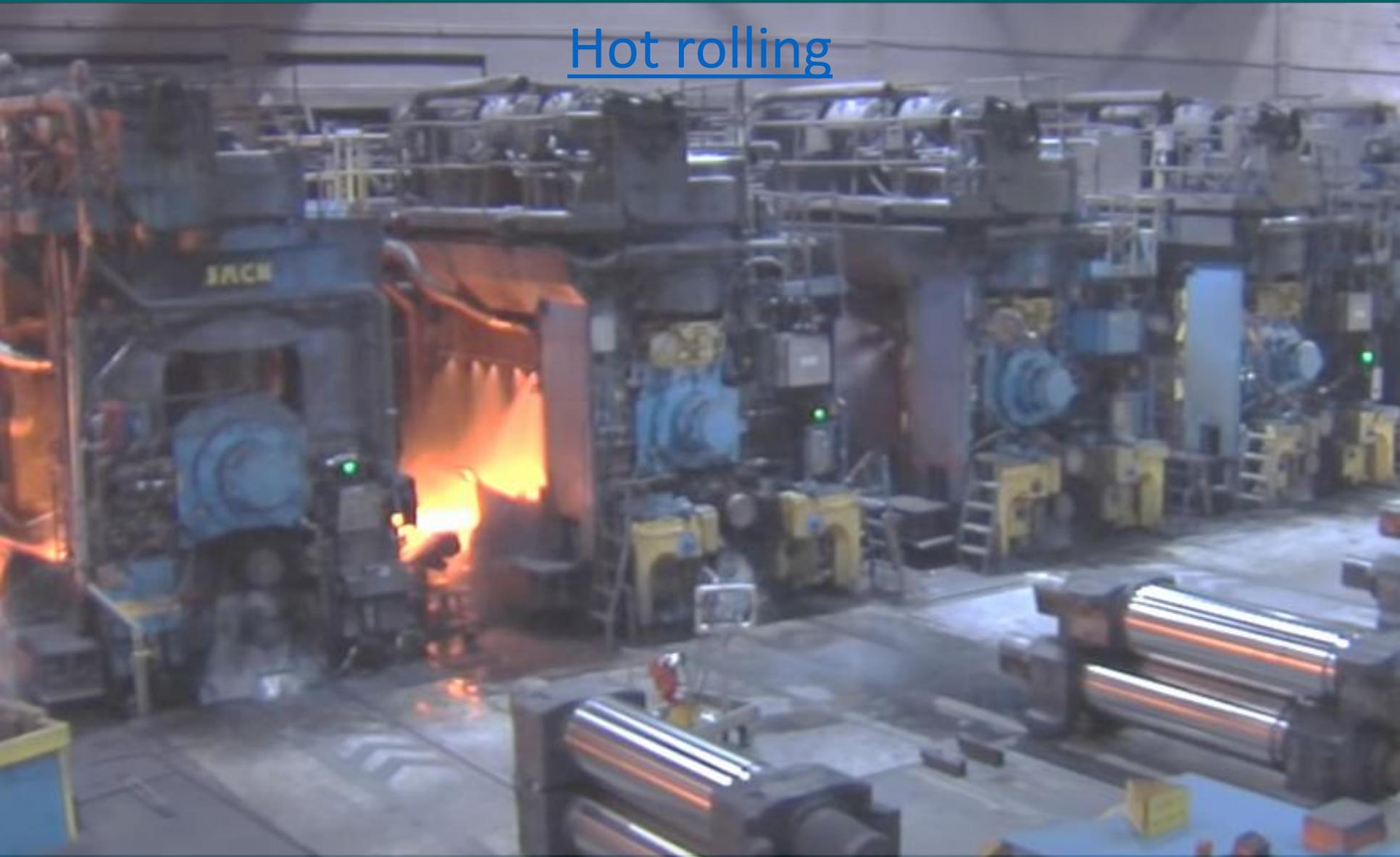


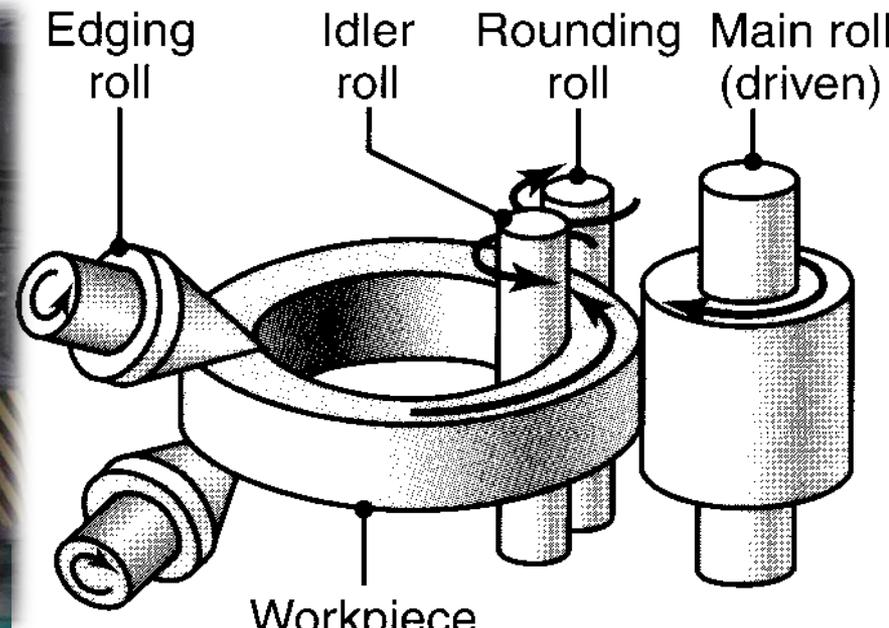
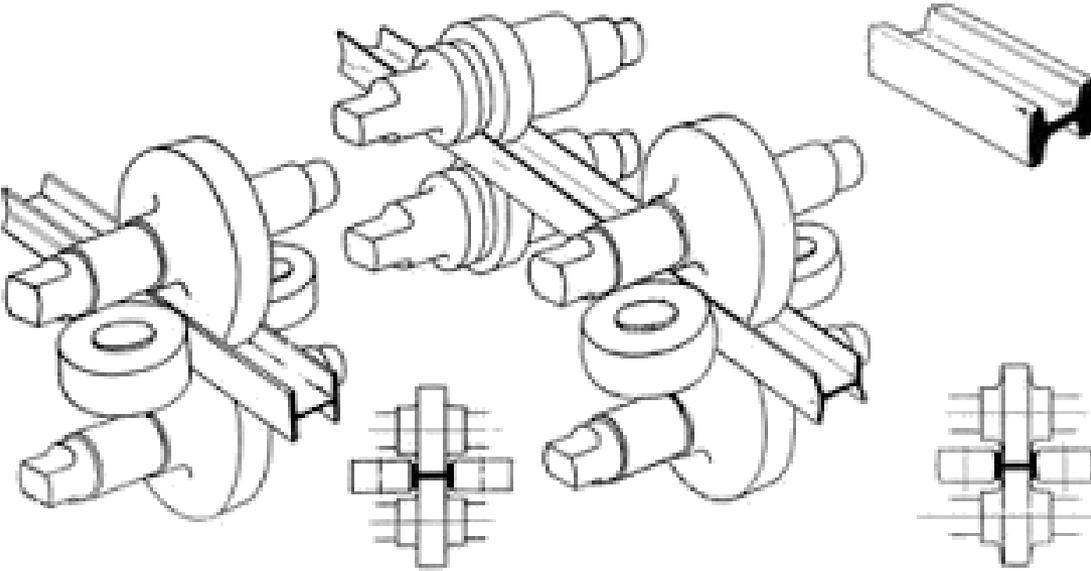


1. Heating up the slab  $\sim 1200\text{ }^{\circ}\text{C}$   
(also dissolve carbides, nitrides)
2. Mill scale cleansing: high pressure water (160 bar)
3. Roughing mill:  $220 \rightarrow 30\text{ mm}$  in a 4 high rolling mill in 5 passes
4. Surface cleansing during the roughing mill process
5. Vertical rollers  $\rightarrow$  width
6. Rolled up in a coil box: save space, temperature equalization  $\sim 1150\text{ }^{\circ}\text{C}$
7. Mill scale removal
8. Finishing mill: 6 passes, 1.8 mm, cooling rate
9. Cooling  $\sim 700\text{ }^{\circ}\text{C}$
10. Coiling

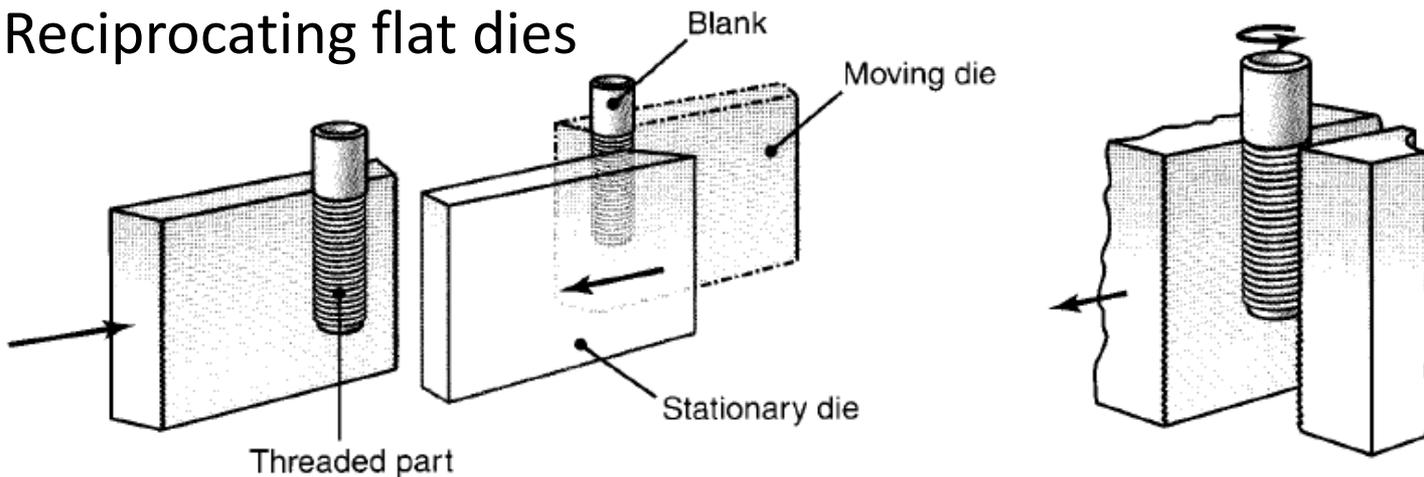


## Hot rolling



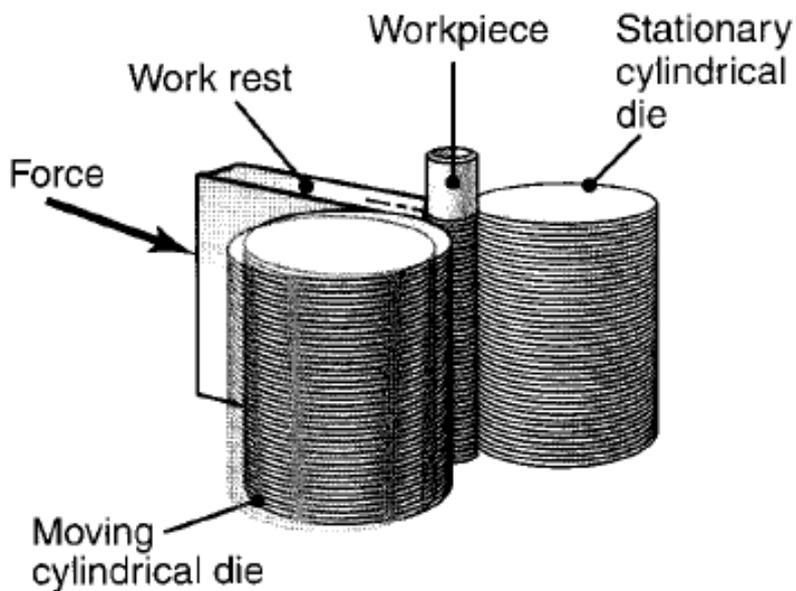


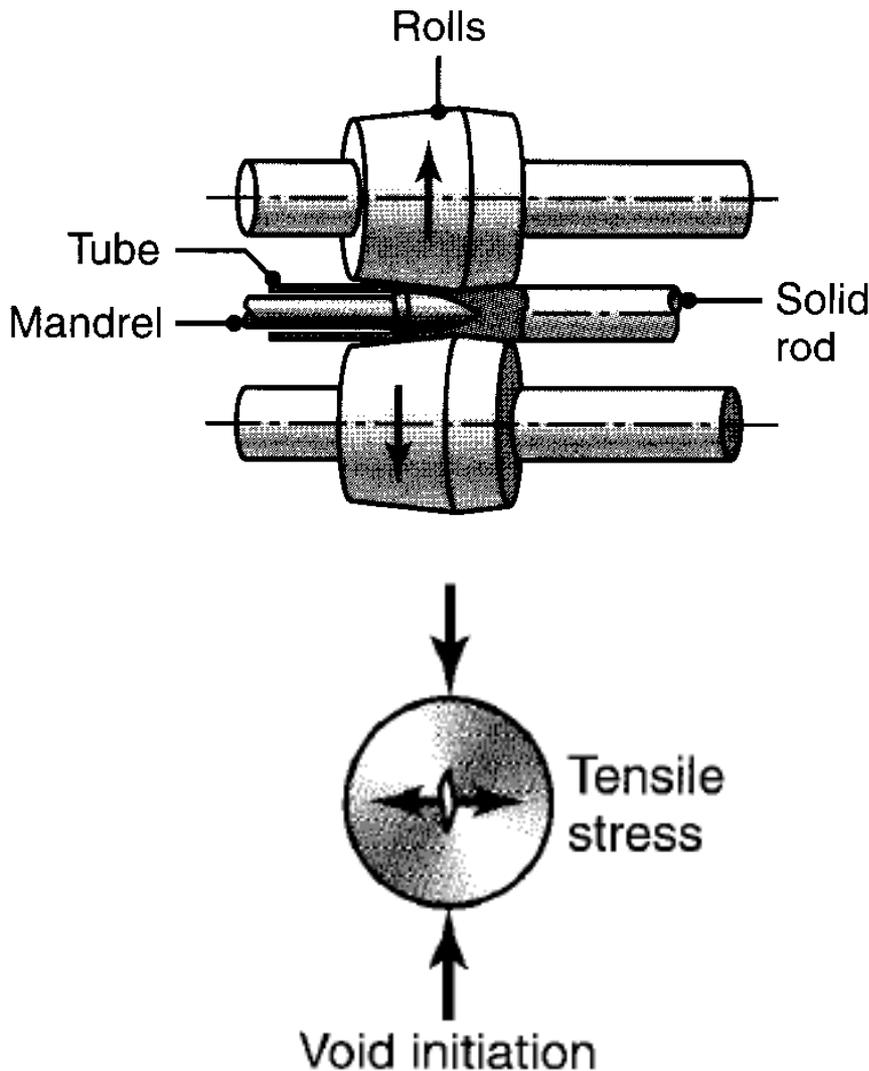
## Reciprocating flat dies



<https://youtu.be/MvWmH3Dr52o>

## Roller dies

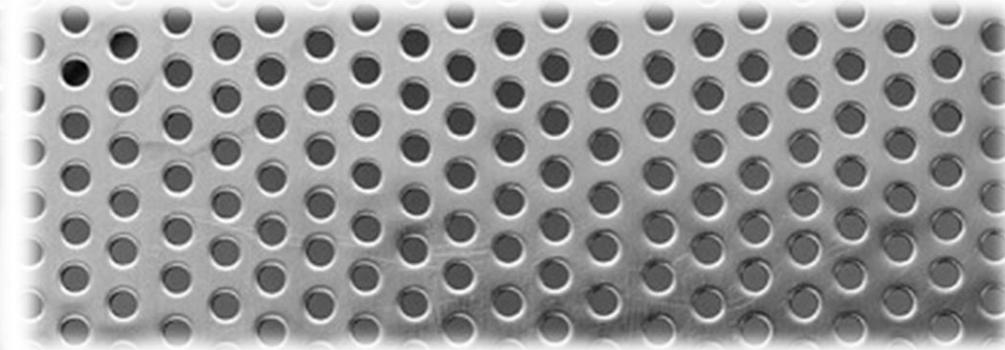
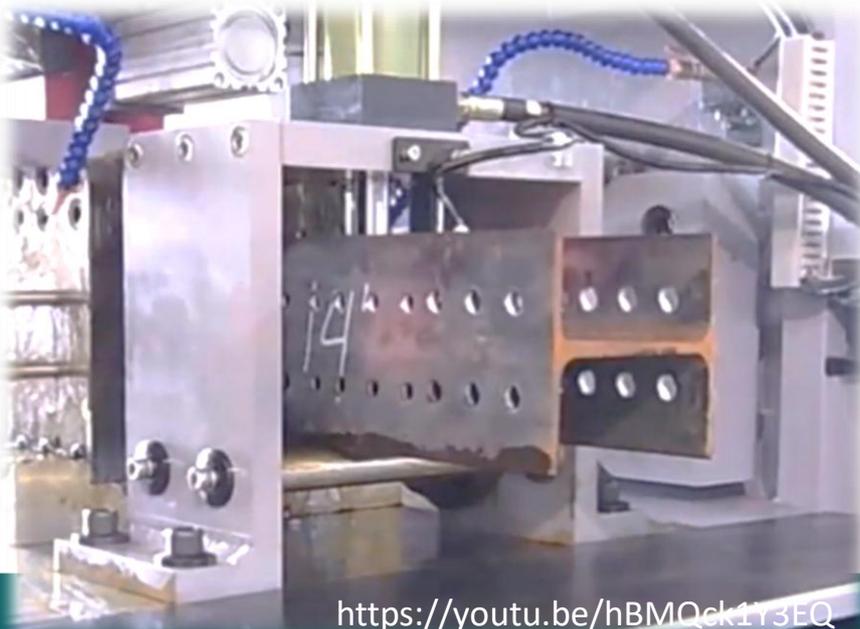
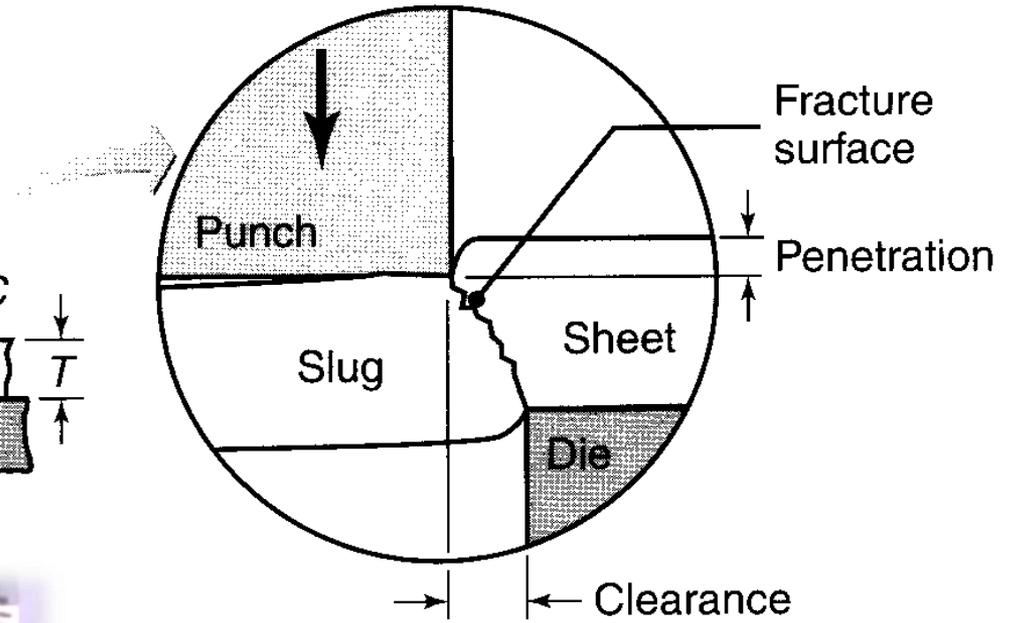
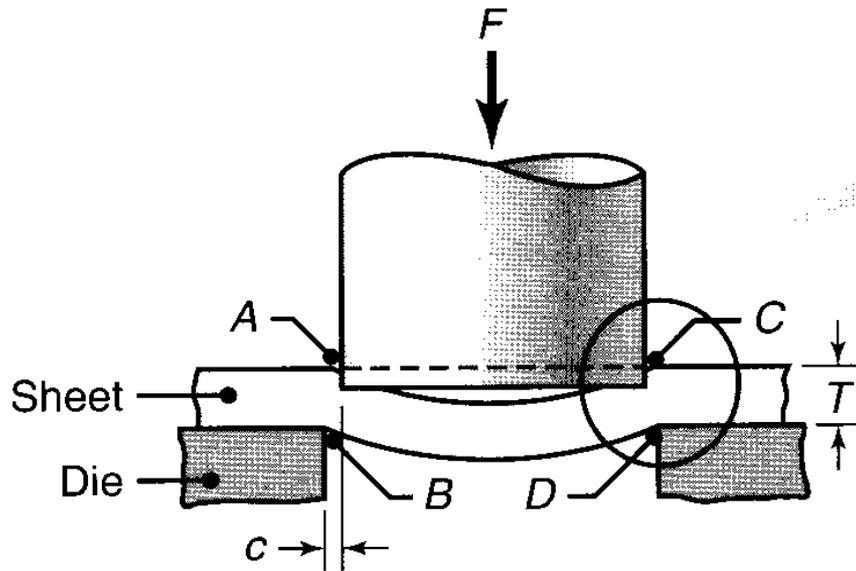




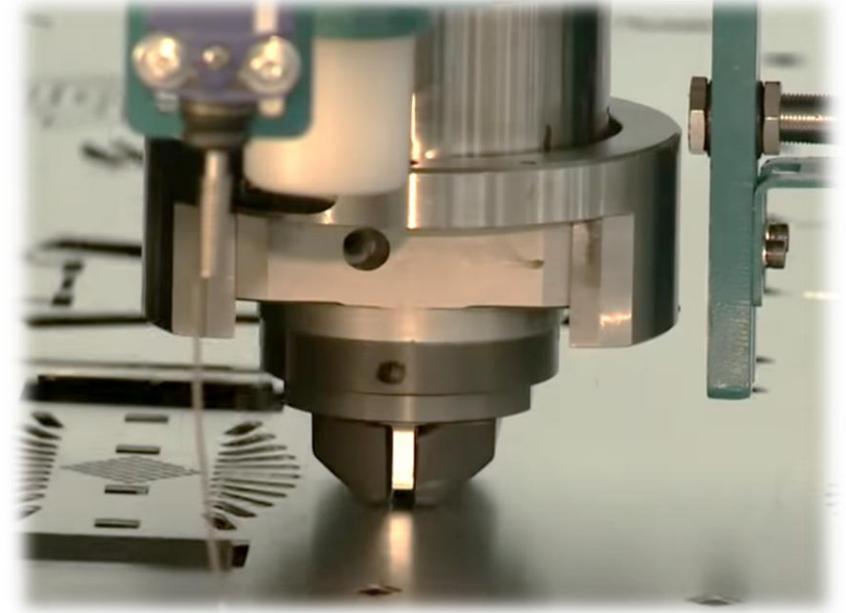
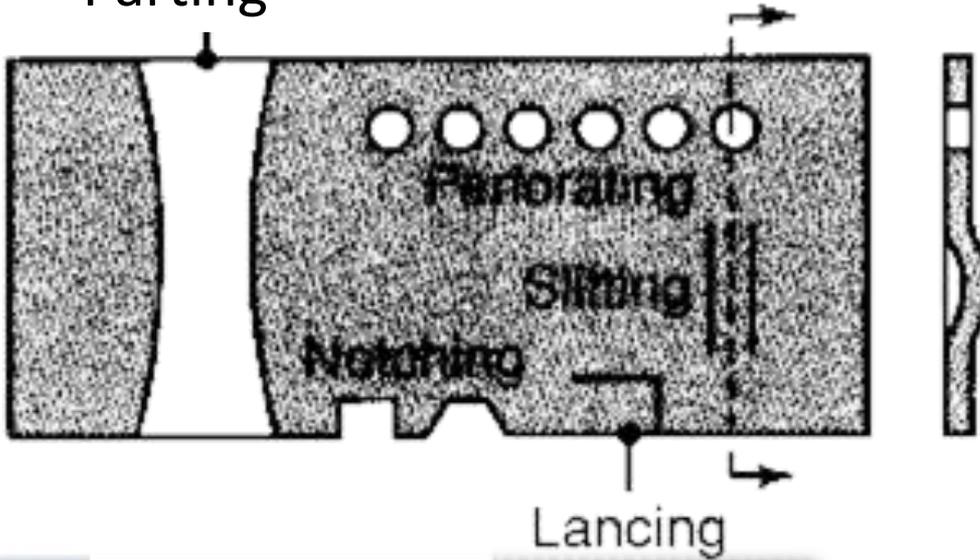
1. Billet is cut and heated up to  $\sim 1250\text{ }^{\circ}\text{C}$
2. Barrel type piercing (Mannesmann effect)
3. Finishing mill
4. Heated up in an induction furnace
5. Reducing mill (stretching for proper outside diameter)
6. Heat treatment
7. Straightening
8. Finishing (quality check, hydrostatic test, eddy current, ultrasonic testing)
9. Coating, marking
10. Bundeling

## Seamless pipe production

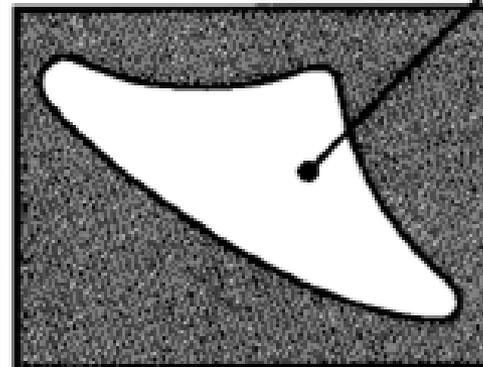




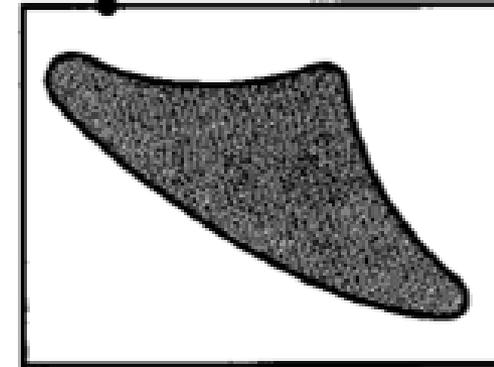
Parting



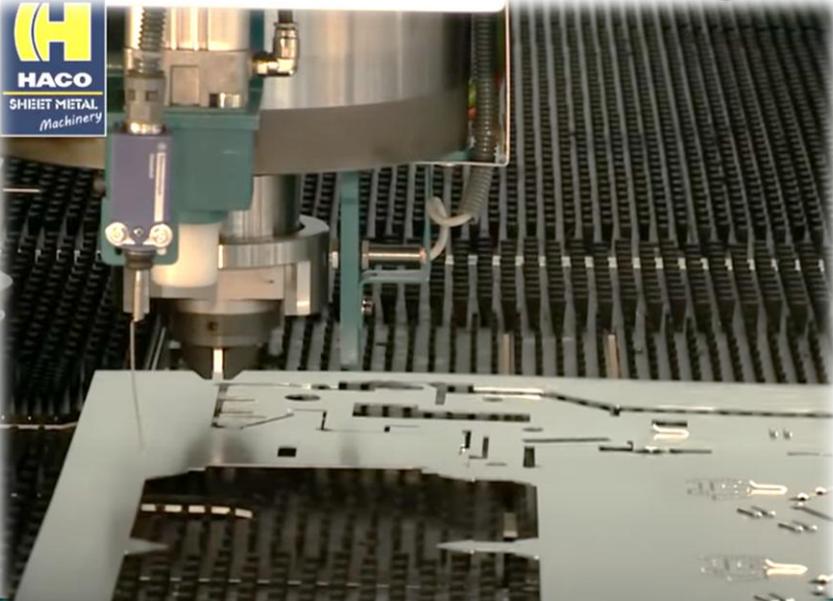
Discarded

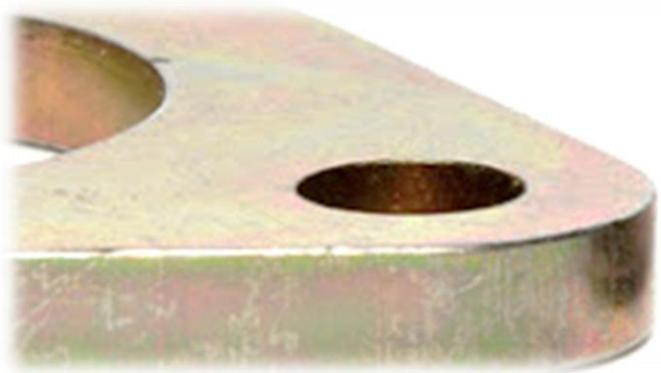
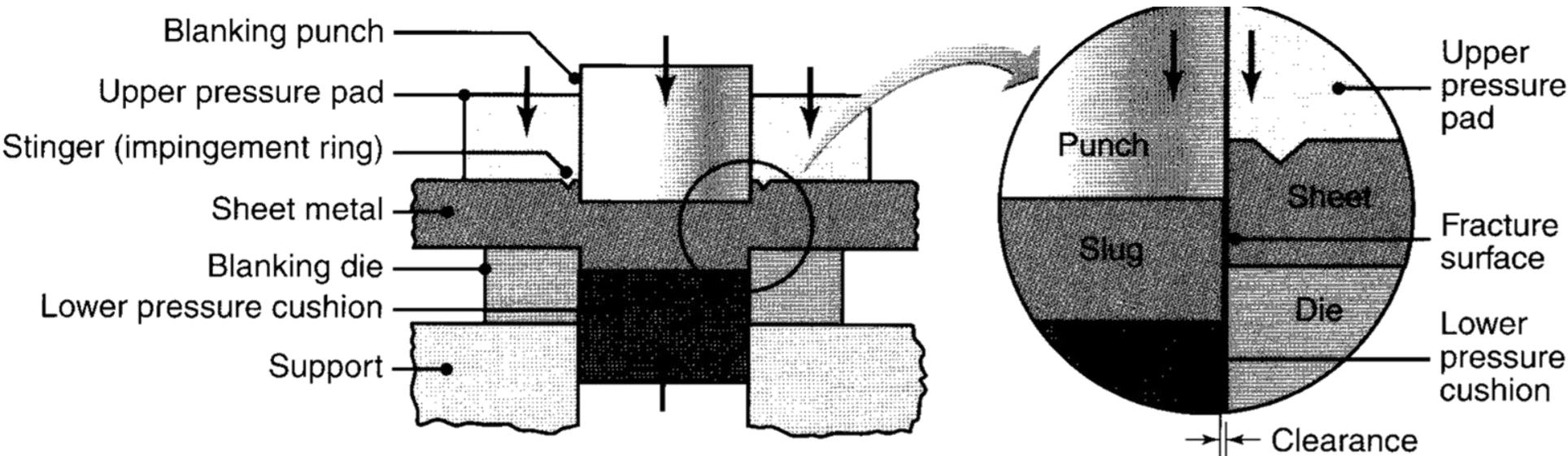


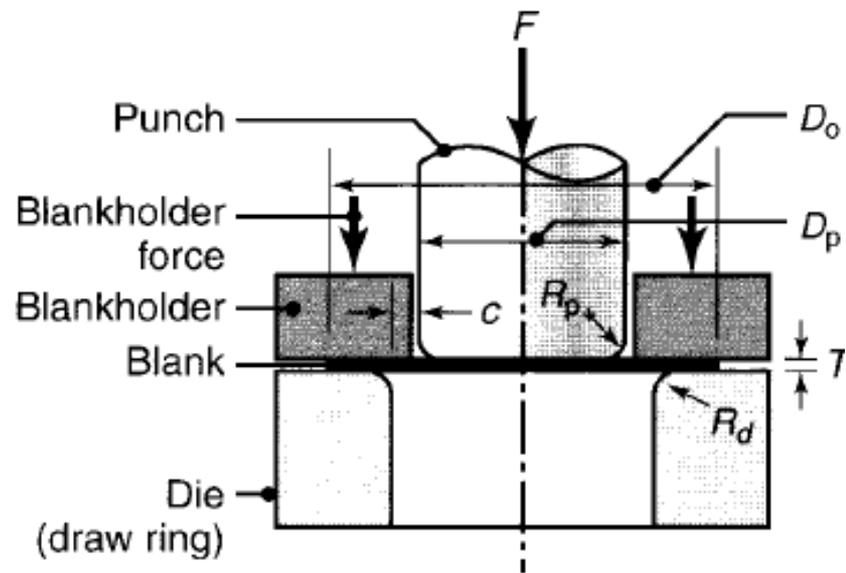
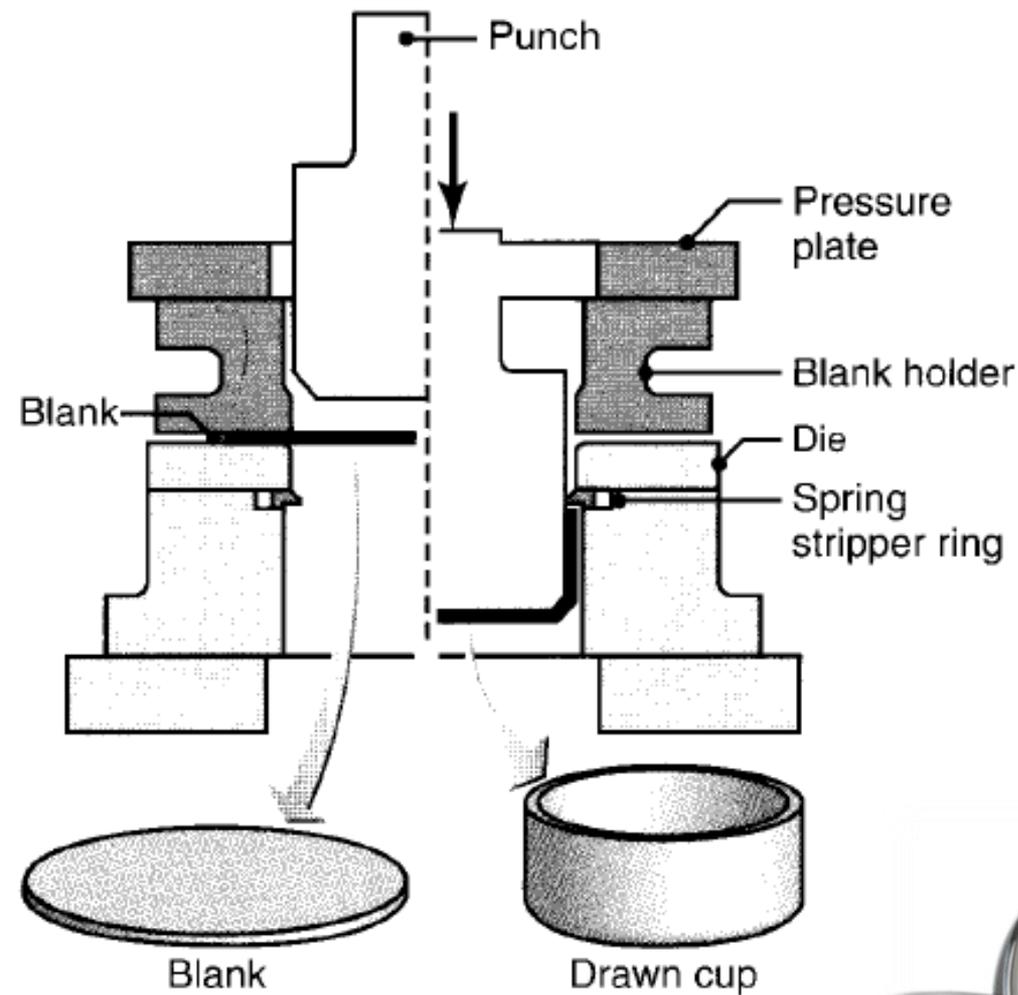
Punching

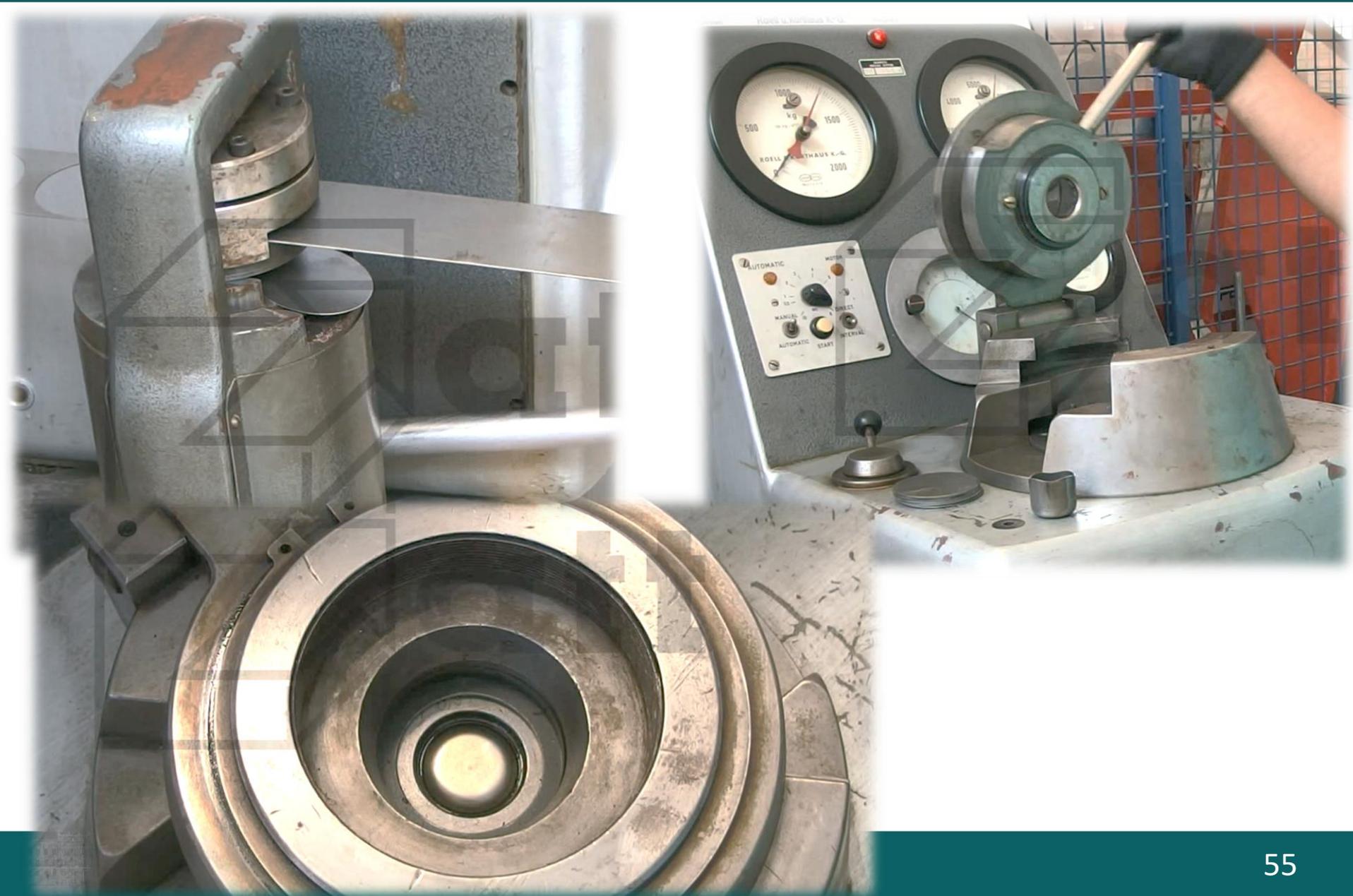


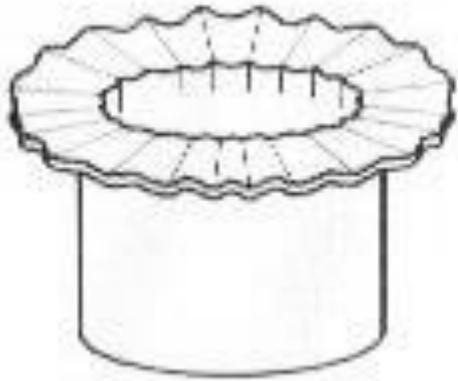
Blanking



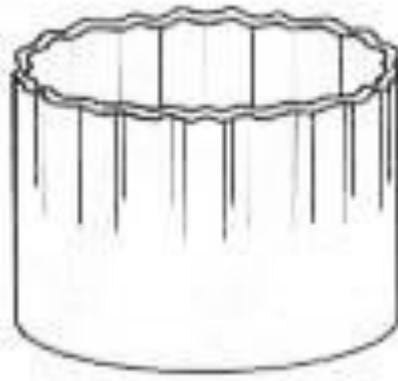




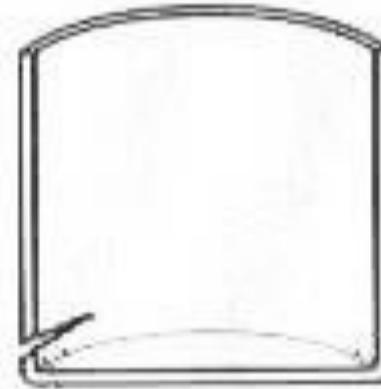




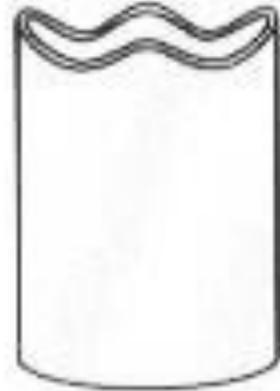
Flange wrinkling



Wall wrinkling

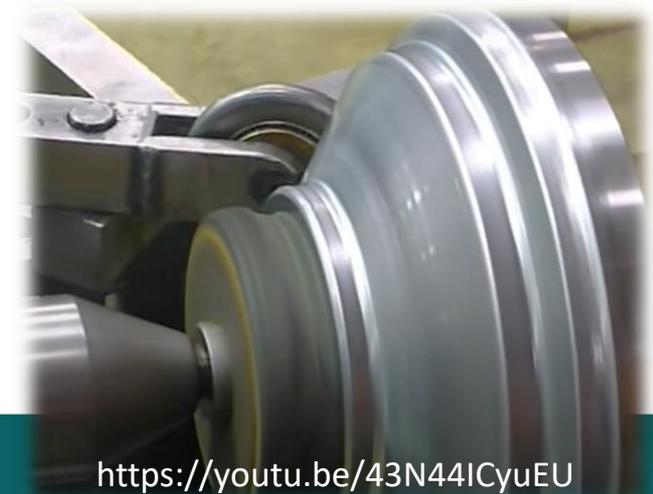
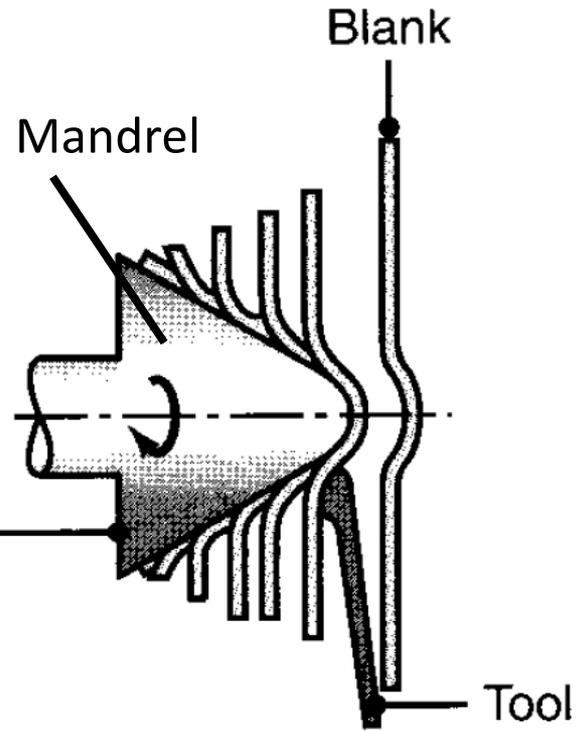


Cracking

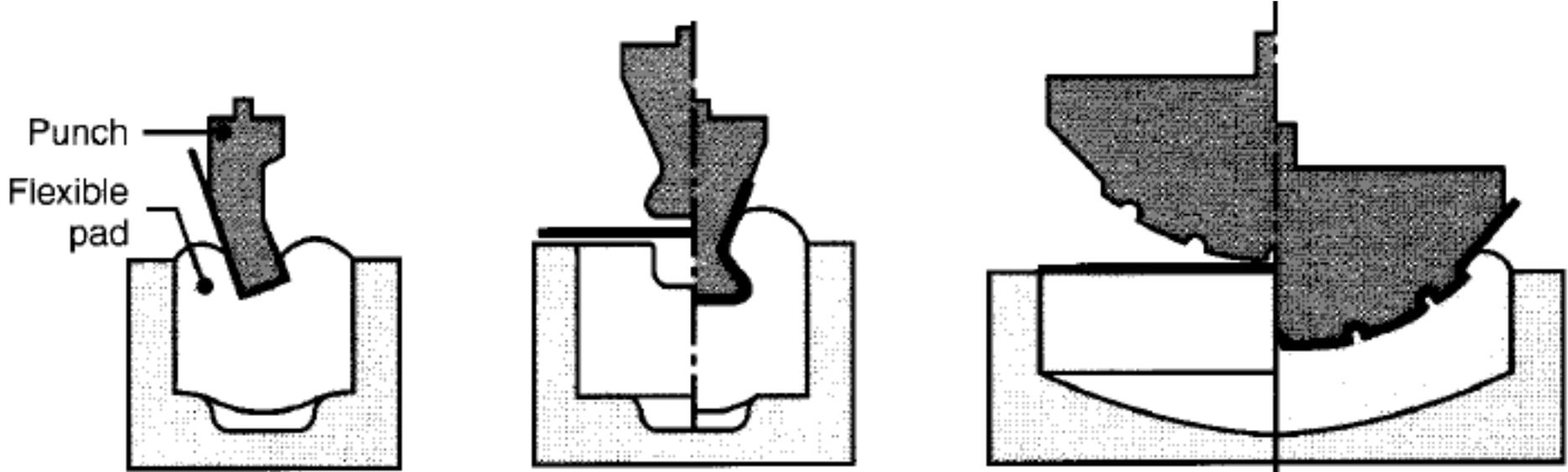


Earing

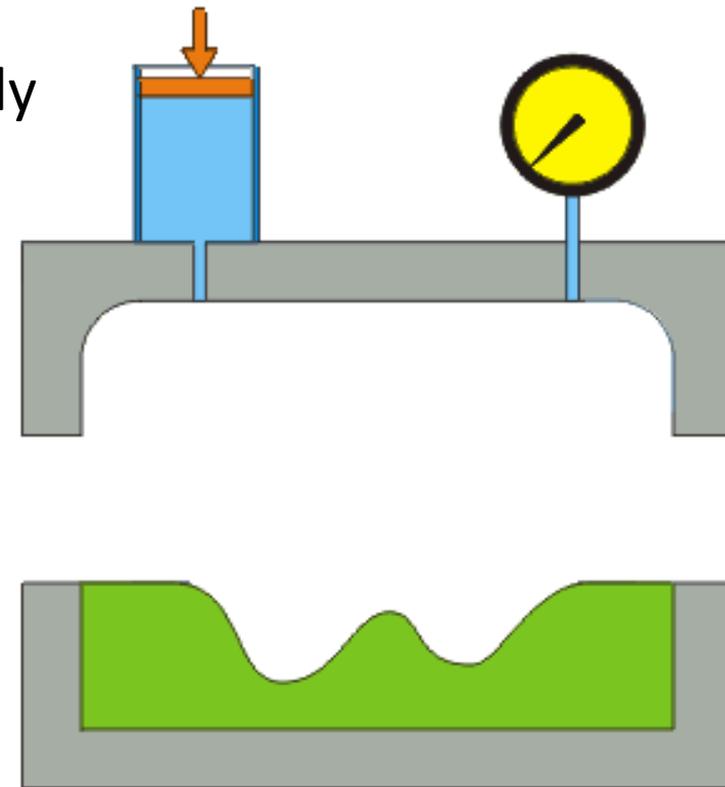




The outer surface of the sheet is protected from damage or scratches: no contact with a hard metal surface during forming.

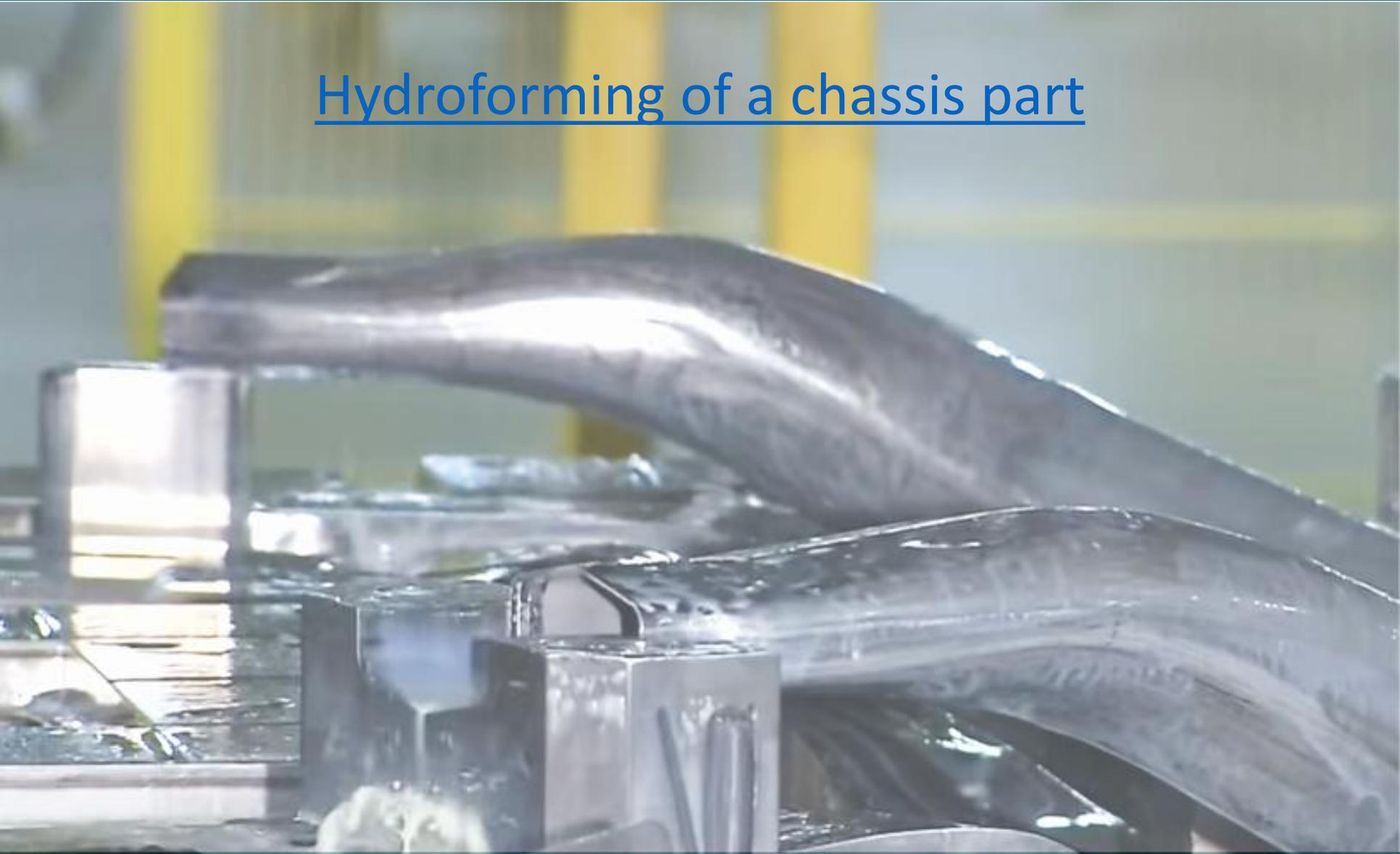


- Aluminium, brass, low alloy steel, and stainless steel into lightweight, structurally stiff and strong pieces.
- One of the largest applications of hydroforming is the automotive industry.
- Sheet hydroforming
- Tube hydroforming



<https://www.wardsauto.com/industry/schuler-hydroforming-expertise-draws-auto-maker-interest>

## Hydroforming of a chassis part



Thank you for your attention!

<https://www.youtube.com/watch?v=1OW4ld8xRzo>

[https://www.youtube.com/watch?v=EXbiEopDJ\\_g](https://www.youtube.com/watch?v=EXbiEopDJ_g)

<https://www.youtube.com/watch?v=oHH5rqtYdrY>

<https://www.youtube.com/watch?v=GDyWyDP3cvs>

[https://www.youtube.com/watch?v=AW\\_sgdZgFCU](https://www.youtube.com/watch?v=AW_sgdZgFCU)

<https://www.youtube.com/watch?v=iiGlq7408ME>

<https://www.youtube.com/watch?v=RE0gz9cD9u8&feature=youtu.be>

<https://www.youtube.com/watch?v=zluelHudt4k>

<https://www.youtube.com/watch?v=doX-uXOFoLY&feature=youtu.be>

<https://www.youtube.com/watch?v=fOkCKOWpUr0>

<https://www.youtube.com/watch?v=AuuP8L-Wppl>

<https://www.youtube.com/watch?v=B1gcSyqLkA0>