Department of Materials Science and Engineering

Forming

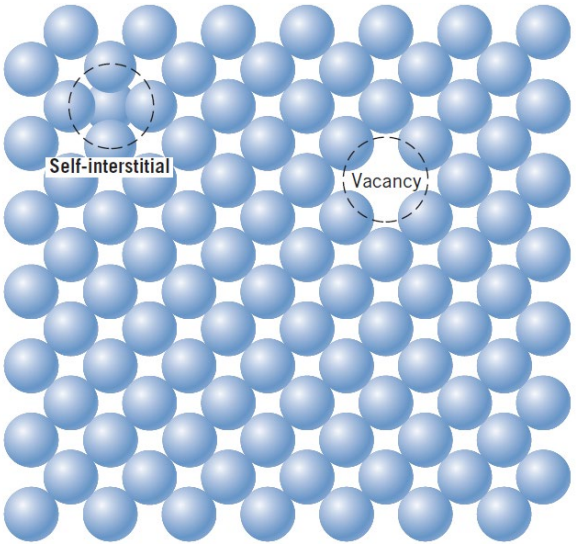
Balázs Varbai, PhD, EWE/IWE

Materials Engineering
BMEGEMTBGF1
2022 Fall semester

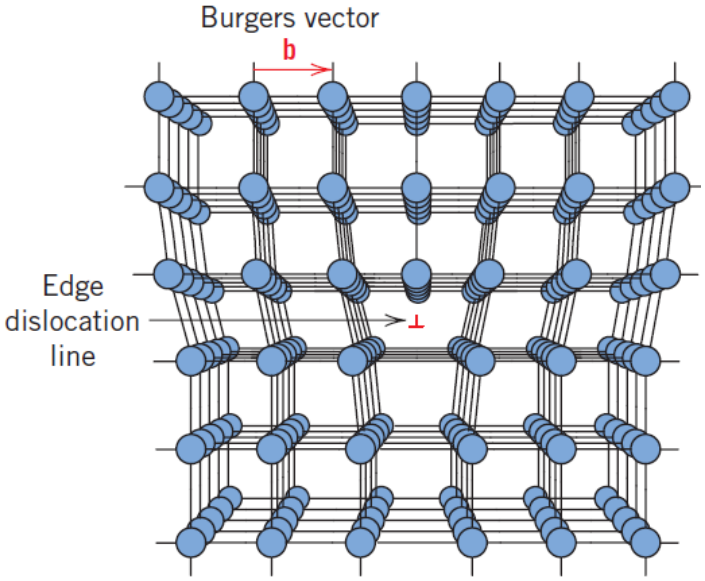
Plastic deformation lattice defects

Ideal lattice: no defects

Real lattice: defects



- Vacancy, interstitial atom *0D*
- Dislocation *1D*
- Grain boundaries *2D*
- Precipitations *3D*



A. G. Guy, Essentials of Materials Science, McGraw-Hill Book Company, New York, 1976, p. 153.

W. G. Moffatt, G.W. Pearsall, and J. Wulff, The Structure and Properties of Materials, Vol. I, Structure, p. 77.

Interstitial vs. substitutial

Plastic deformation

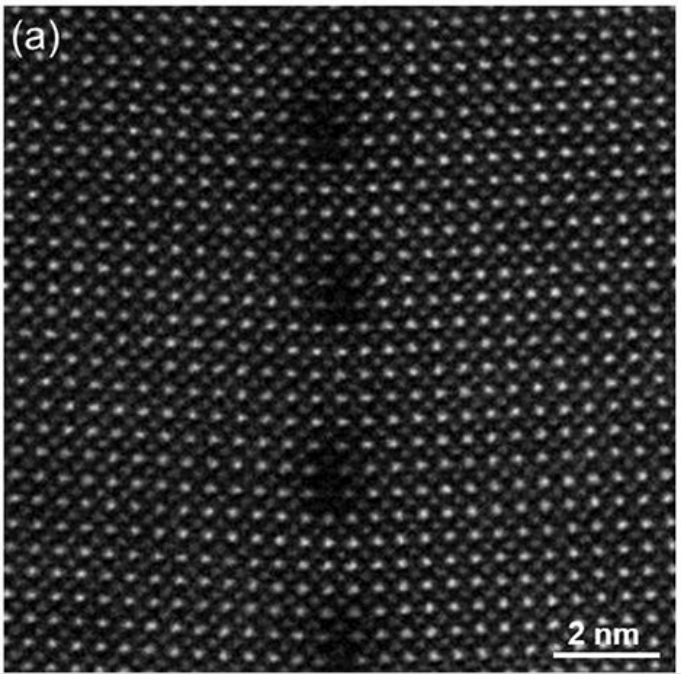
Mechanical properties ~ plastic deformation

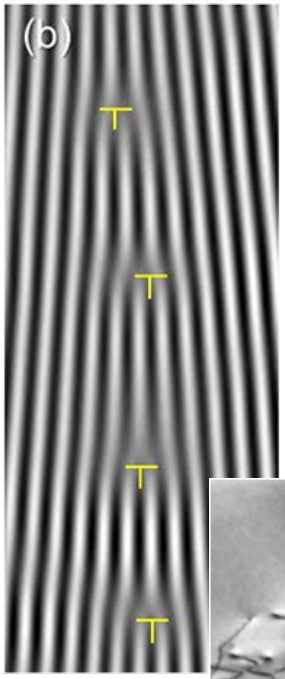
- hardness, toughness, yield stress
- formability

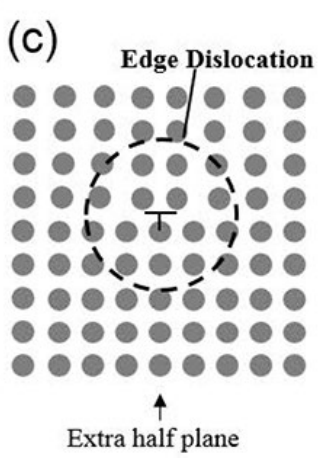
Mechanism of the plastic deformation:

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

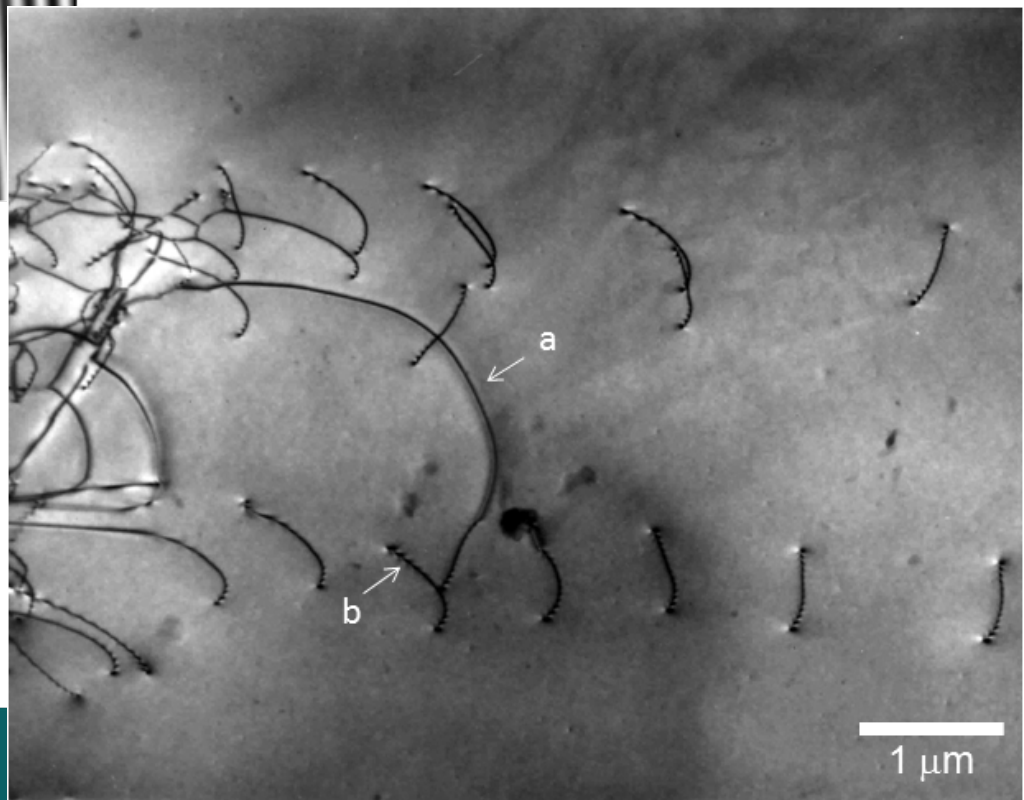
Plastic deformation lattice defects







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.

https://www.jeol.co.jp/en/words/emterms/search_result.html?keyword=dislocation

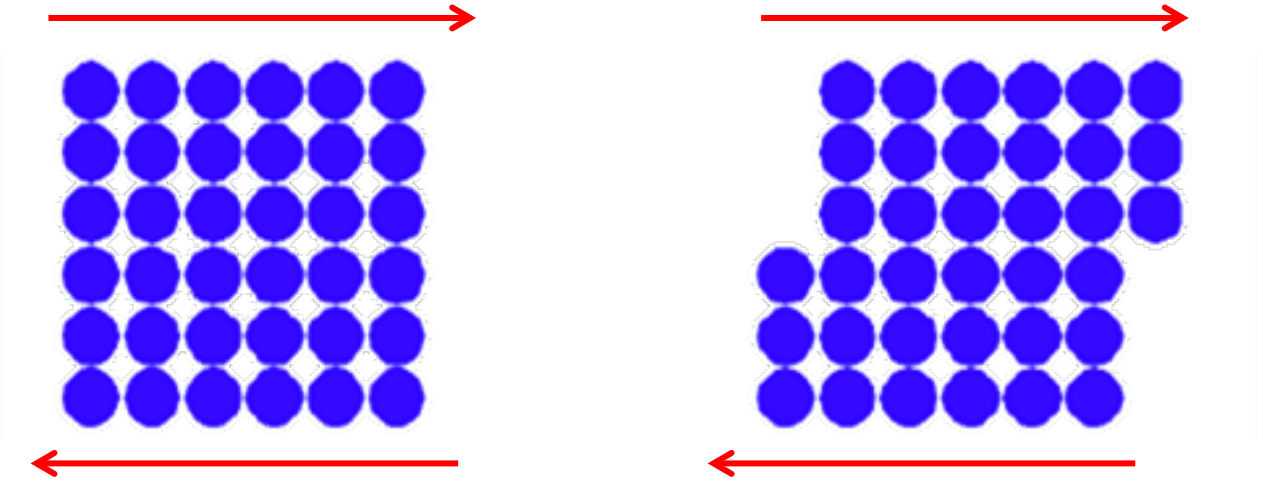
Elastic and plastic deformation

Elastic deformation

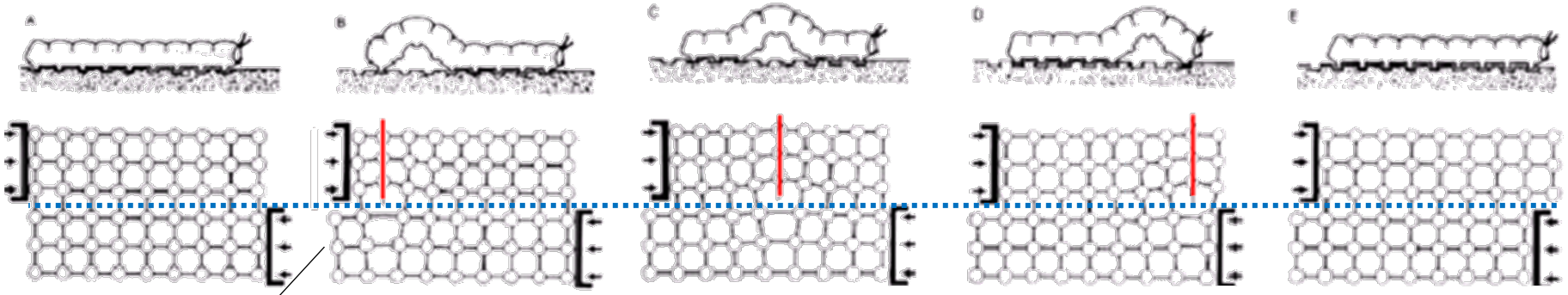
- after the load is removed, no deformation remains
- no rearrangements in the atomic order

Plastic deformation

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



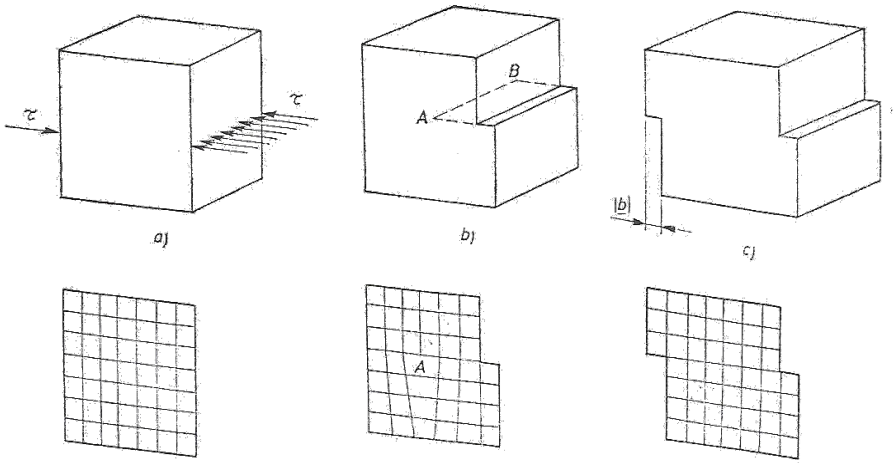
Plastic deformation – slip of dislocations



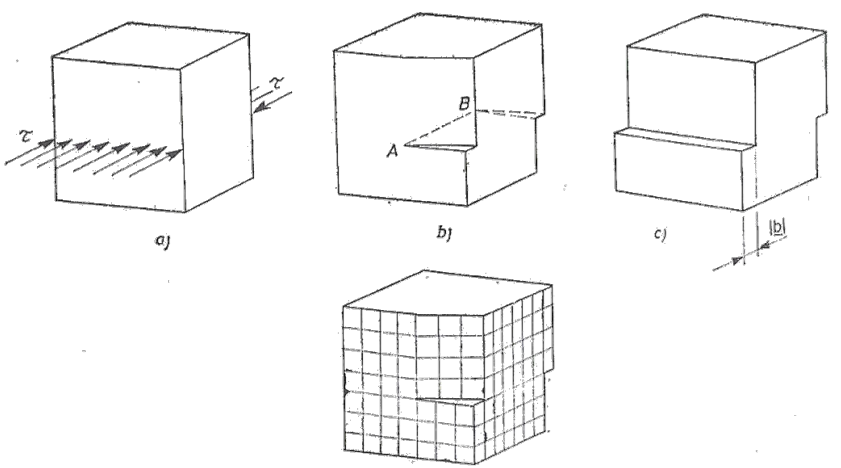
Slip plane

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

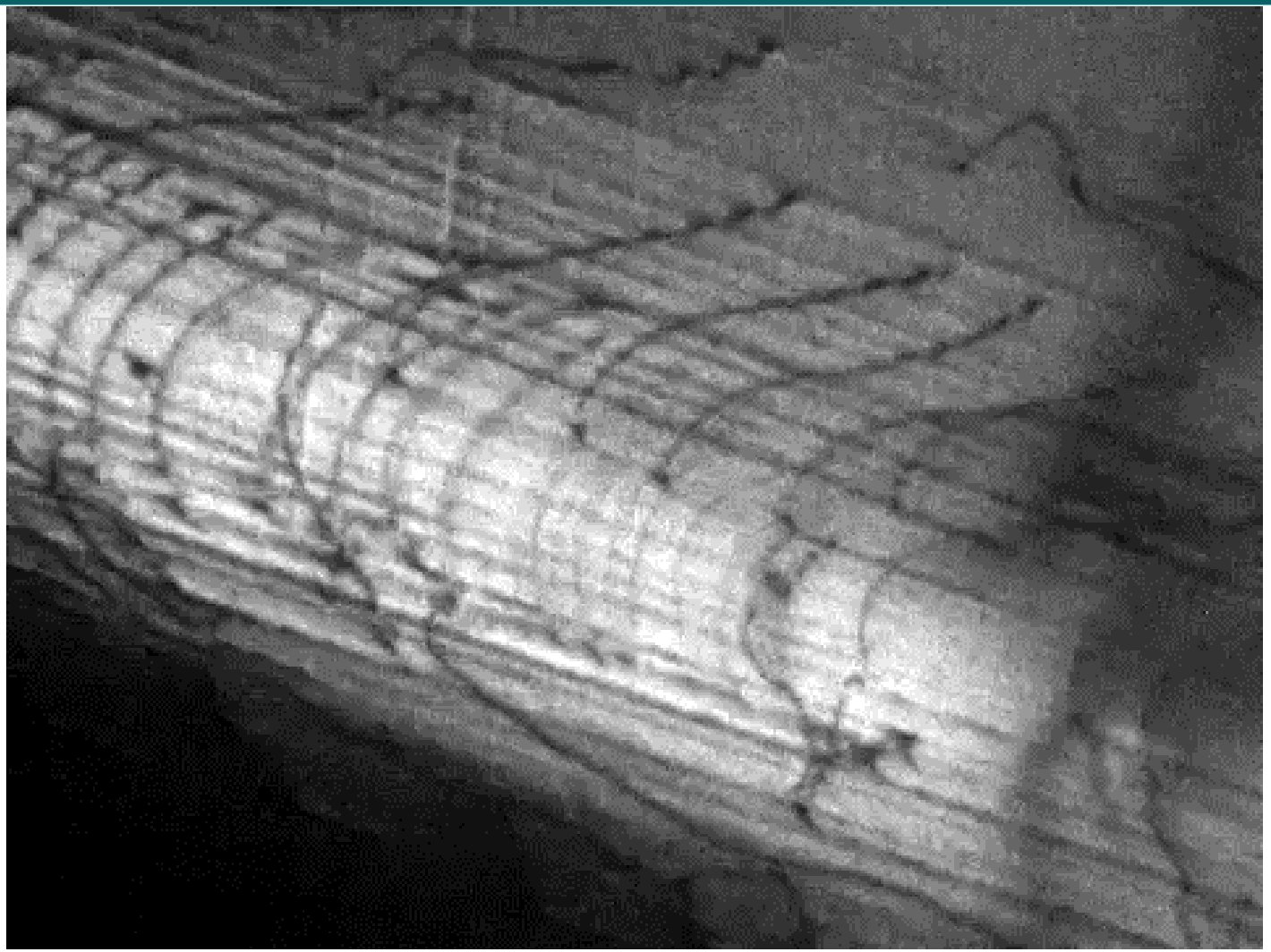
Edge dislocation



Screw dislocation



Dislocation glide



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

Deformation of a single crystal

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

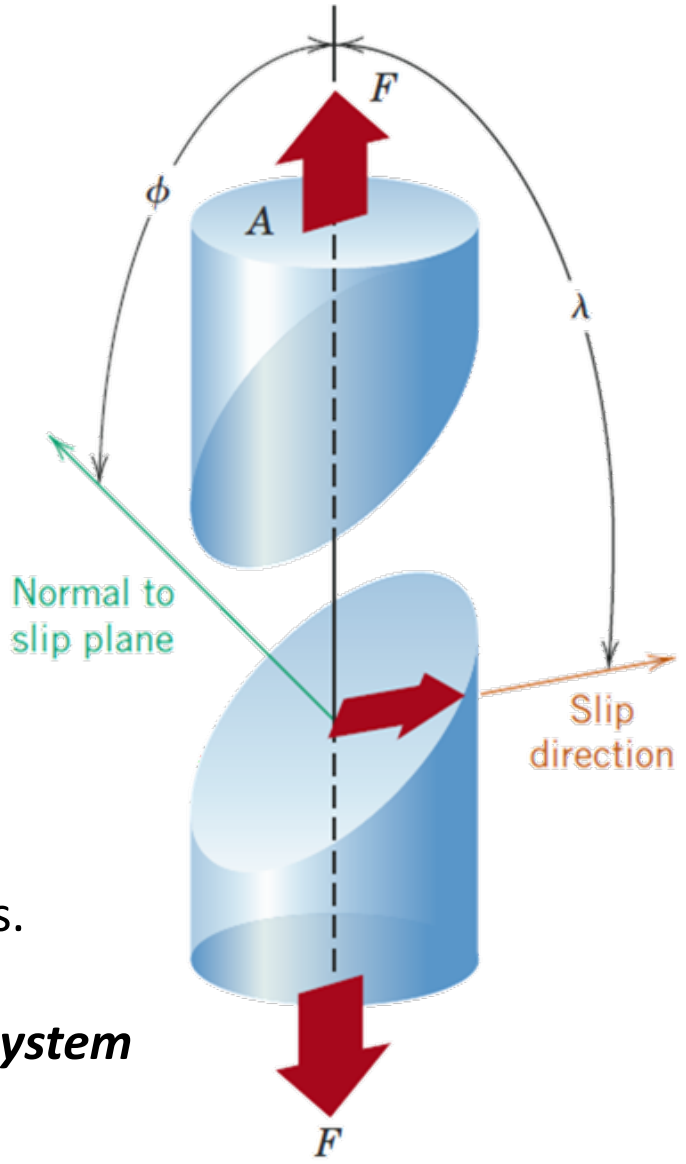
Driving force for slip:
Tensile stress leads to *resolved shear stress* τ_r in slip system

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

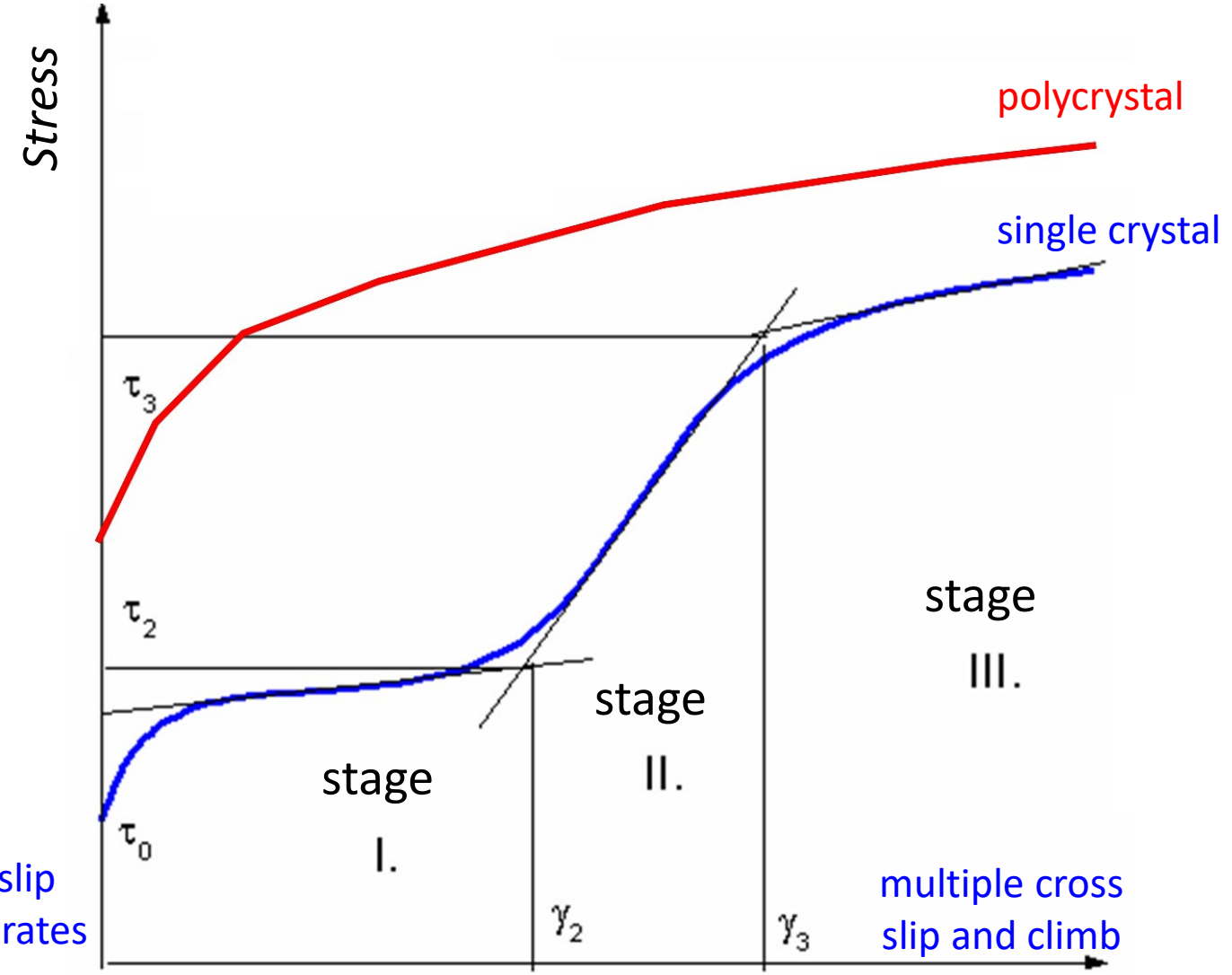
No shear stress: slip direction or slip plane normal are perpendicular to the tensile axis

Maximum shear stress: slip plane and slip direction are under 45° to the tensile axis.

In single crystals:
Slip starts on slip system with highest τ_r → ***active slip system***



Deformation of crystalline materials



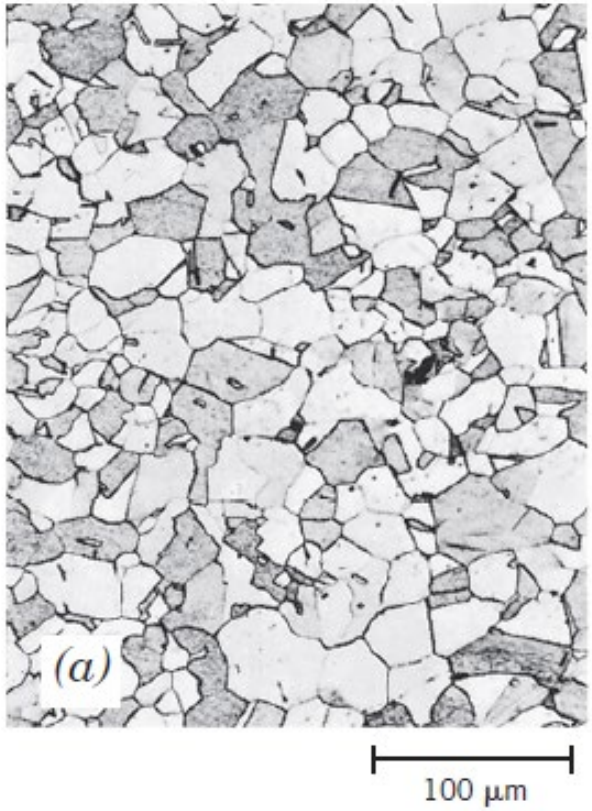
only one slip system operates

multiple cross slip and climb

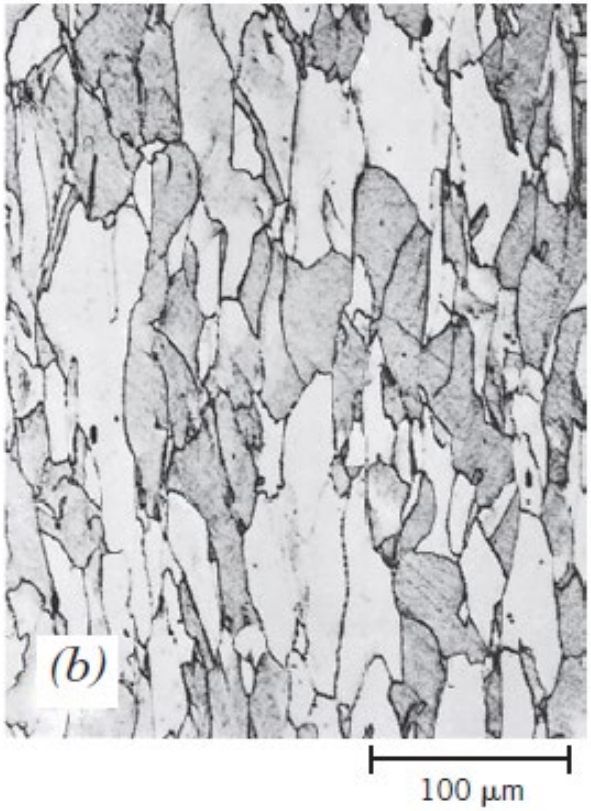
multiplication and interaction of dislocations

Deformation of a polycrystalline materials

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



(*a*) Before deformation the grains are equiaxed.

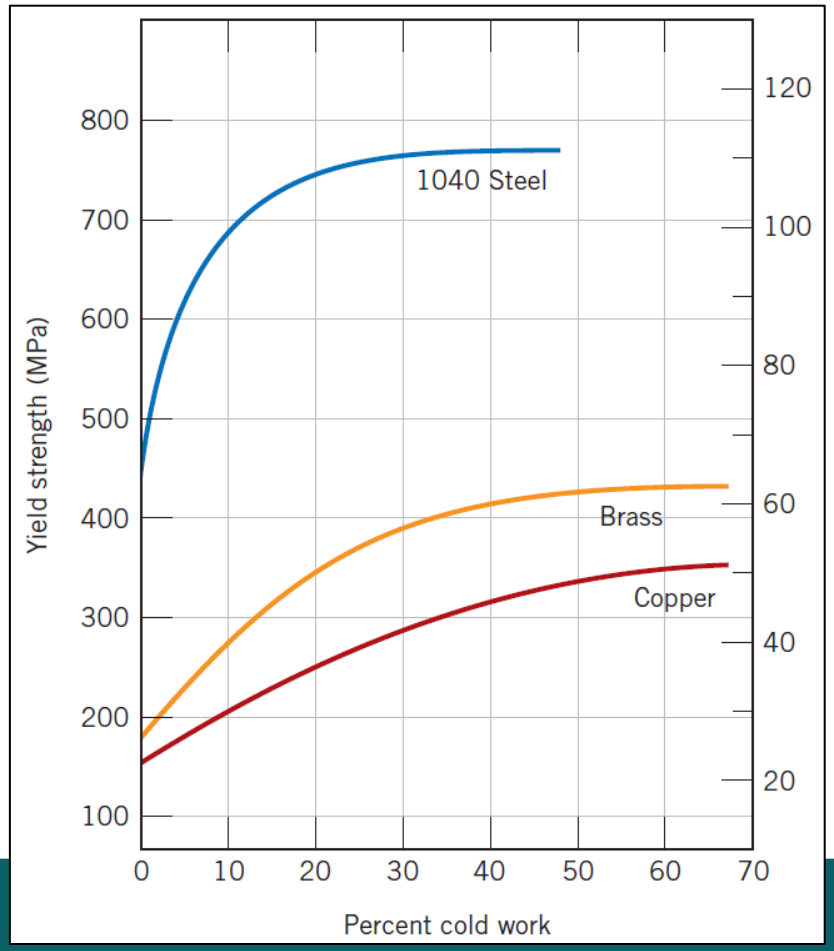


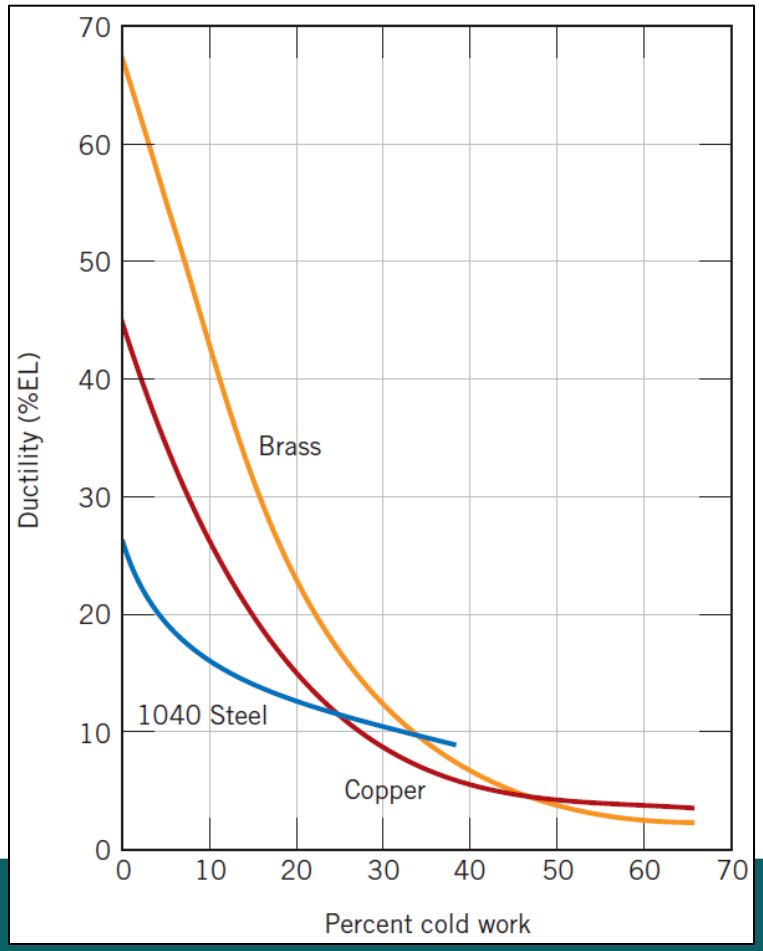
(*b*) The deformation has produced elongated grains.

Flow curve

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.

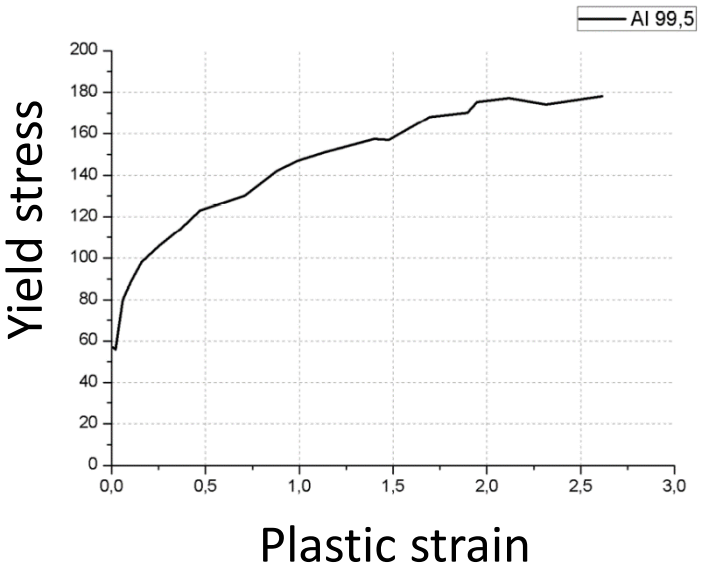
Callister: Materials Science and Engineering, 7th ed.



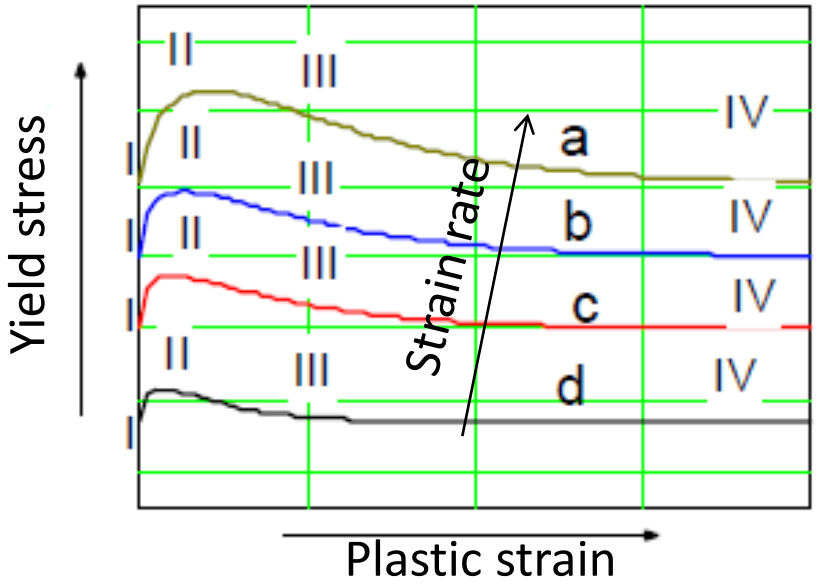


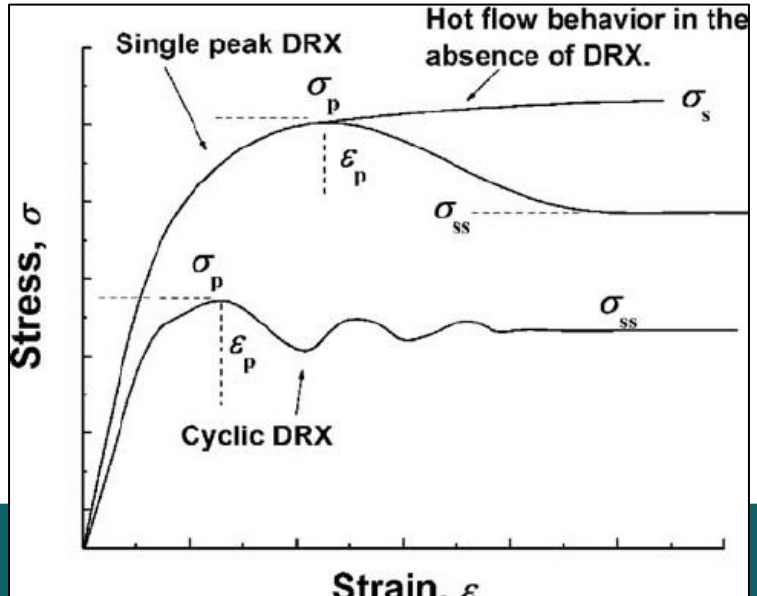
Flow curve

flow curves – cold deformation



flow curves – hot deformation

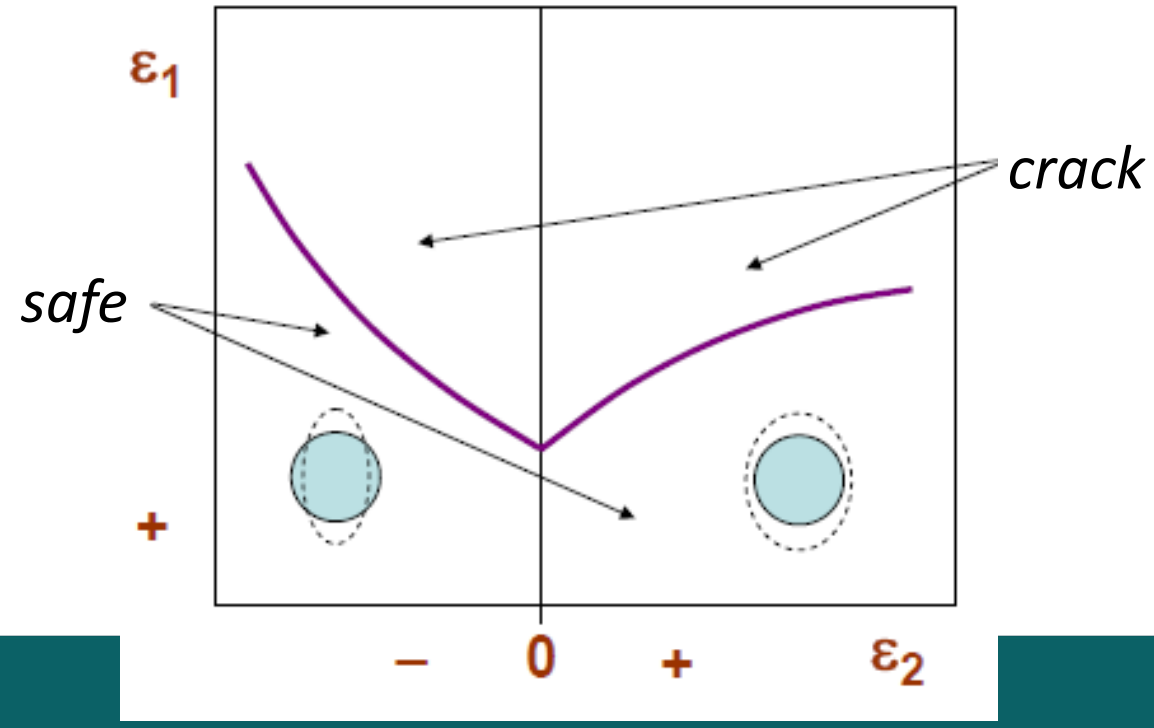


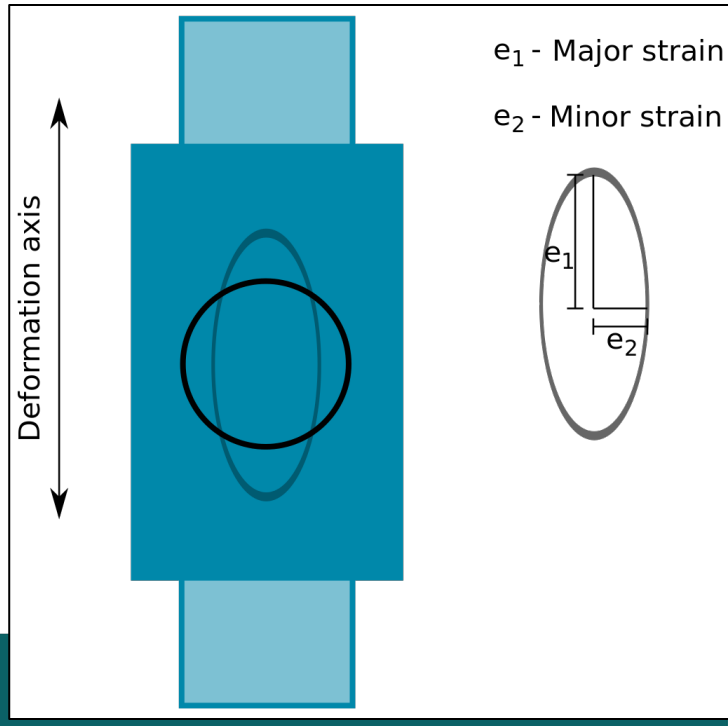


https://www.researchgate.net/publication/250196836_Modeling_of_the_hot_deformation_behavior_of_boron_microalloyed_steels_under_uniaxial_hot-compression_conditions/figures?lo=1

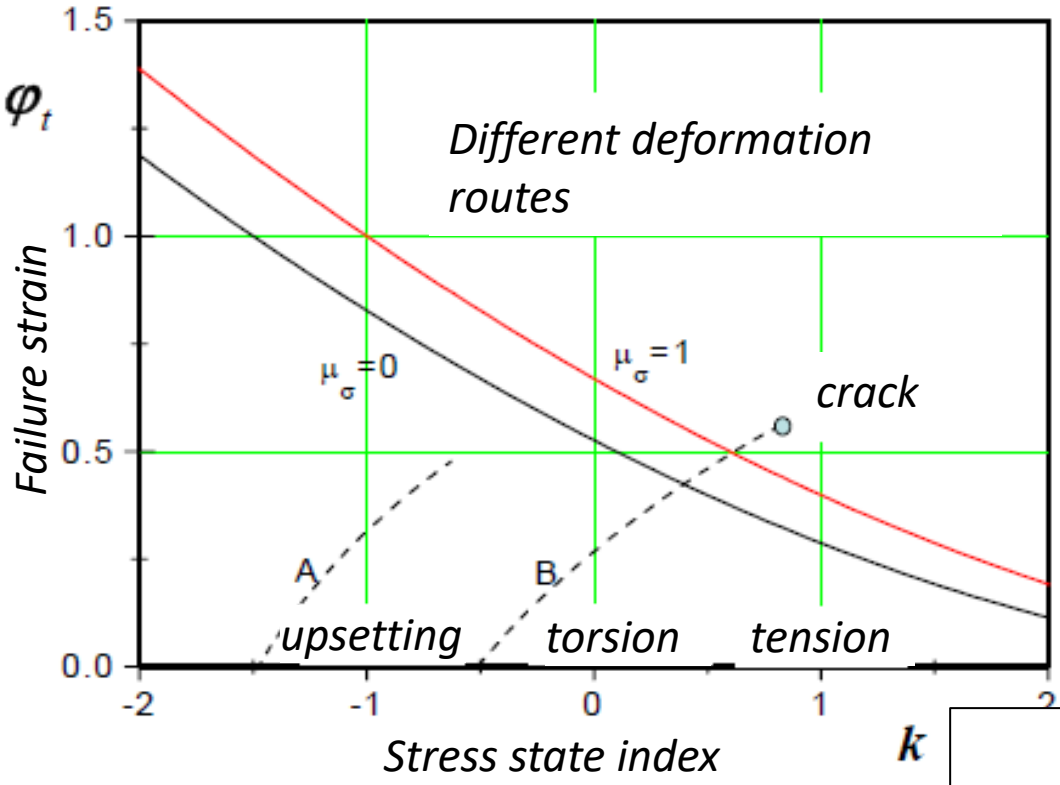
Forming limit diagram

- 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.





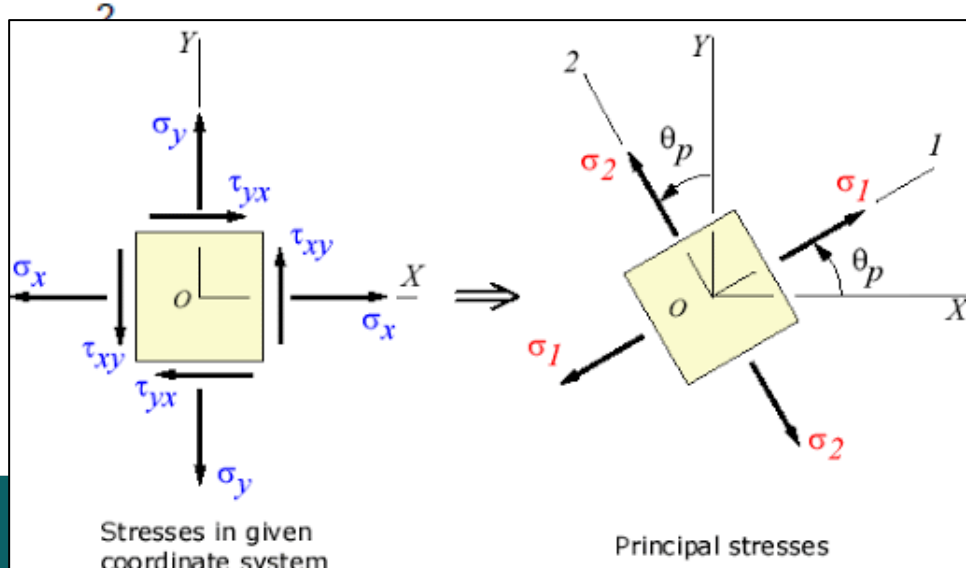
Forming limit – bulk materials



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.

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

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



Classification - temperature

Cold working

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

Hot working

- Above the *recrystalization* 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

Classification – workpiece type

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

Classification – primary / component process.

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.

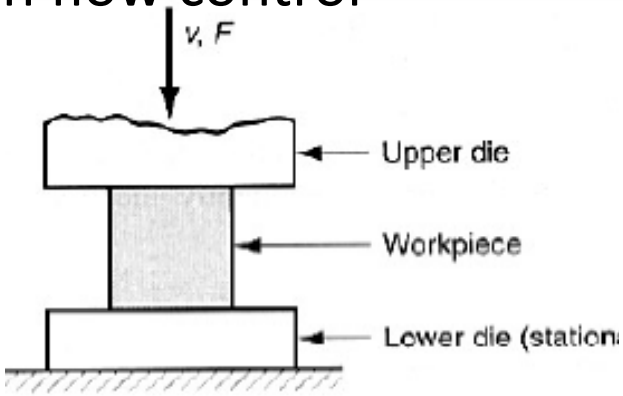
Range of forming processes

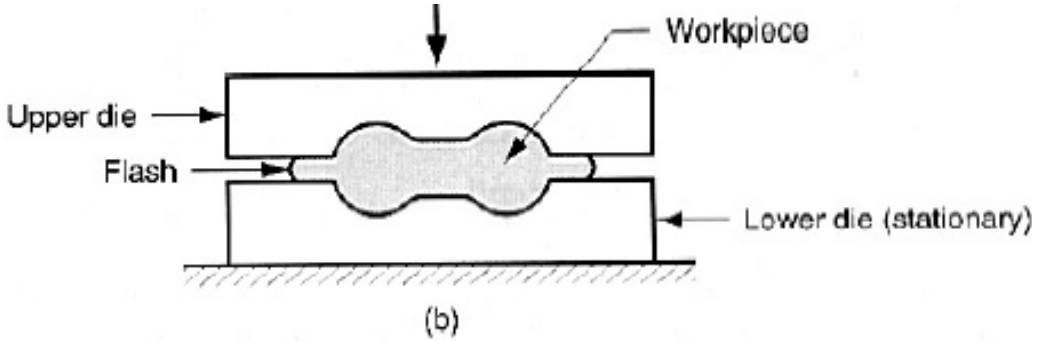
- **Free forming**
  - –Tool does not contain the desired shape
- **Two dimensional forming**
  - –Point contact between tool and work material
  - –Two relative motions required to produce geometry
  - –Incremental forming processes
- **One dimensional forming**
  - –Line or surface contact with work 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**

Forging techniques

Cold warm and hot forging depending on the temperature

Grain flow control





Open die

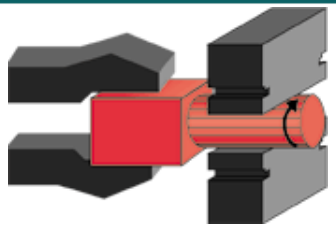
+ Simple and inexpensive dies
+ Small quantity

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

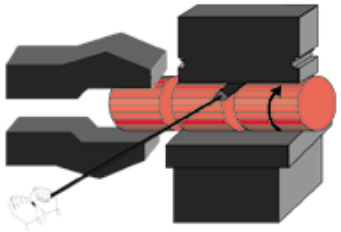
Closed die

+ 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

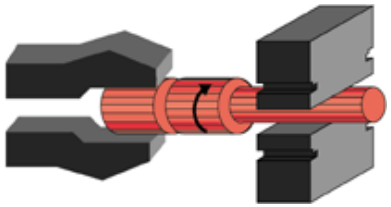
Open die forging - stages



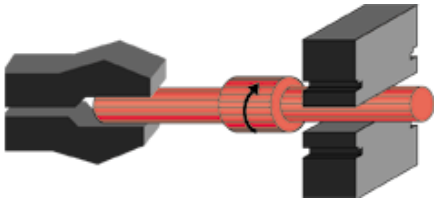
(a) forge hot billet to max diameter



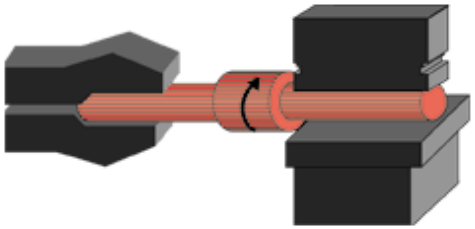
(b) fuller: tool to mark step-locations



(c) forge right side



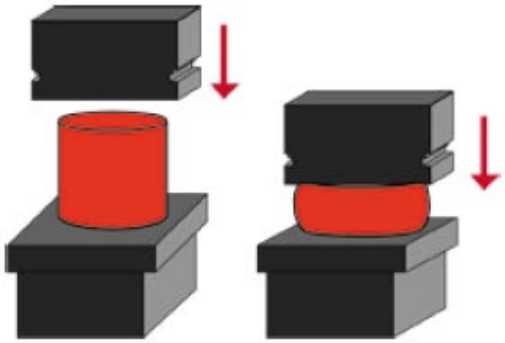
(d) reverse part, forge left side

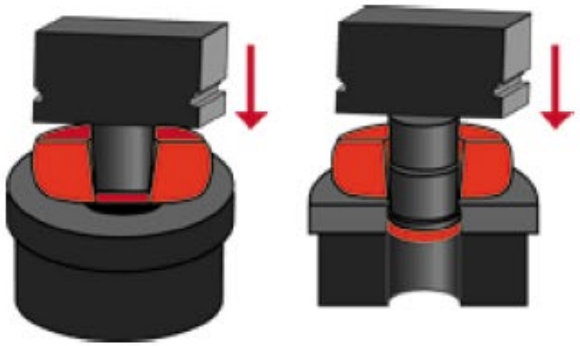


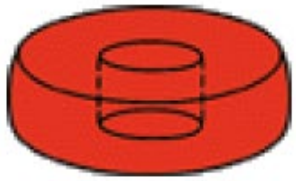
(e) finish (dimension control)

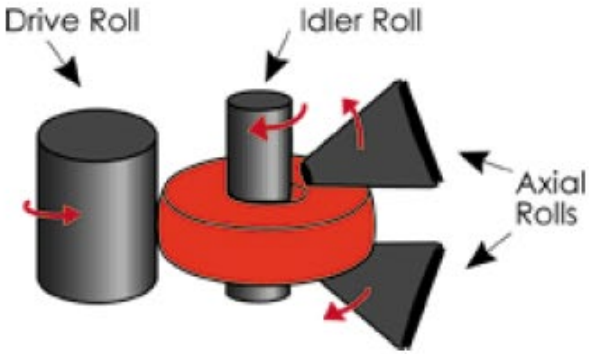
[source:www.scotforge.com]

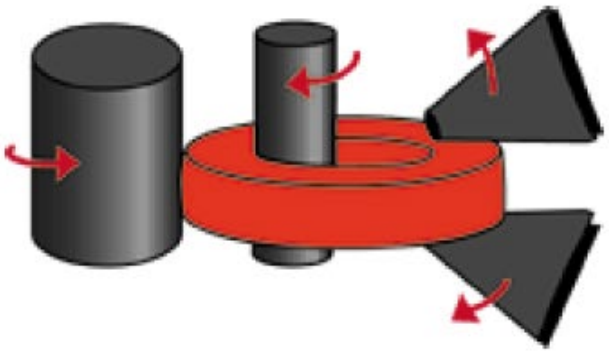
Ring forging and rolling

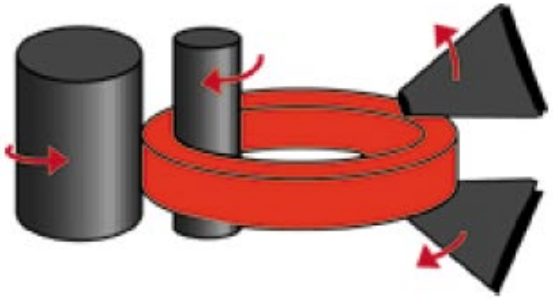


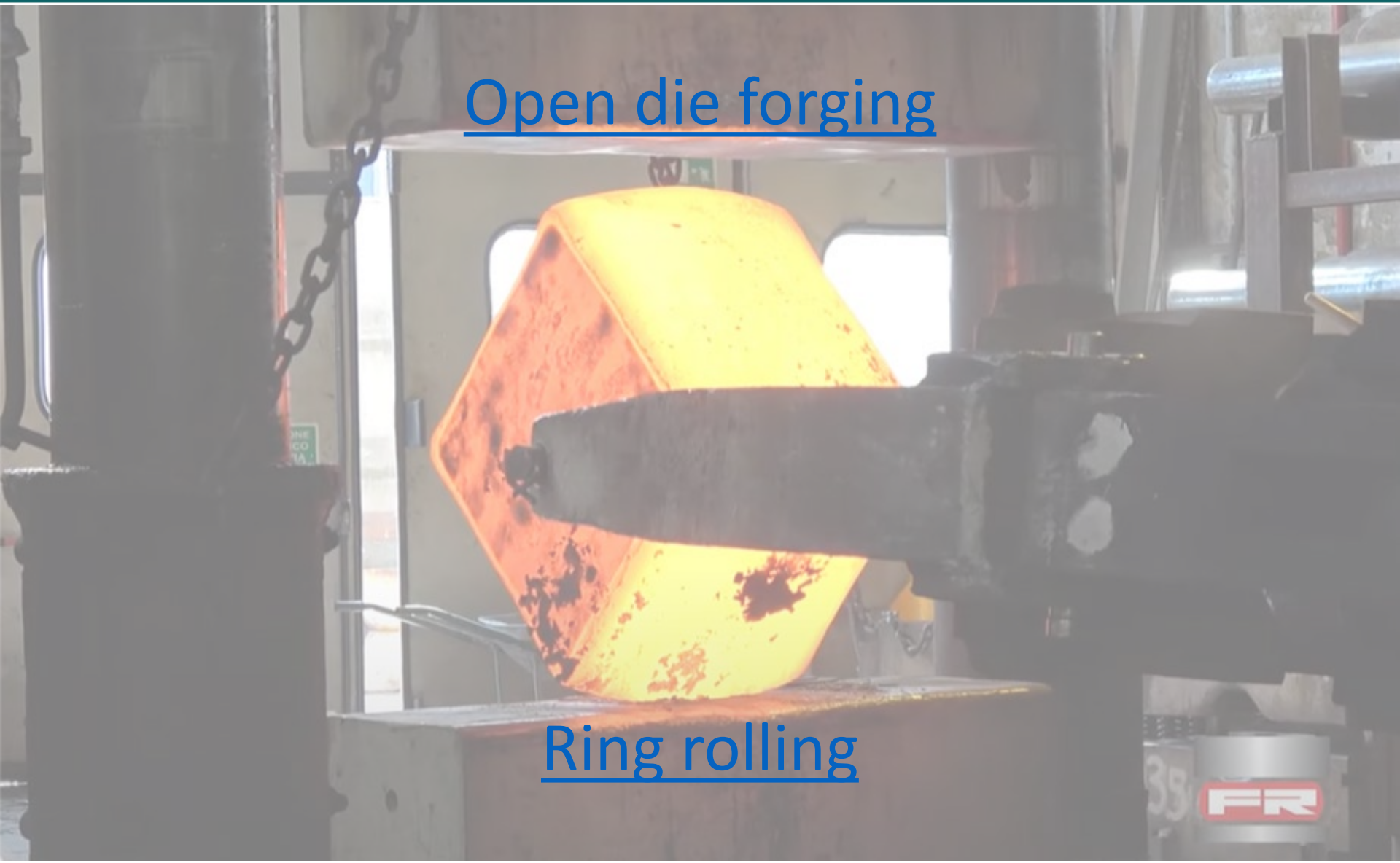




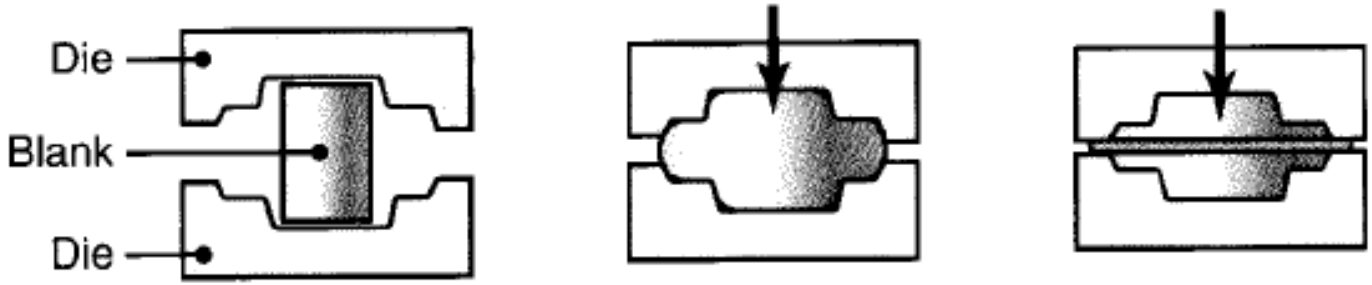


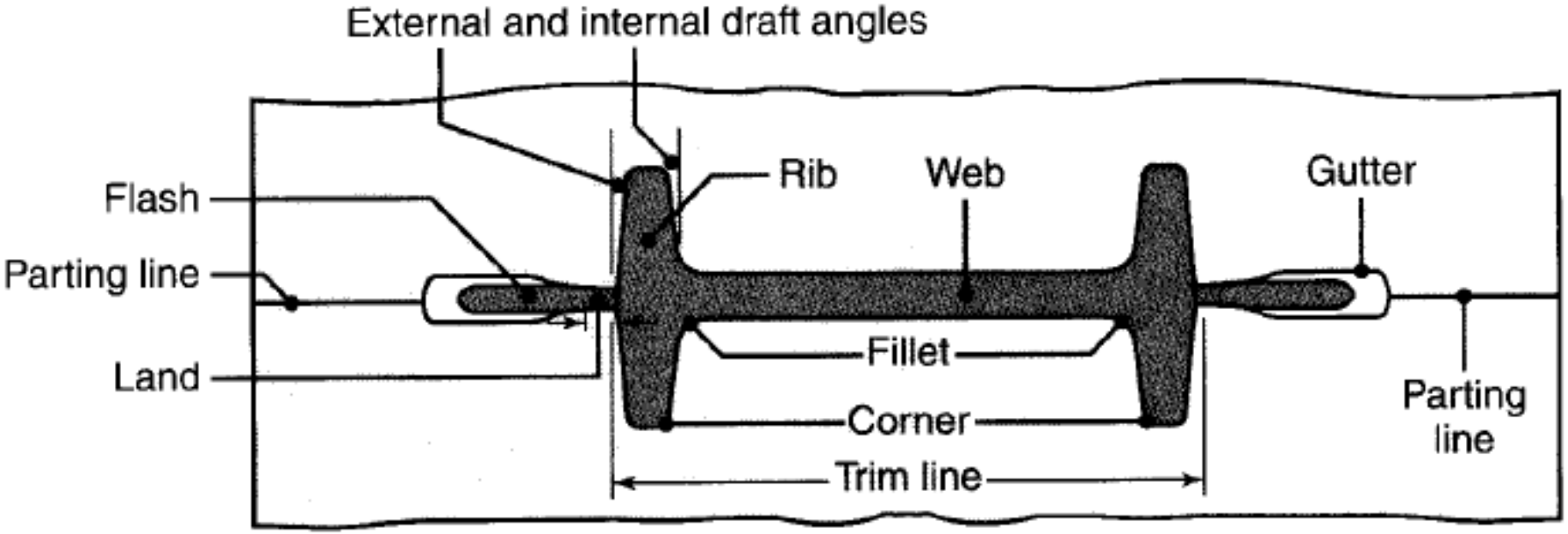




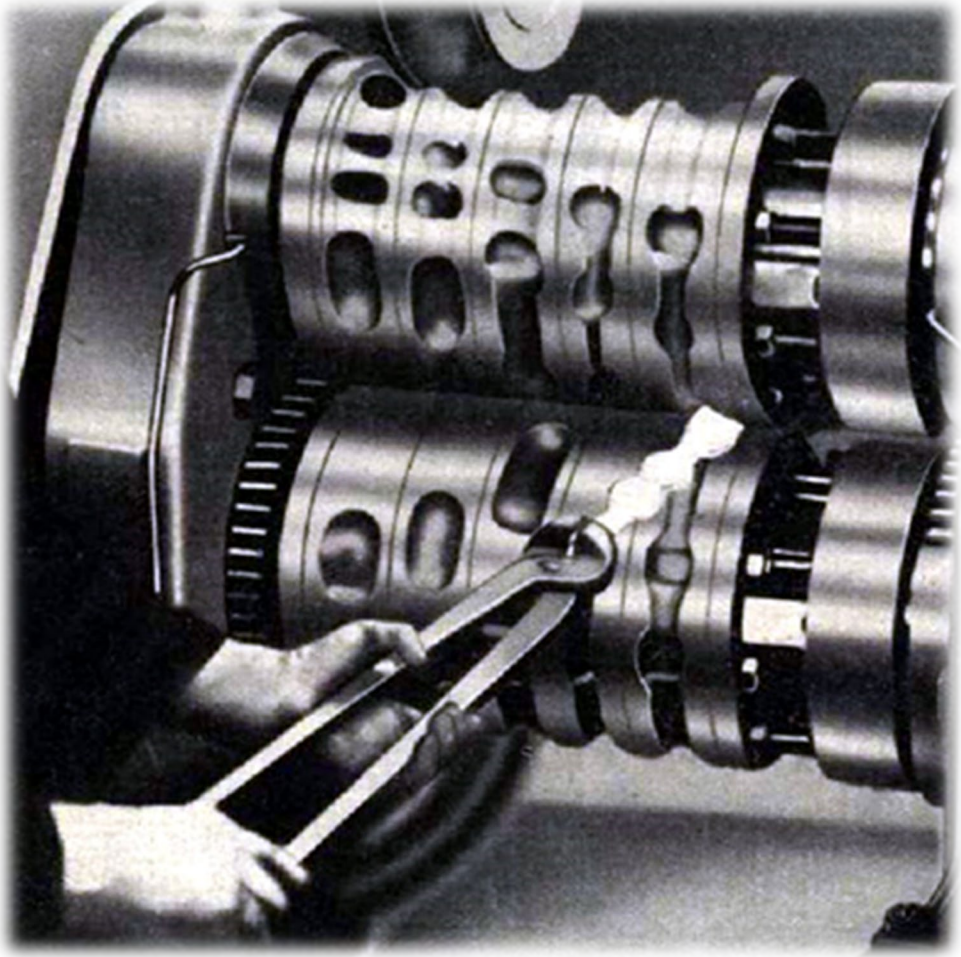

Open die forging
Ring rolling

Closed die forging



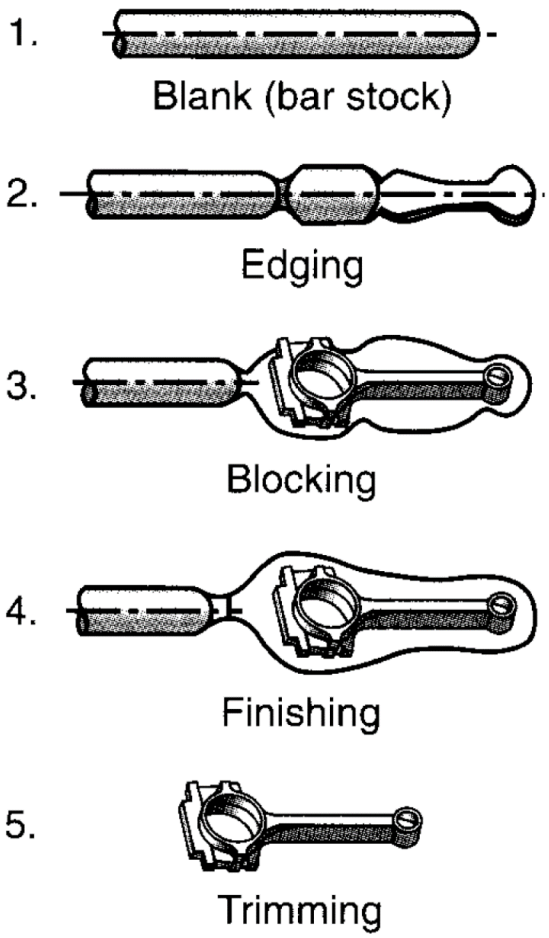


Forge rolling



https://www.tradekorea.com/product/detail/P711035/ZGD-1000-Automatic-forging-roll-for-connecting-rod-forging.html?RLGOODS=D46-165x1200%20Cross%20Wedge%20Roll%20for%20Crankshafts%20Forging

Closed die forging

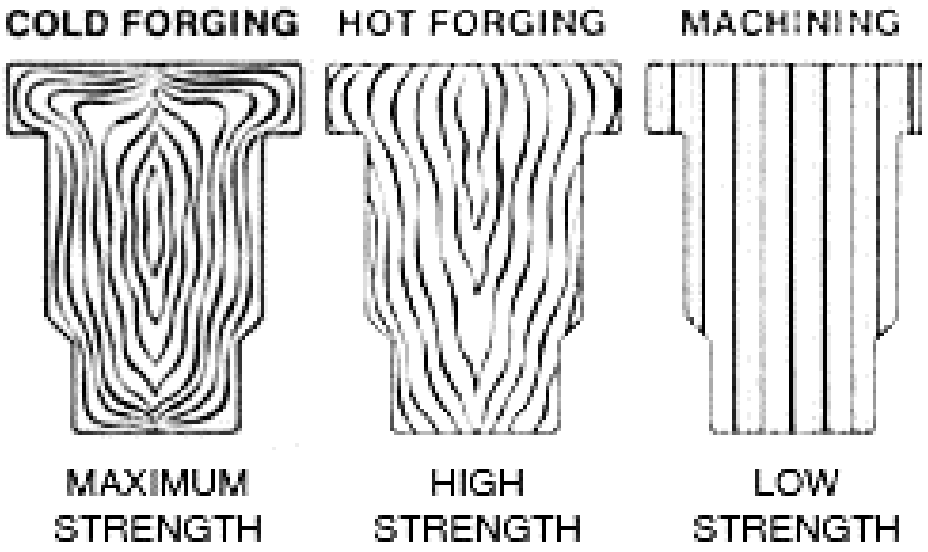


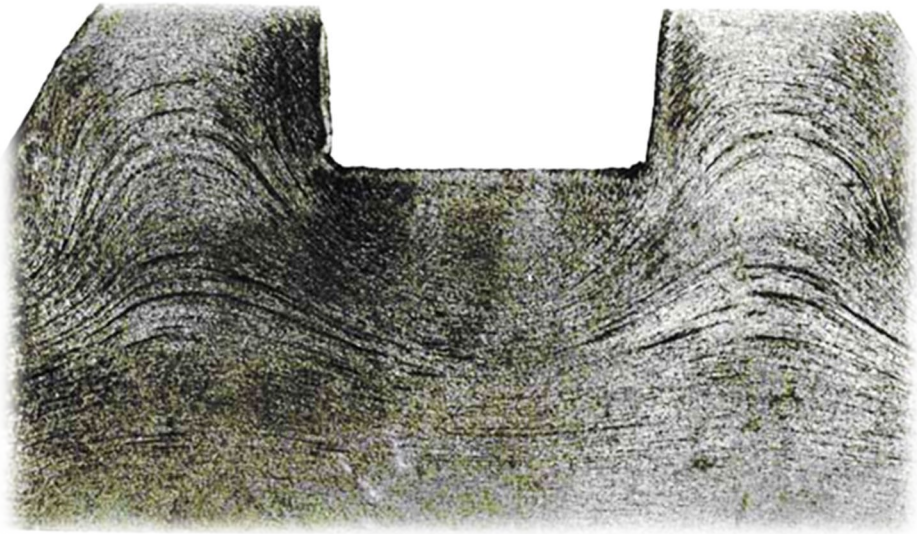
Forging steps of a connecting rod

Closed die forging – technology sequence

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.

Forging – grain flow





Quality of forged parts

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

Stronger/tougher than cast/machined parts of same material


Closed die forging

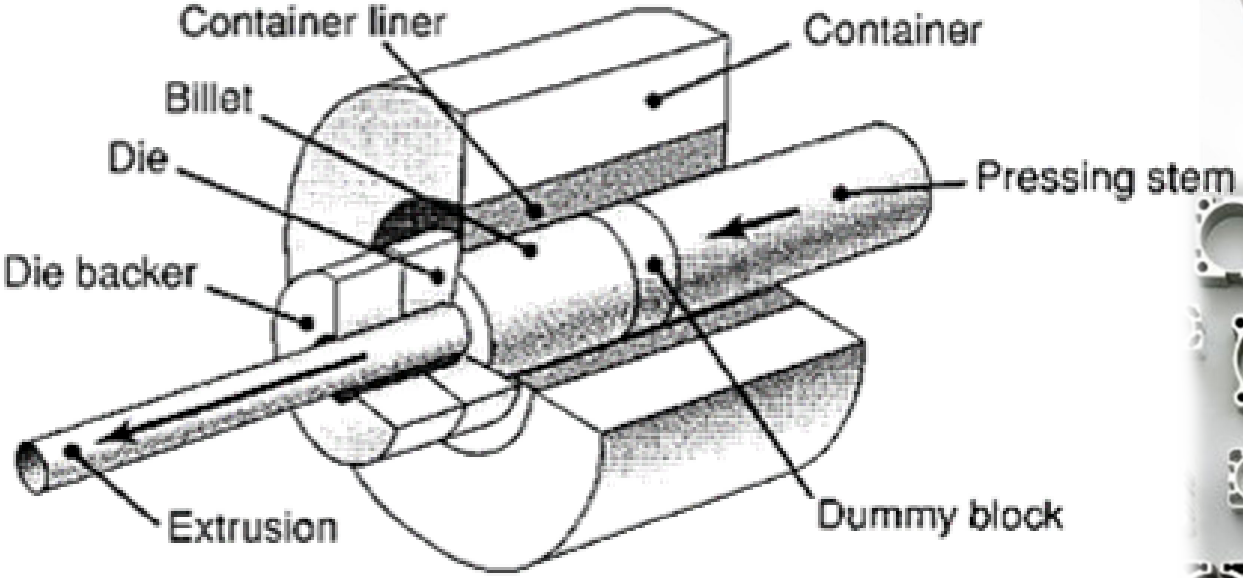
Extrusion processes

Hot and cold extrusion

Forward and backward extrusion

Extrusion of other shapes

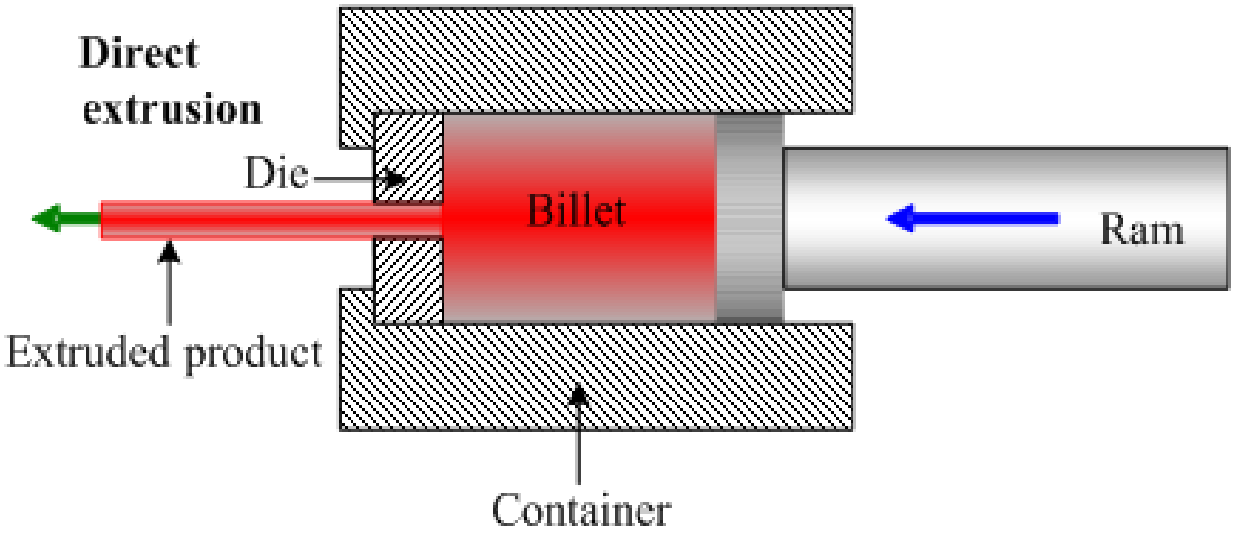
Drawing of rod and wire

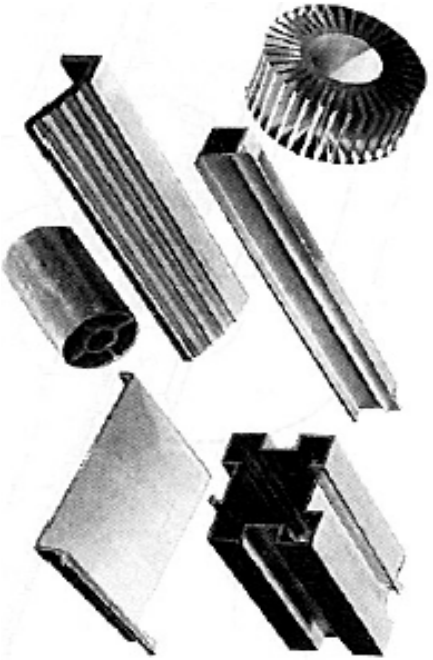


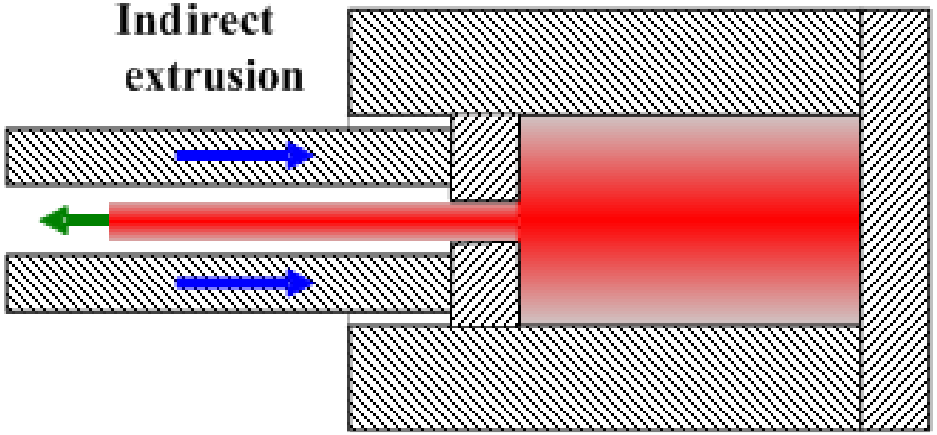
https://www.alibaba.com/product-detail/Aluminum-Extrusion-Die-Mould-China-Moulds_60169109589.html

https://tr.pinterest.com/pin/426575395938085457/

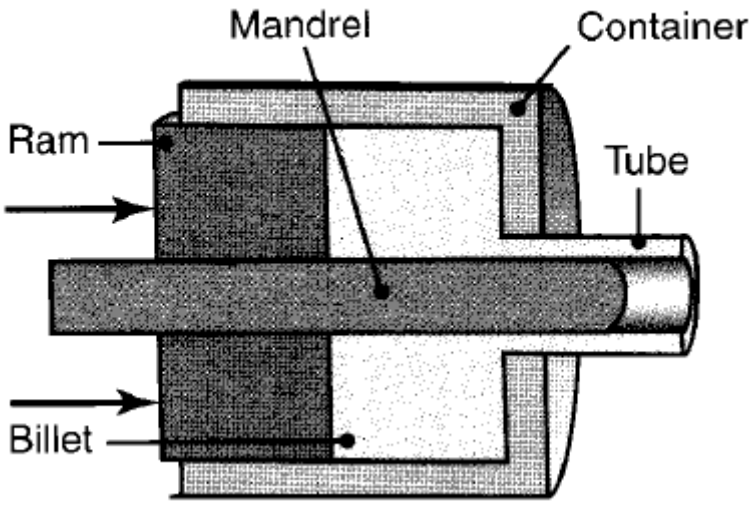
Direct and indirect extrusion





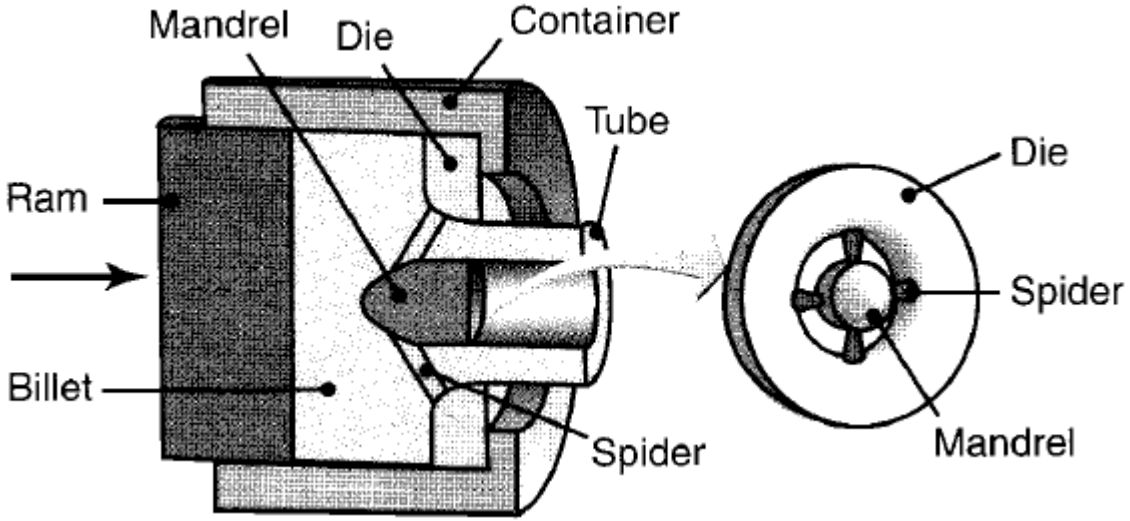


Extrusion of a seamless tubes



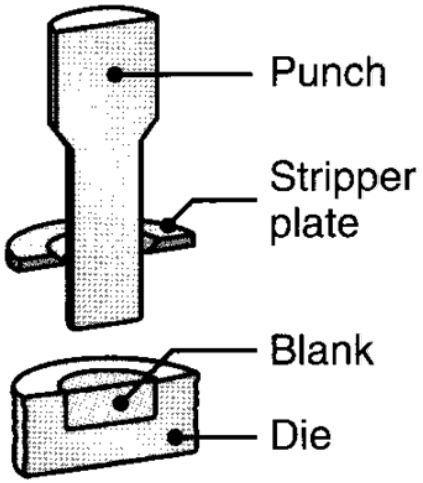
using an internal mandrel

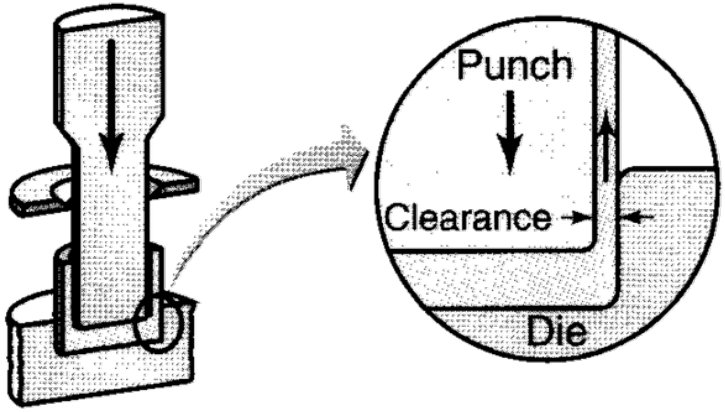
using a spider die

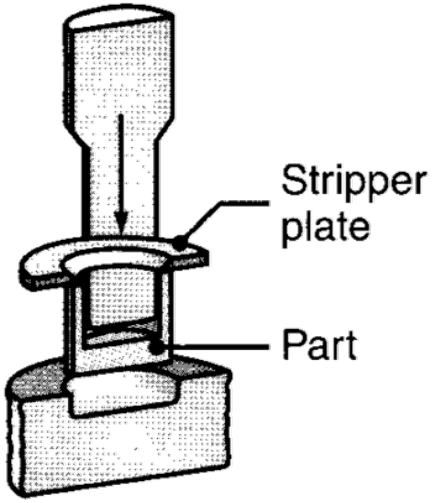



Aluminum extrusion

Impact extrusion

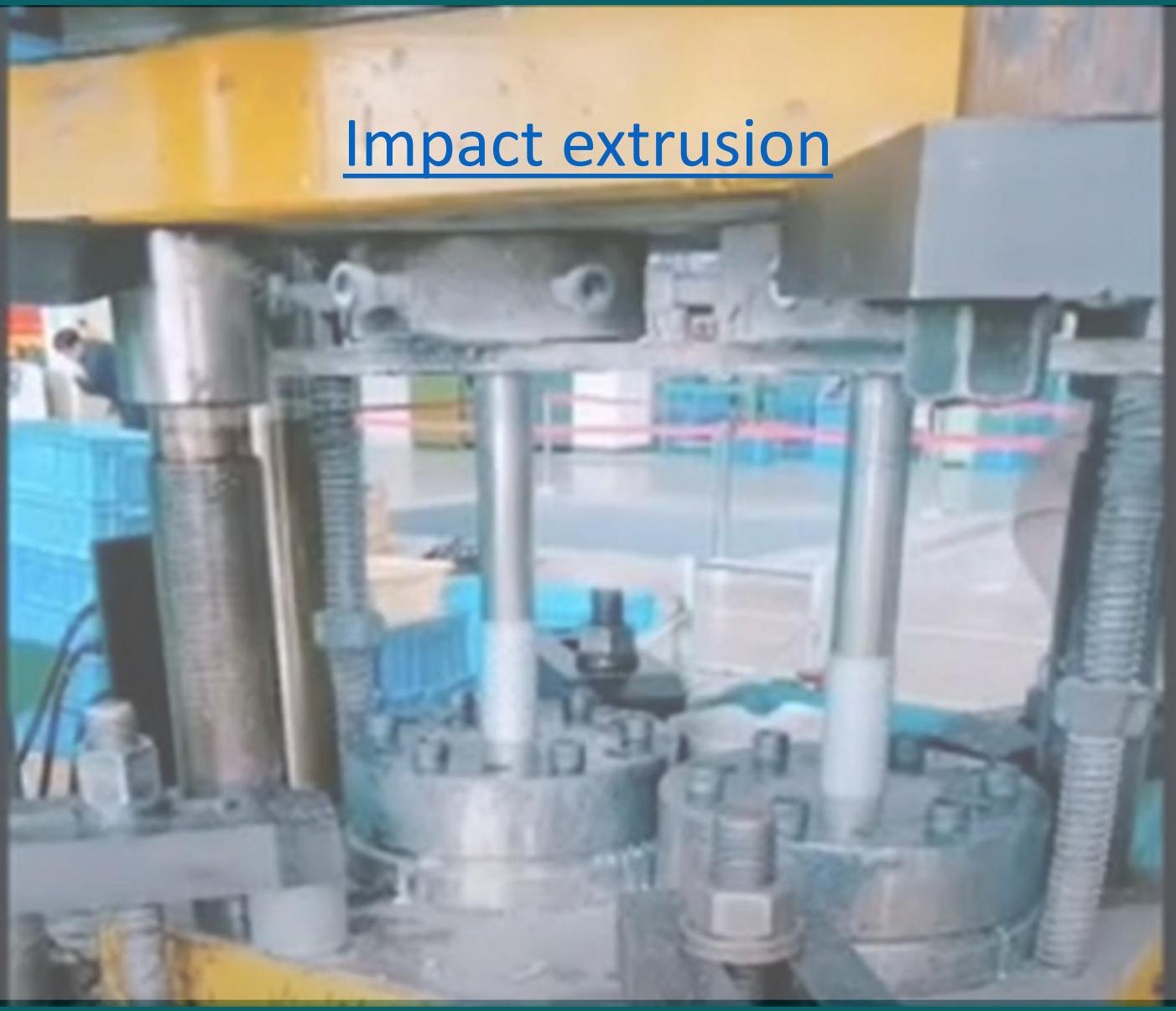






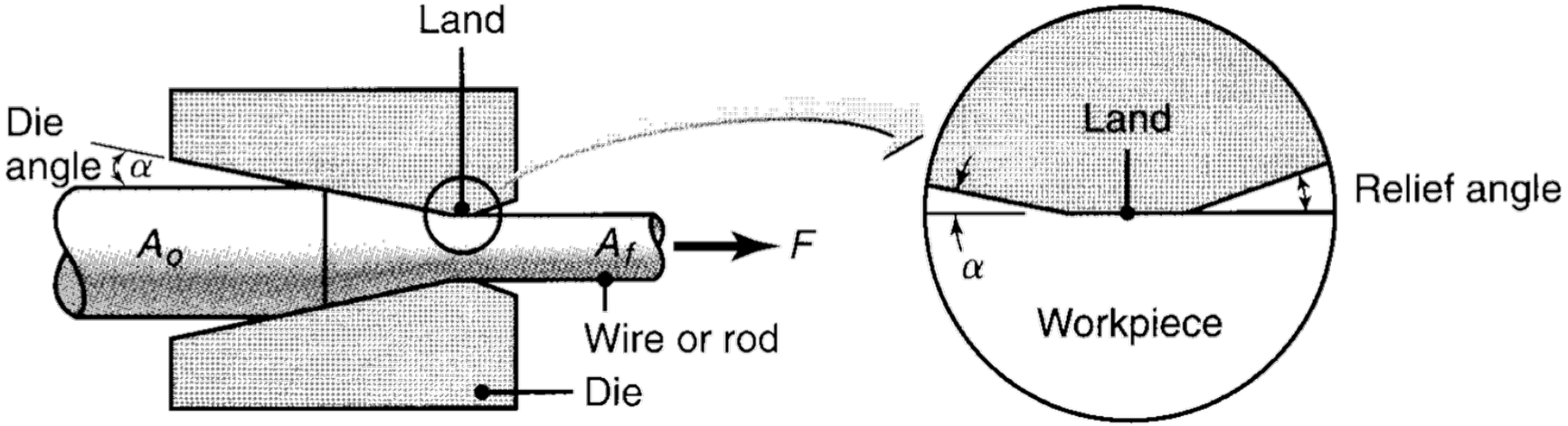
https://www.plastprintpack.fairtrade-messe.com/en/Impact-Extrusion-our-core-expertise,p1546107

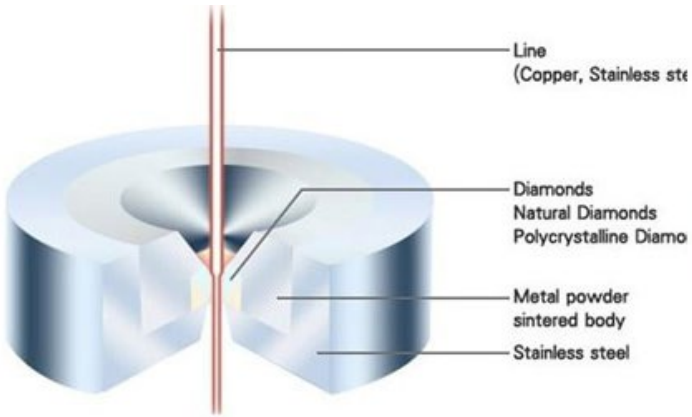
http://www.ashfield-extrusion.co.uk/products/technical/


Impact extrusion

Drawing

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

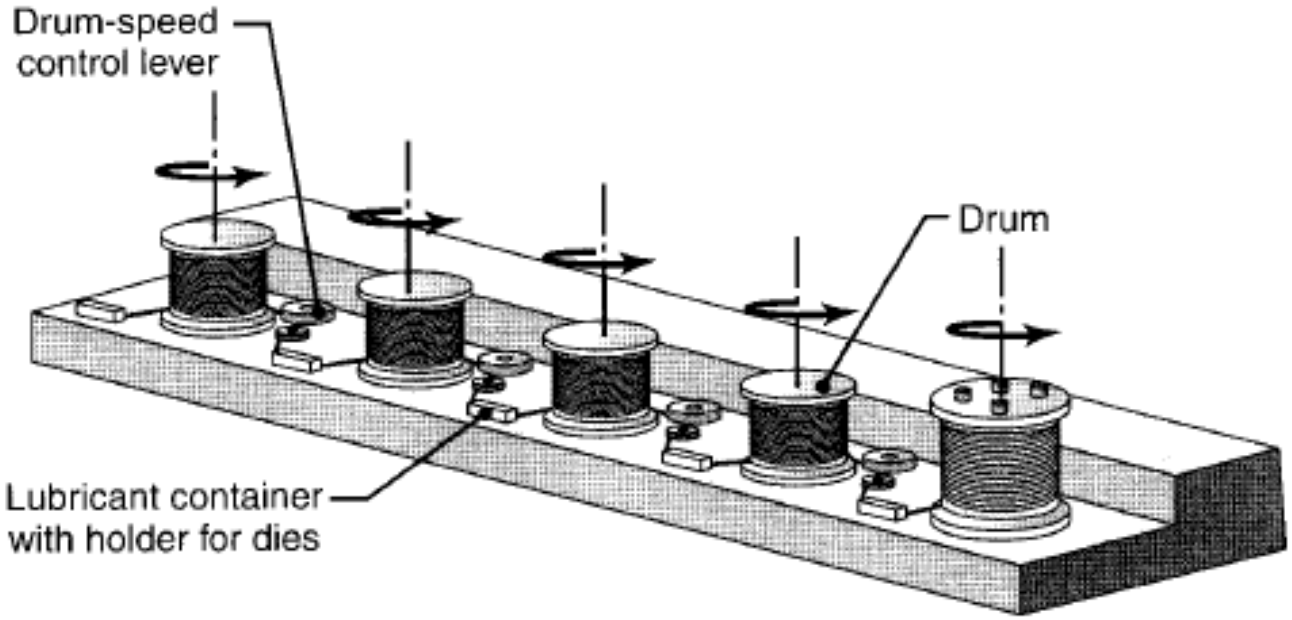




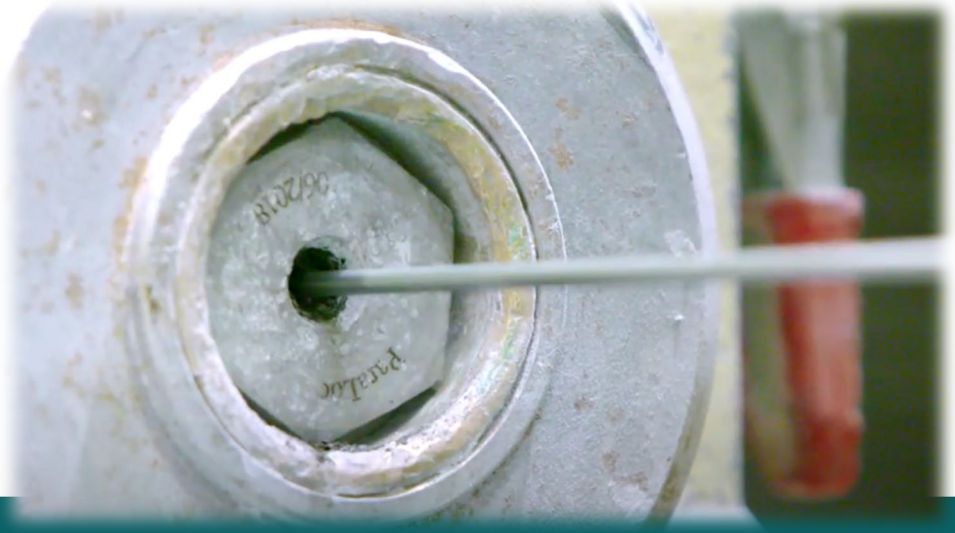
https://www.estevesgroup.com/products/wire-drawing-dies/tc-drawing-dies

https://www.3betterdiamond.com/diamond-materials/wire-drawing-die/pcd_wire_drawing_die.html

Wire drawing

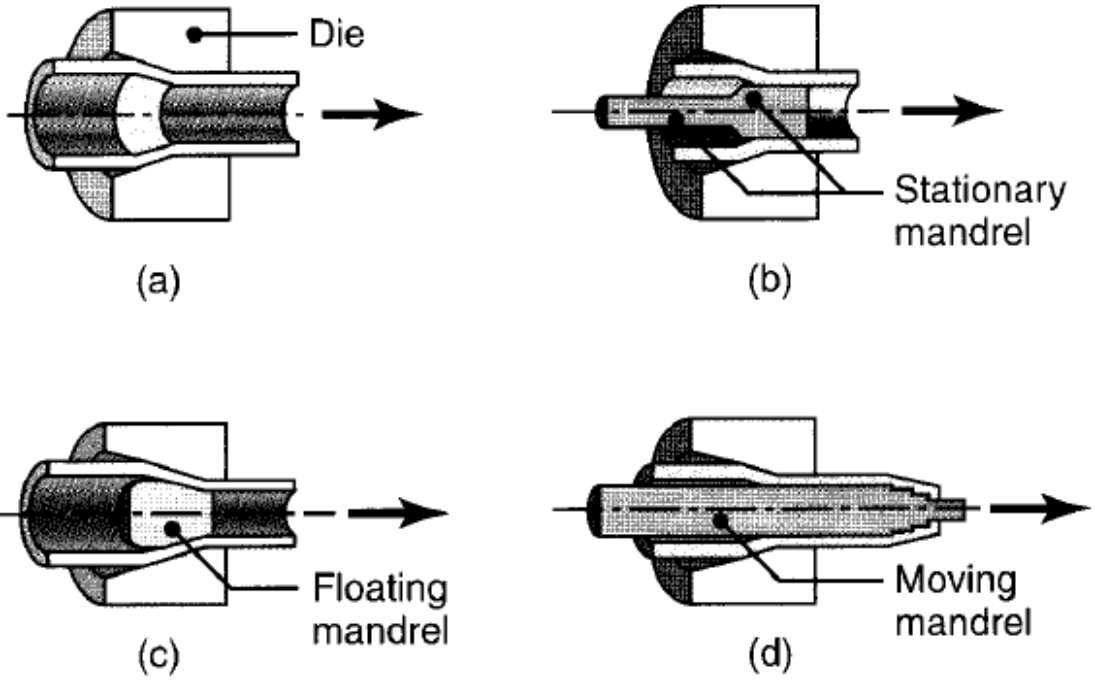


1. Descaling: machining, sand belt
2. Lubrication
3. WC wire drawing dies
4. 4.6 mm → 1.3 mm after 11 dies
5. Storing → cooling (24 h)
6. Tensile, torsion tetst
7. Straightening
8. Spring making

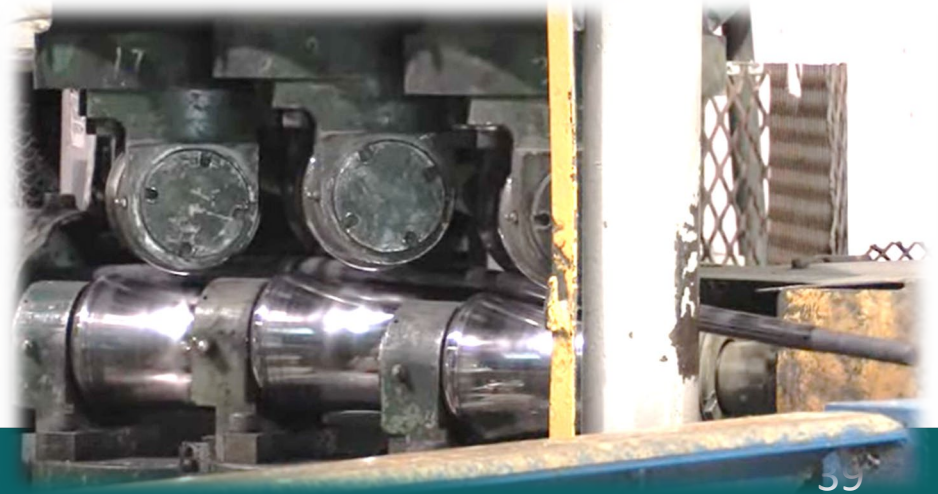



Wire drawing

Tube drawing

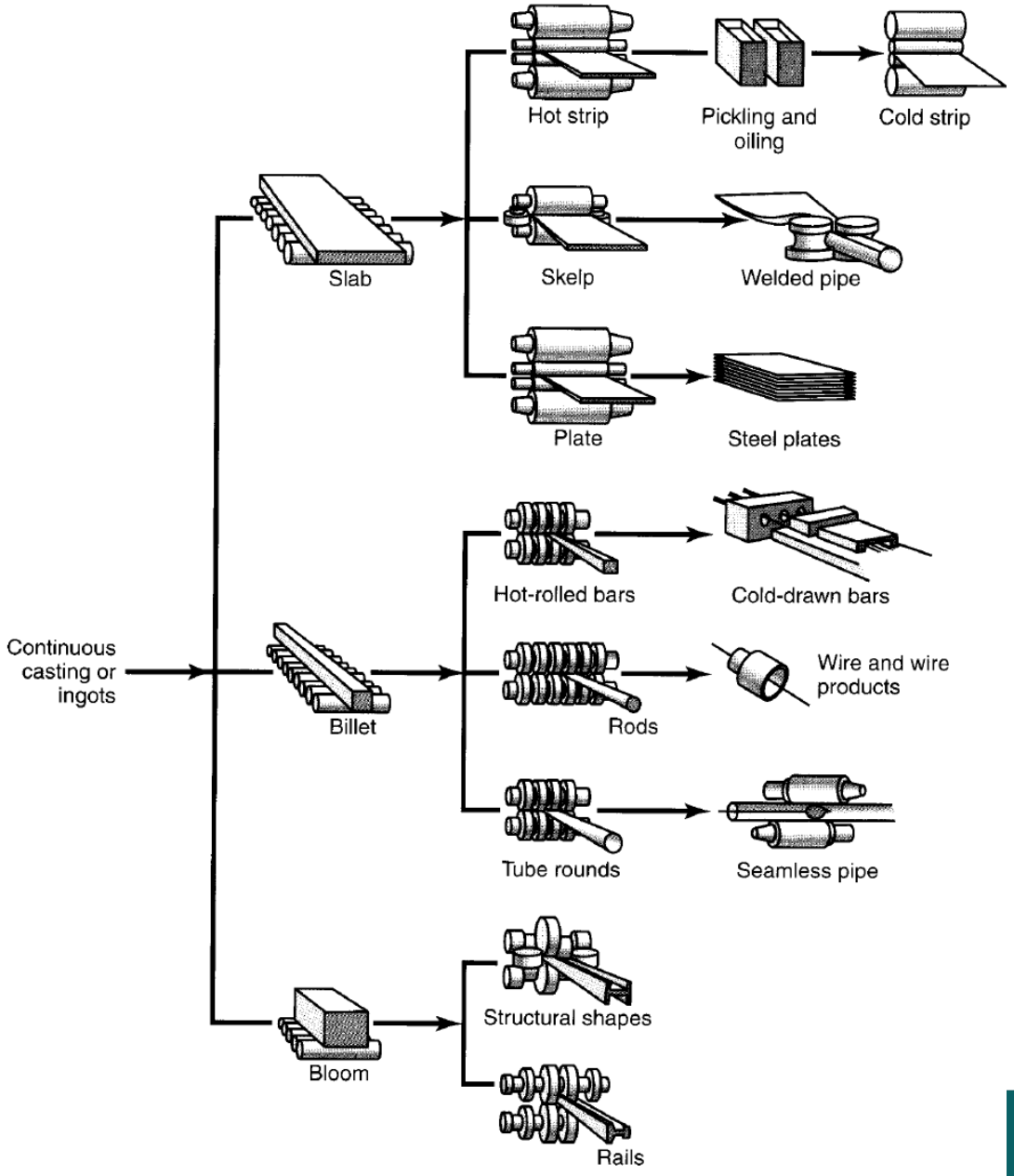


1. Annealing → softening
2. Pickling → cleaning, lubrication
3. Pointing → reducing diameter for drawing
4. Drawing
5. Anneling, repeating
6. Final annealing
7. Straightening
8. NDT: eddy current testing
9. Cutting
10. Final checking (dimensions, quality, etc.)
11. Shipping




Tube drawing

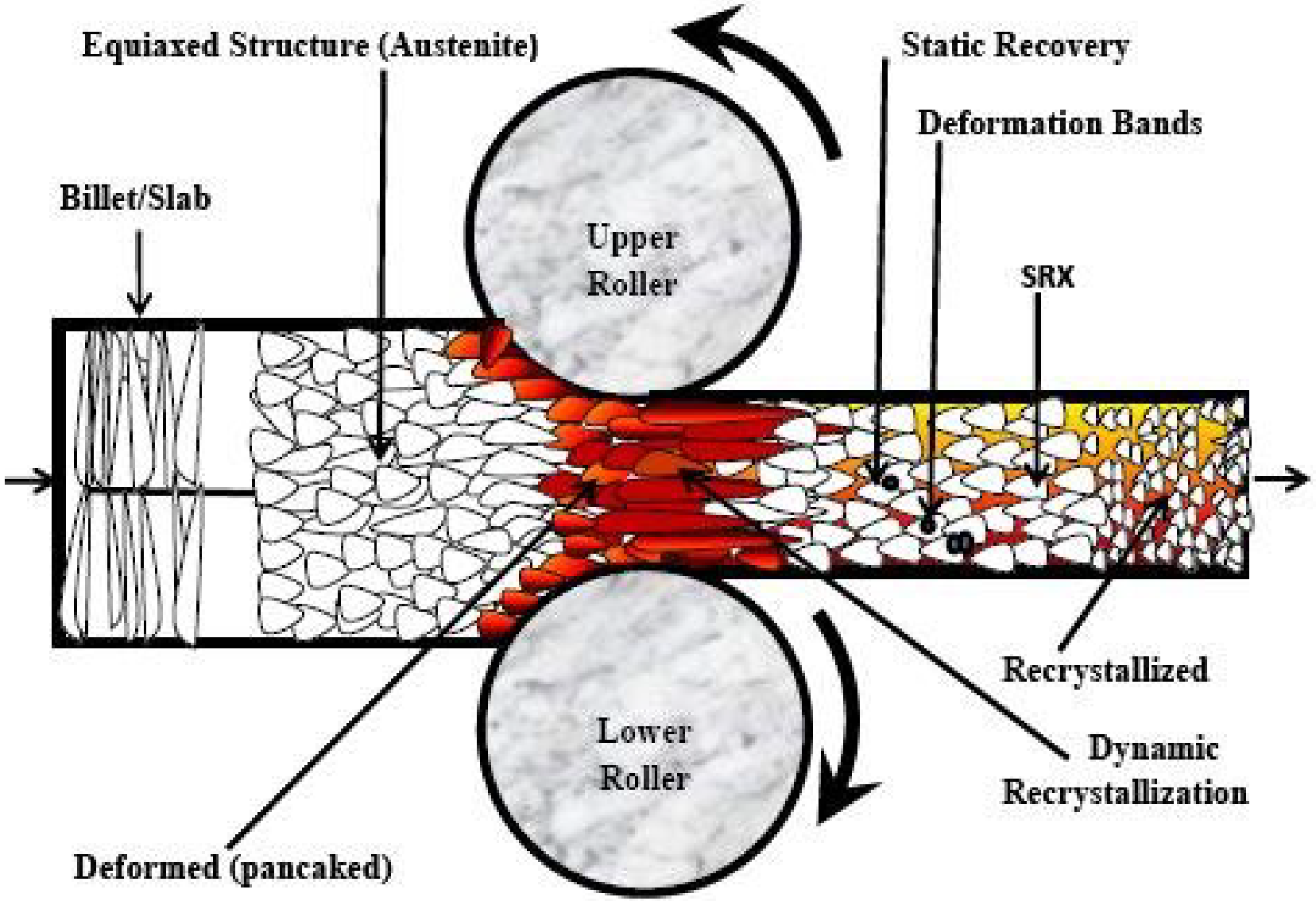
Rolling techniques



https://www.indiamart.com/proddetail/cold-rolling-mills-for-sheet-strip-coils-6942320788.html

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

Hot rolling process

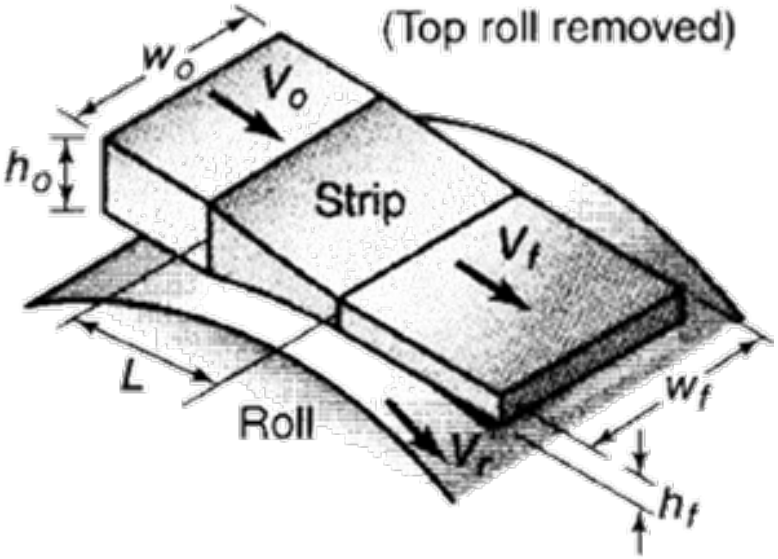


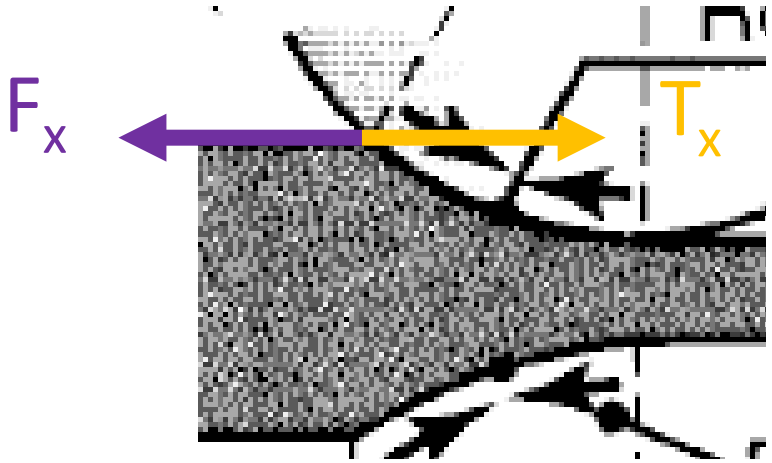
DOI: 10.18178/ijmerr.7.2.126-130

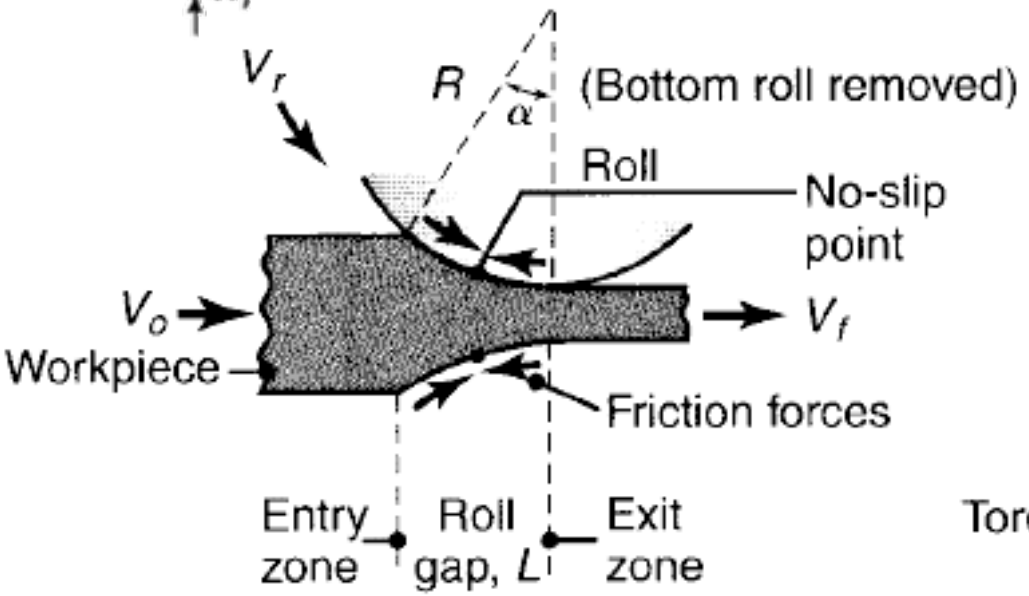
Flat rolling

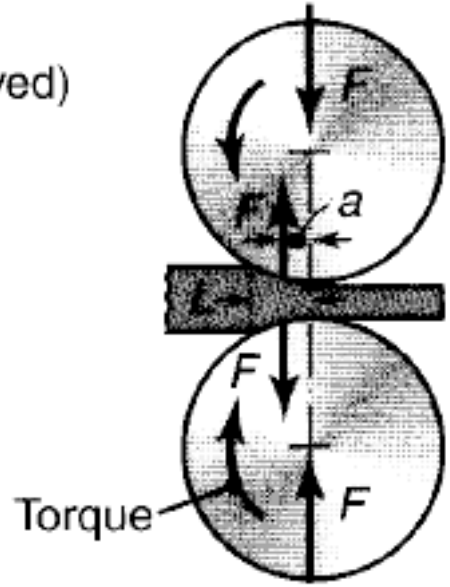
Material flow in the rolling gap

$tg\alpha < \mu$





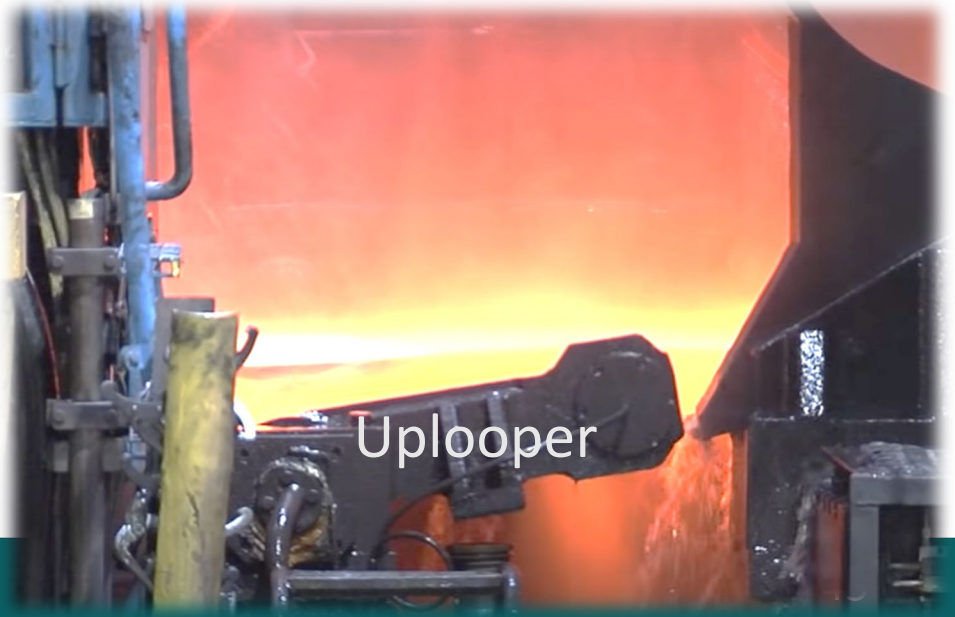




Flat rolling

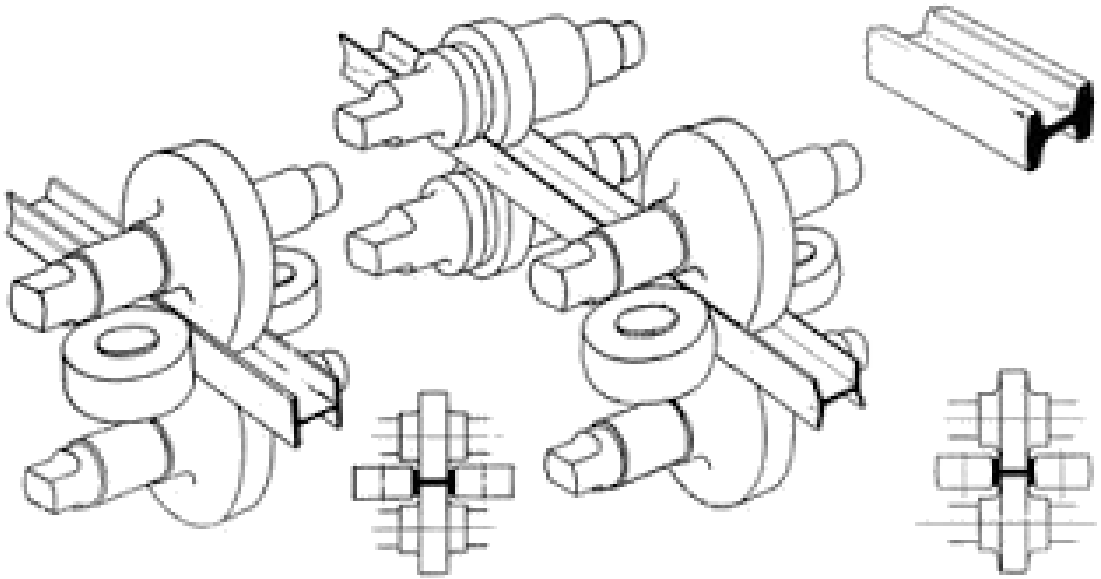
Hot rolling steps

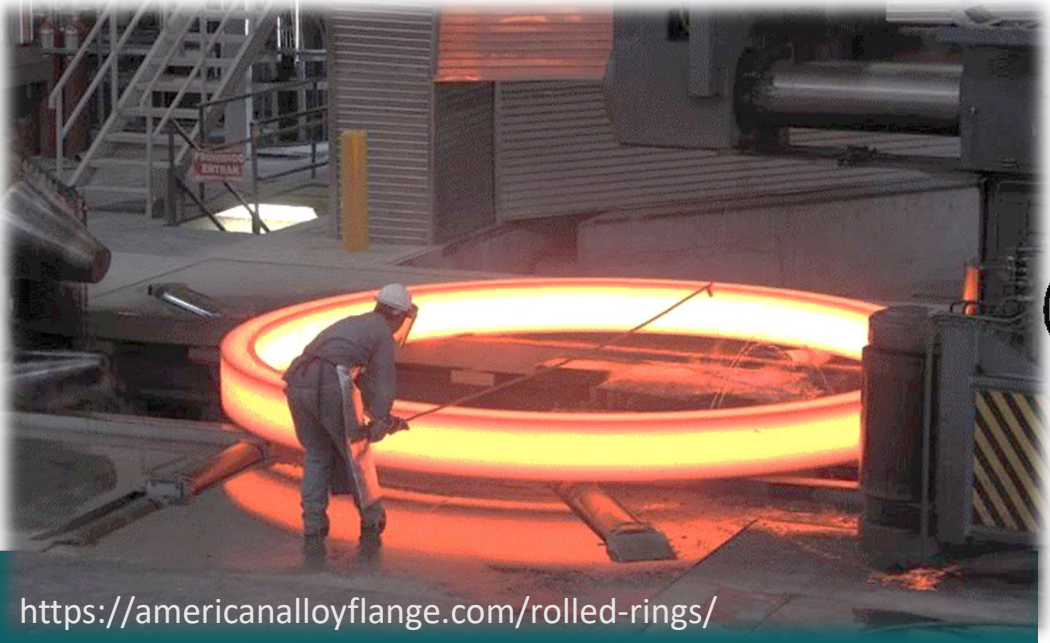
1. Heating up the slab ~1200 °C (also dissolve carbides, nitrides)
2. Mill scale cleansing: high pressure water (160 bar)
3. Roughing mill: 220 → 30 mm in a 4 high rolling mill in 5 passes
4. Surface cleansing during the roughing mill process
5. Vertical rollers → width
6. Rolled up in a coil box: save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

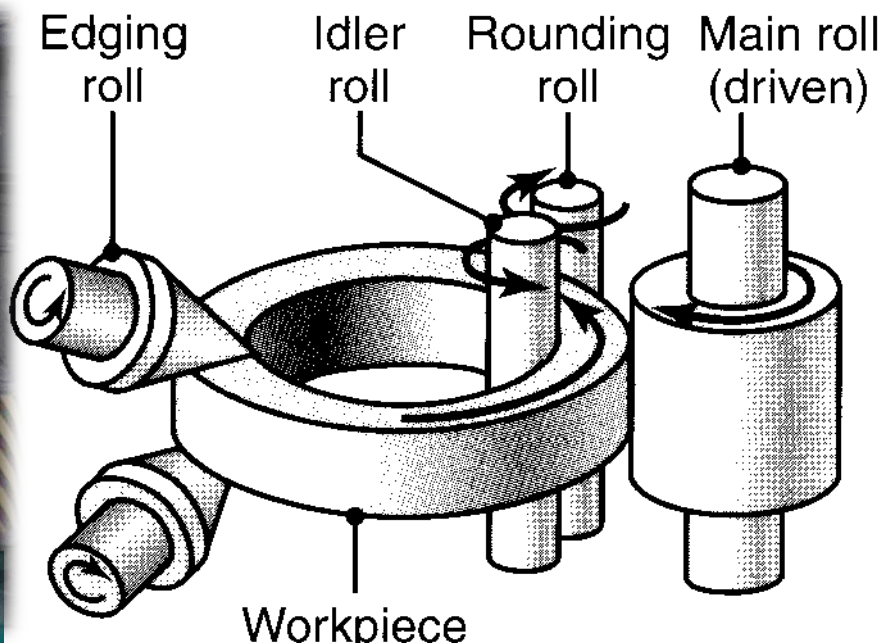



Hot rolling

Shape and ring rolling

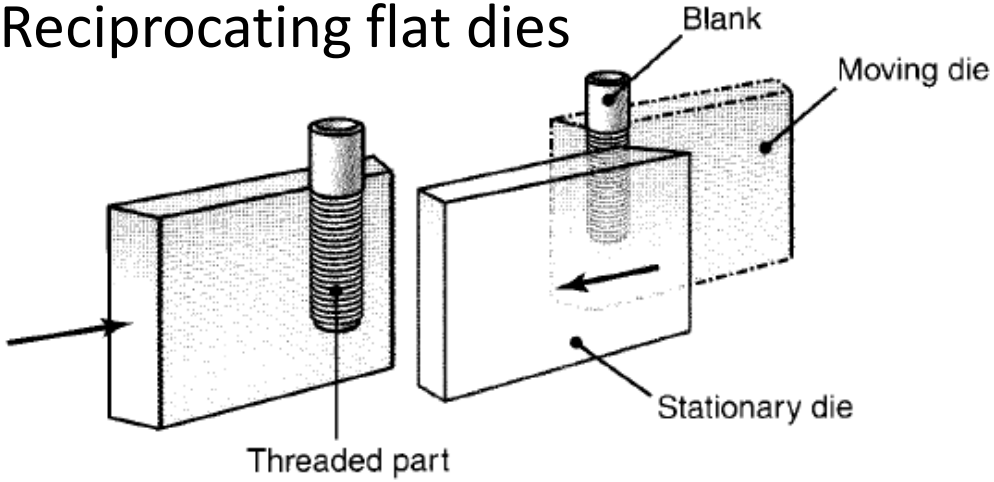


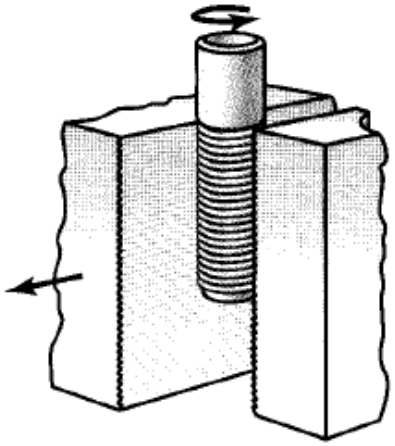




Thread rolling

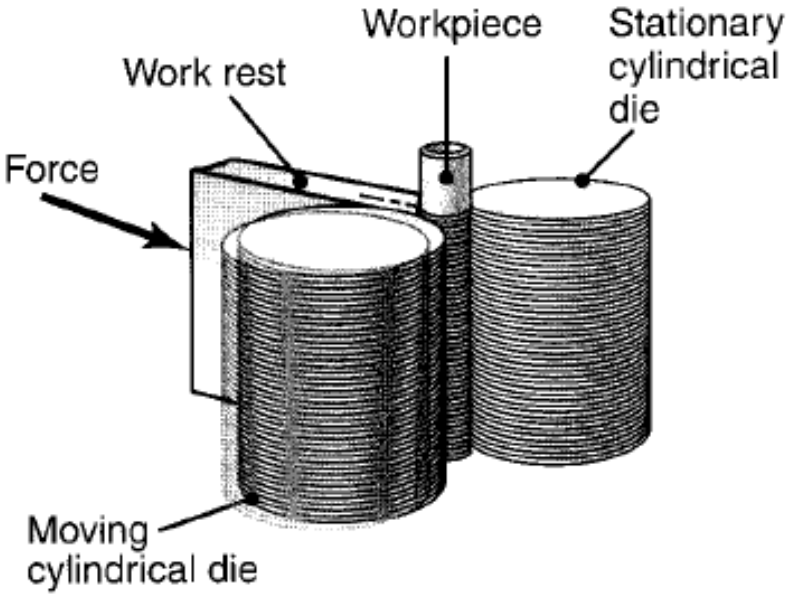
Reciprocating flat dies

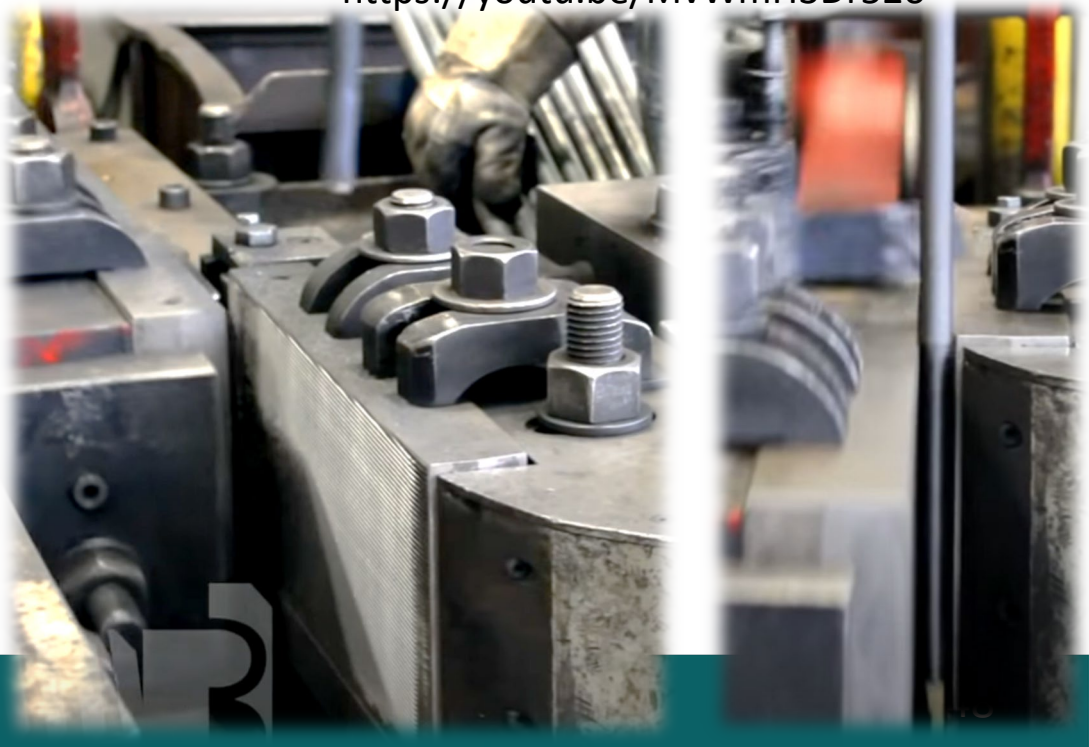




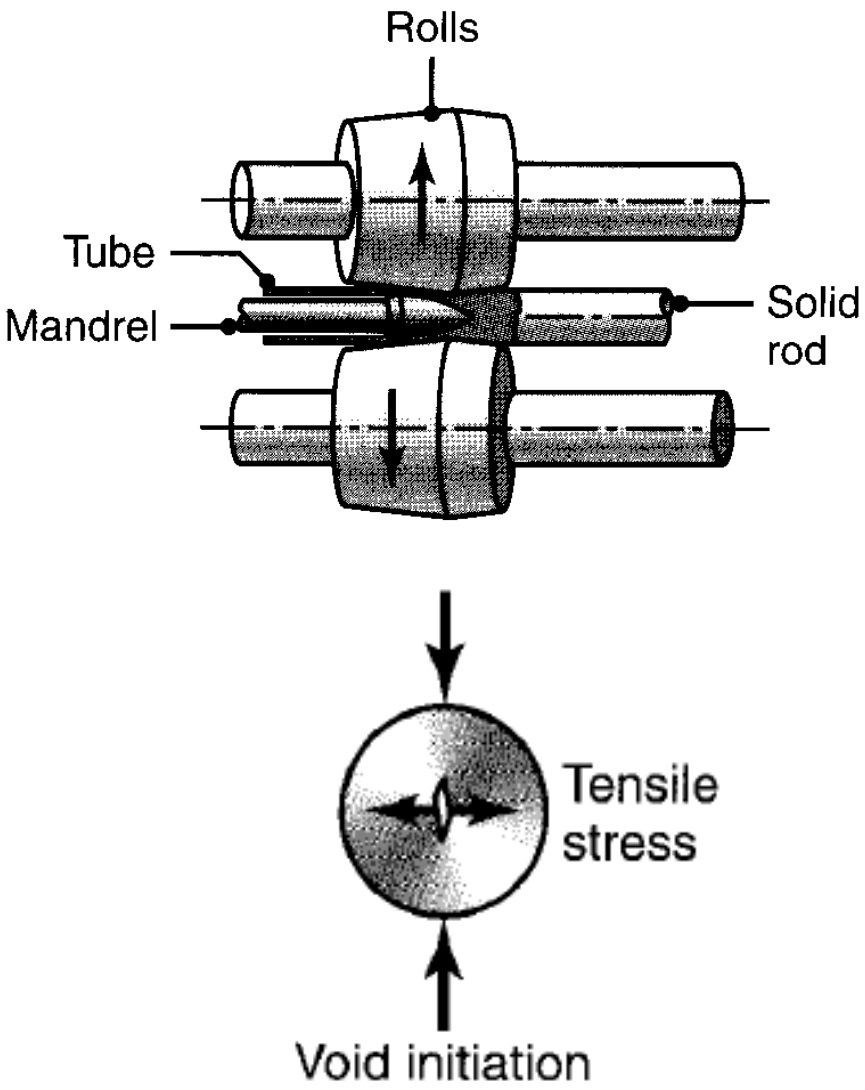
https://youtu.be/MvWmH3Dr52o

Roller dies





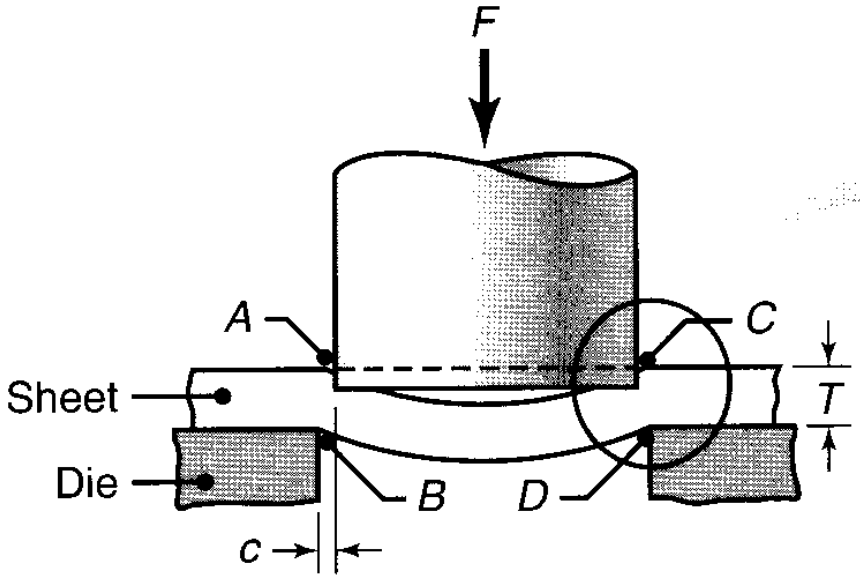
Seamless tubes and pipes by rolling

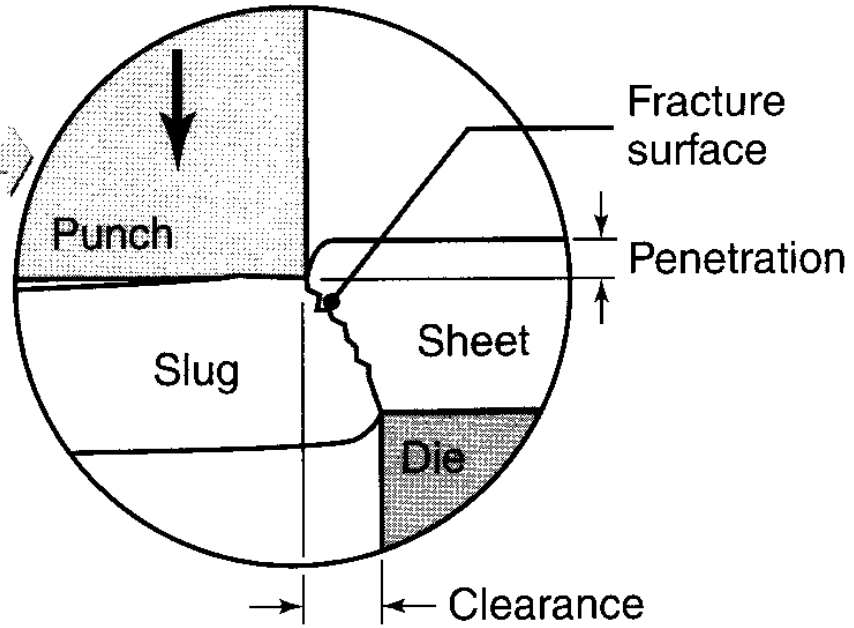


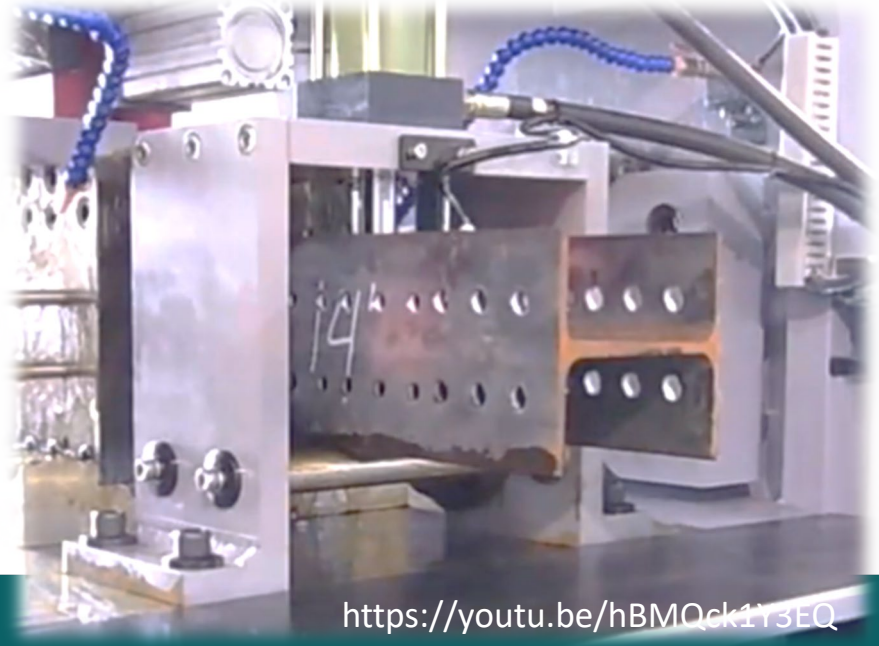
1. Billet is cut and heated up to ~1250 °C
2. Barrel type piercing (Mannesmann effect)
3. Finishing mill
4. Heated up in an induction furnace
5. Reducing mill (stretching for proper outside diameter)
6. Heat treatment
7. Straightening
8. Finishing (quality check, hydrostatic test, eddy current, ultrasonic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

Seamless pipe production

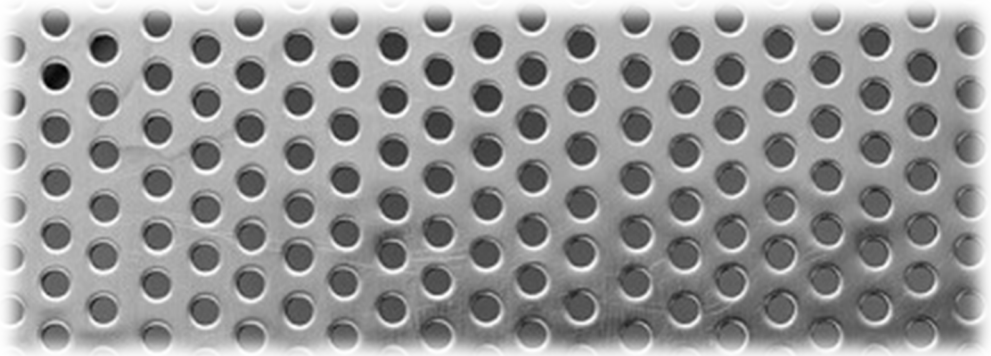
Shearing



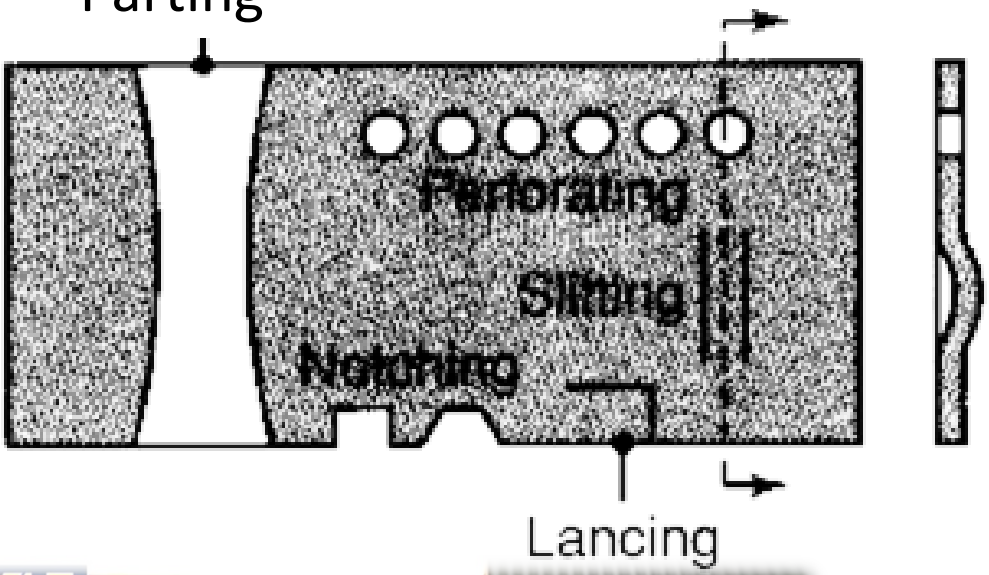


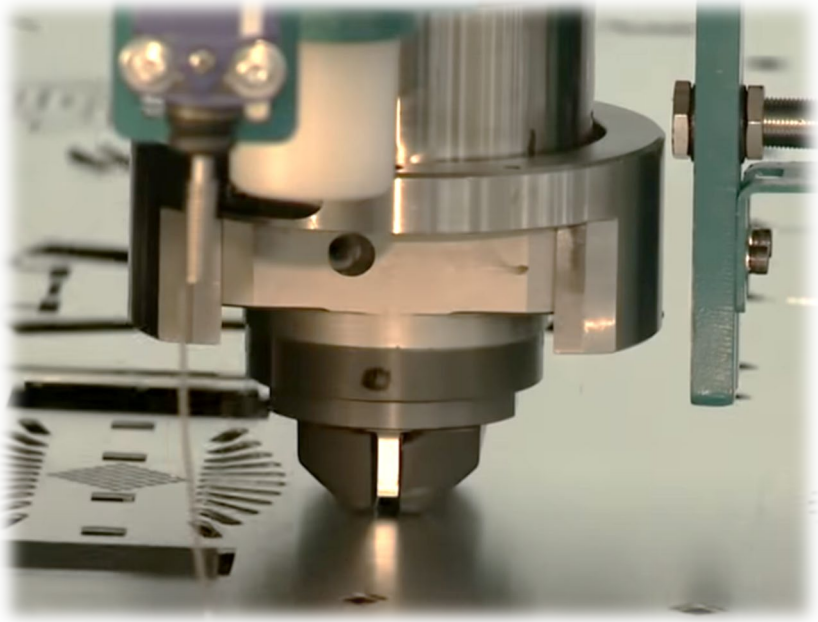


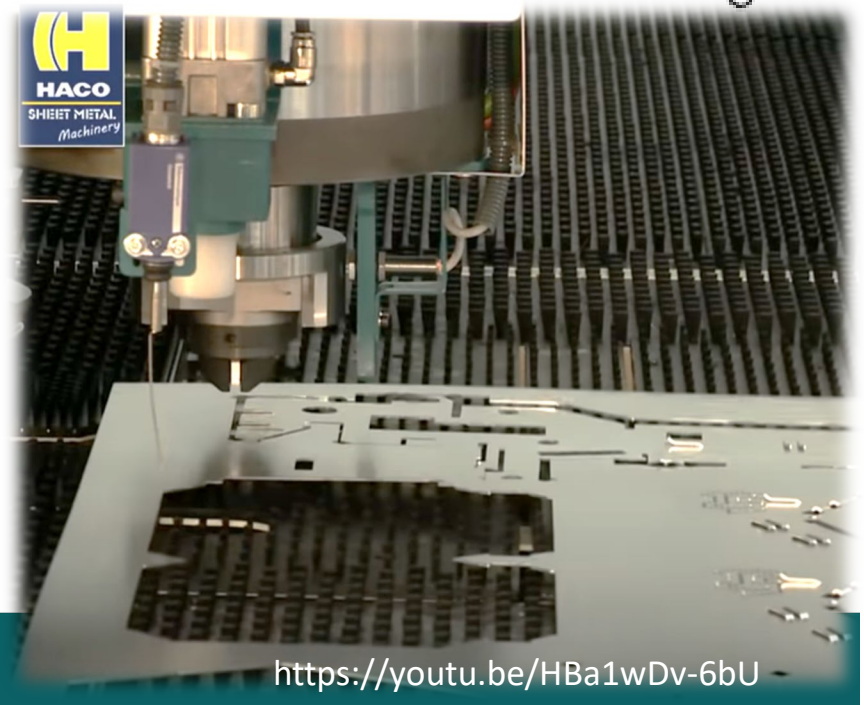
https://youtu.be/hBMQck1Y3EQ



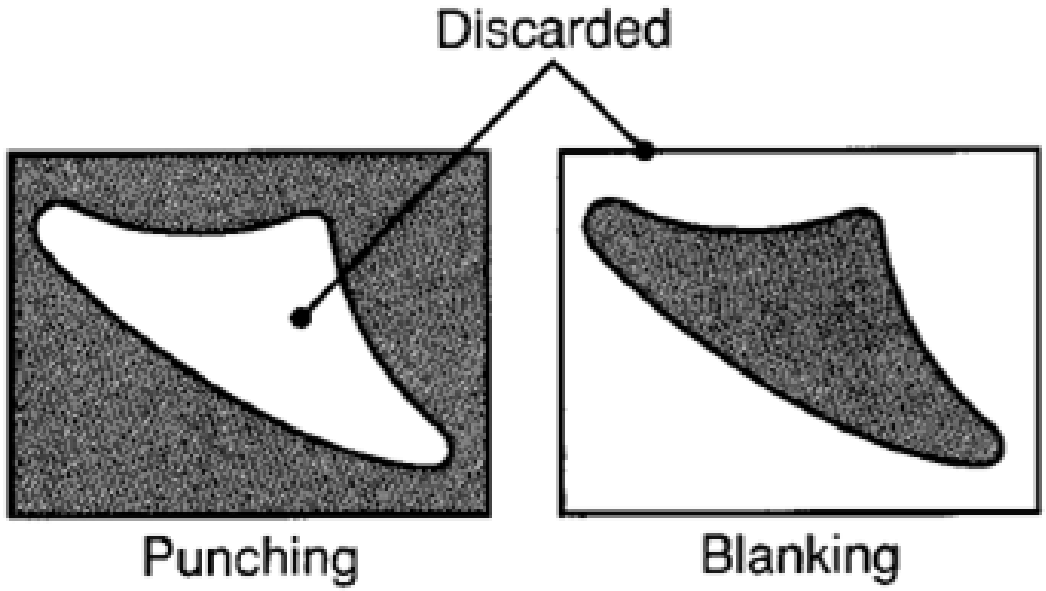
Punching and blanking



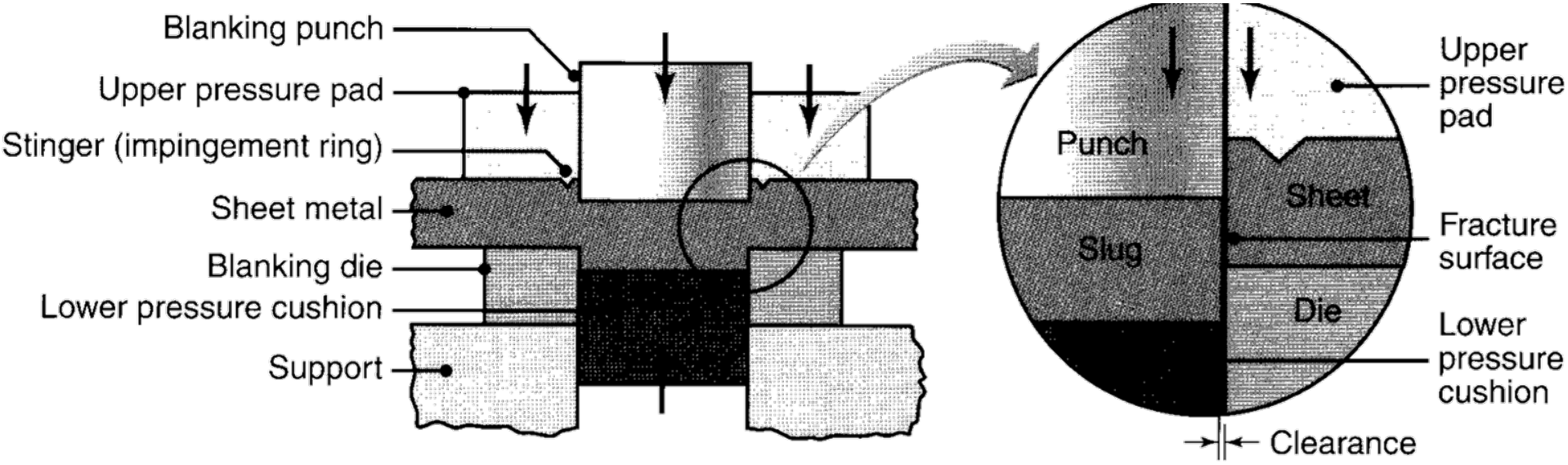


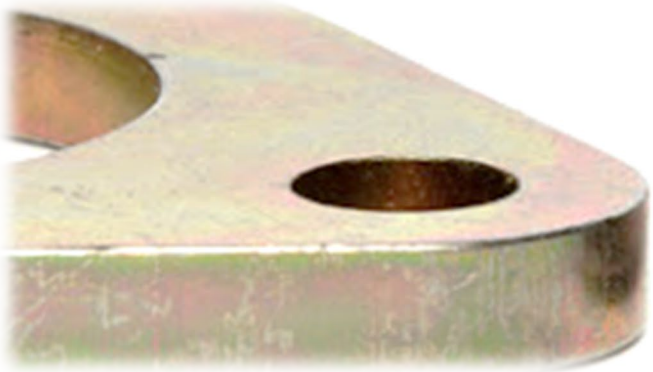


https://youtu.be/HBa1wDv-6bU



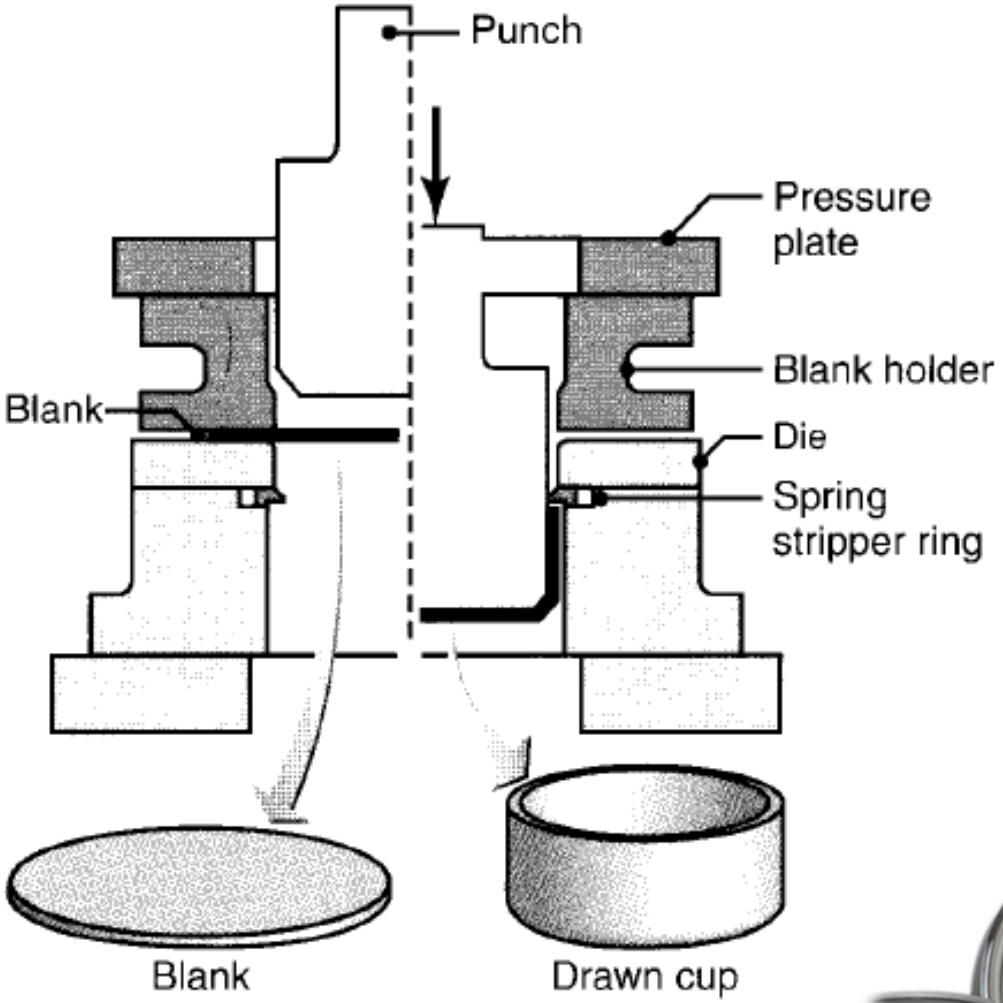
Fine blanking

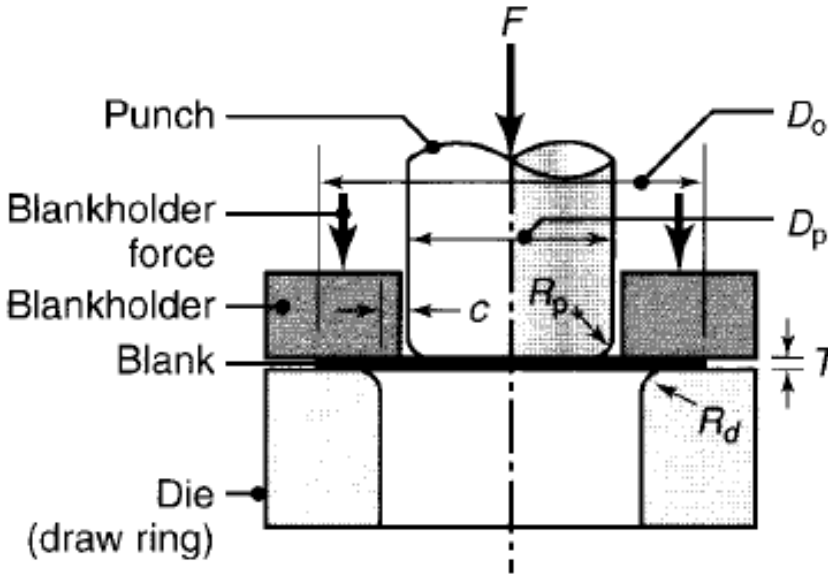




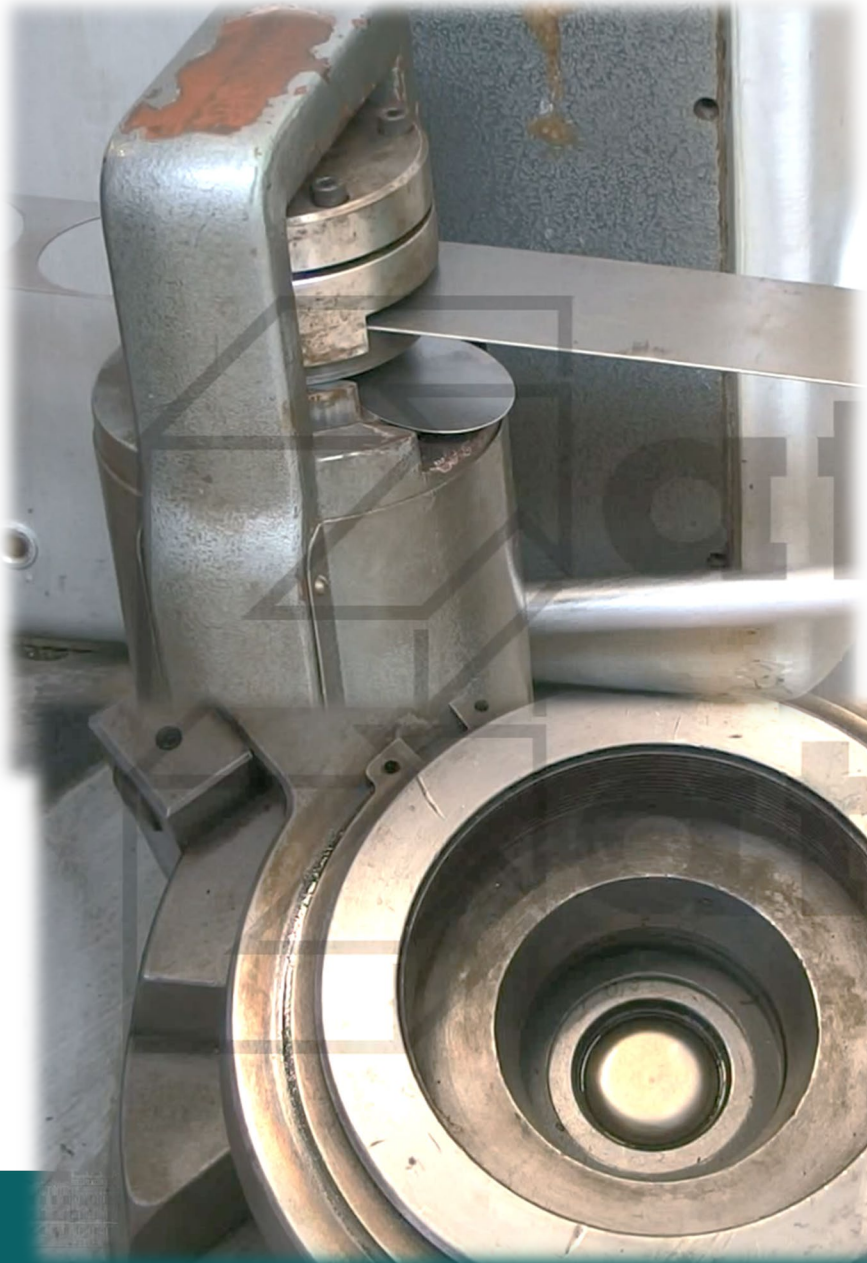
http://precomp.se/en/technology/technology-areas/fineblanking

Deep drawing

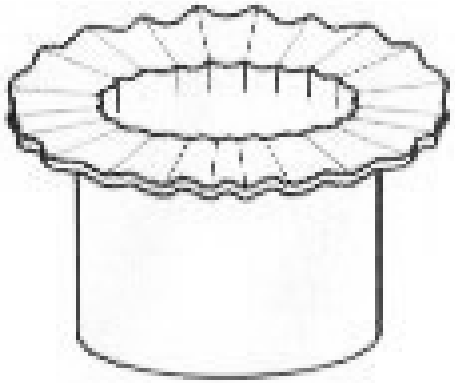




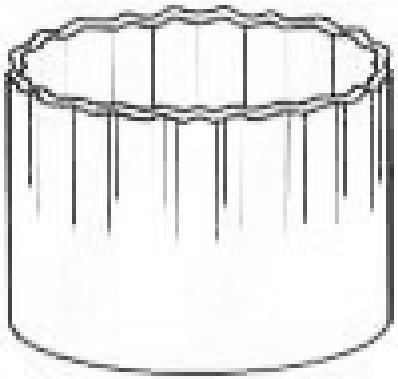
Deep drawing



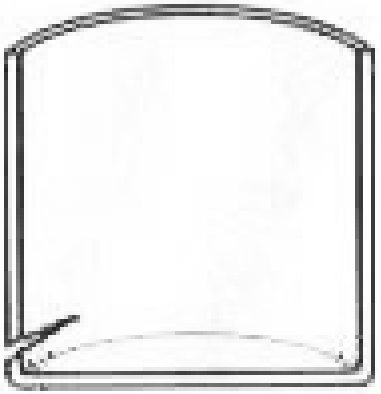
Deep drawing defects



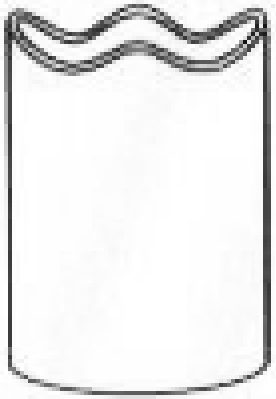
Flange wrinkling



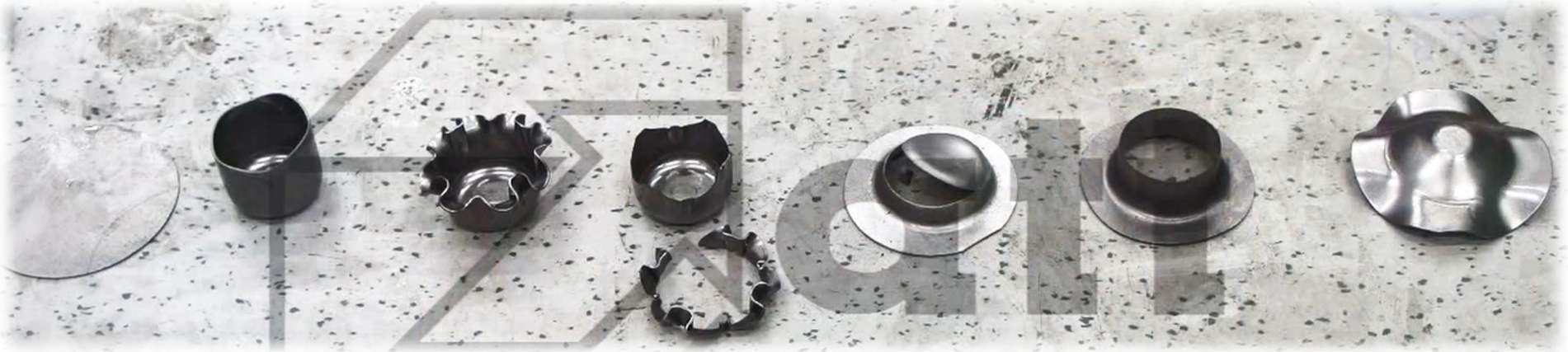
Wall wrinkling



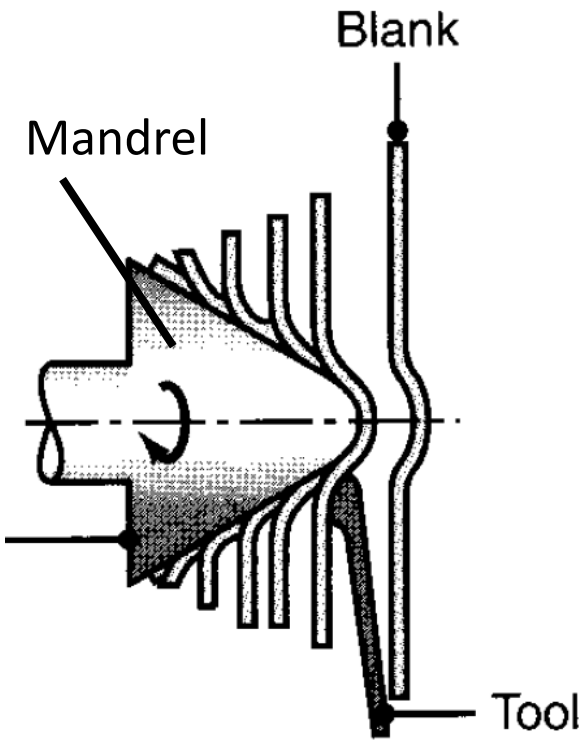
Cracking

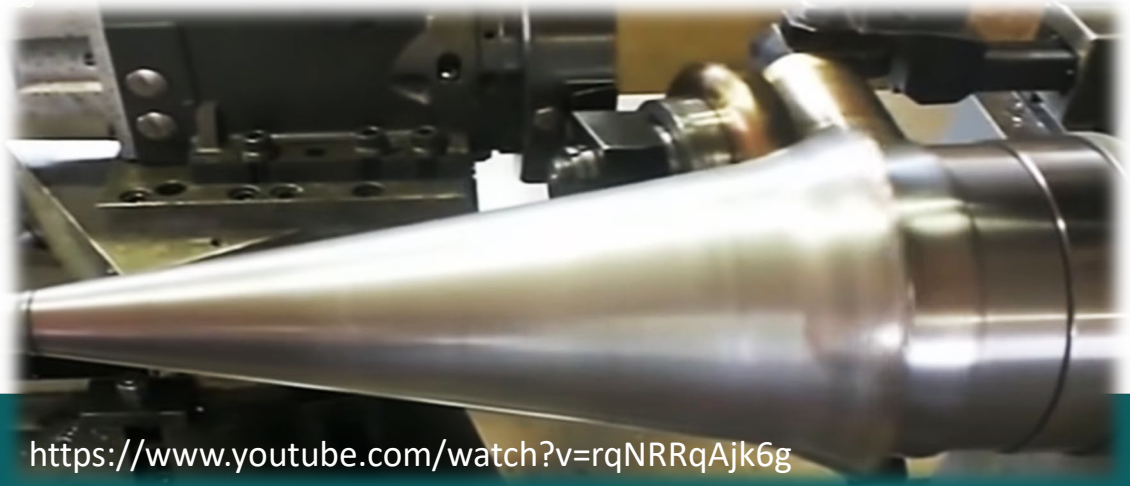


Earing

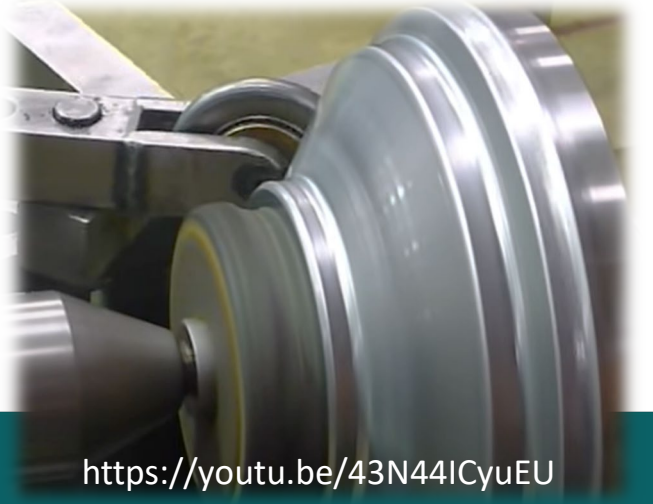


Spinning





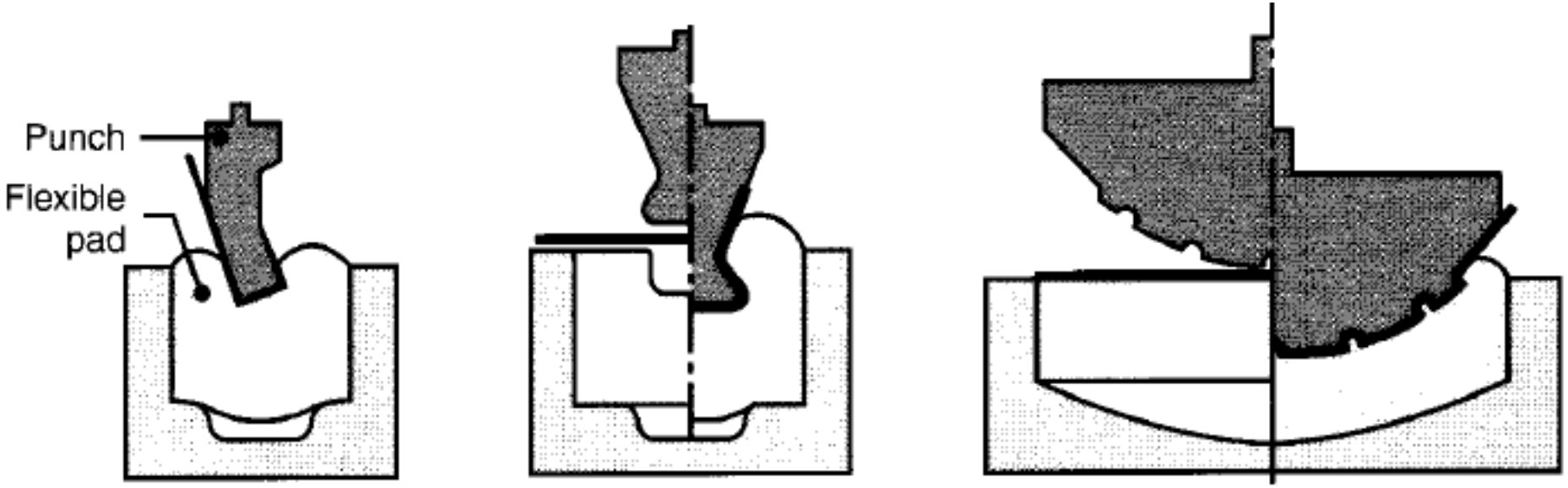
https://www.youtube.com/watch?v=rqNRRqAjk6g



https://youtu.be/43N44ICyuEU

Rubber pad forming

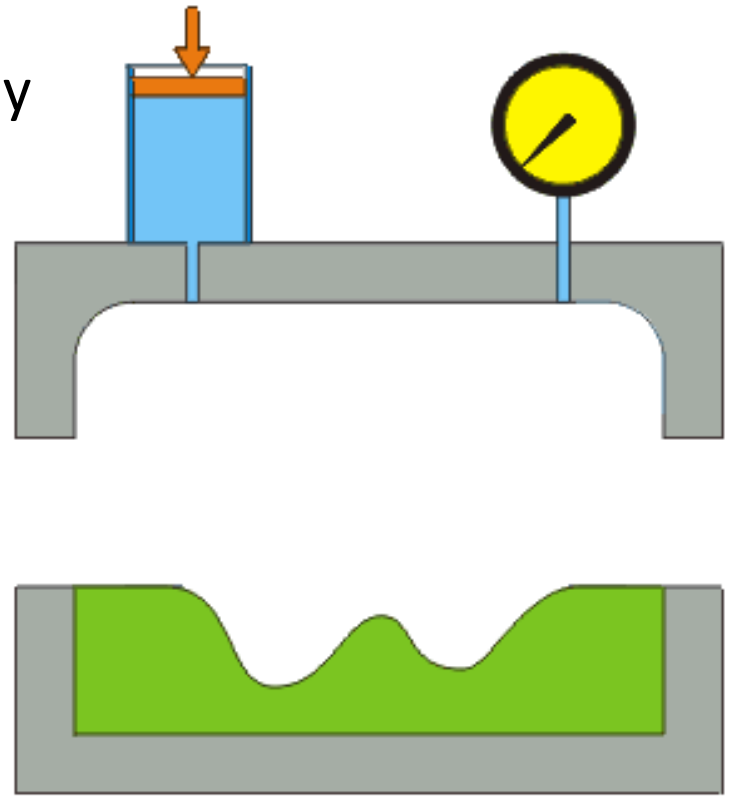
The outer surface of the sheet is protected from damage or scratches: no contact with a hard metal surface during forming.



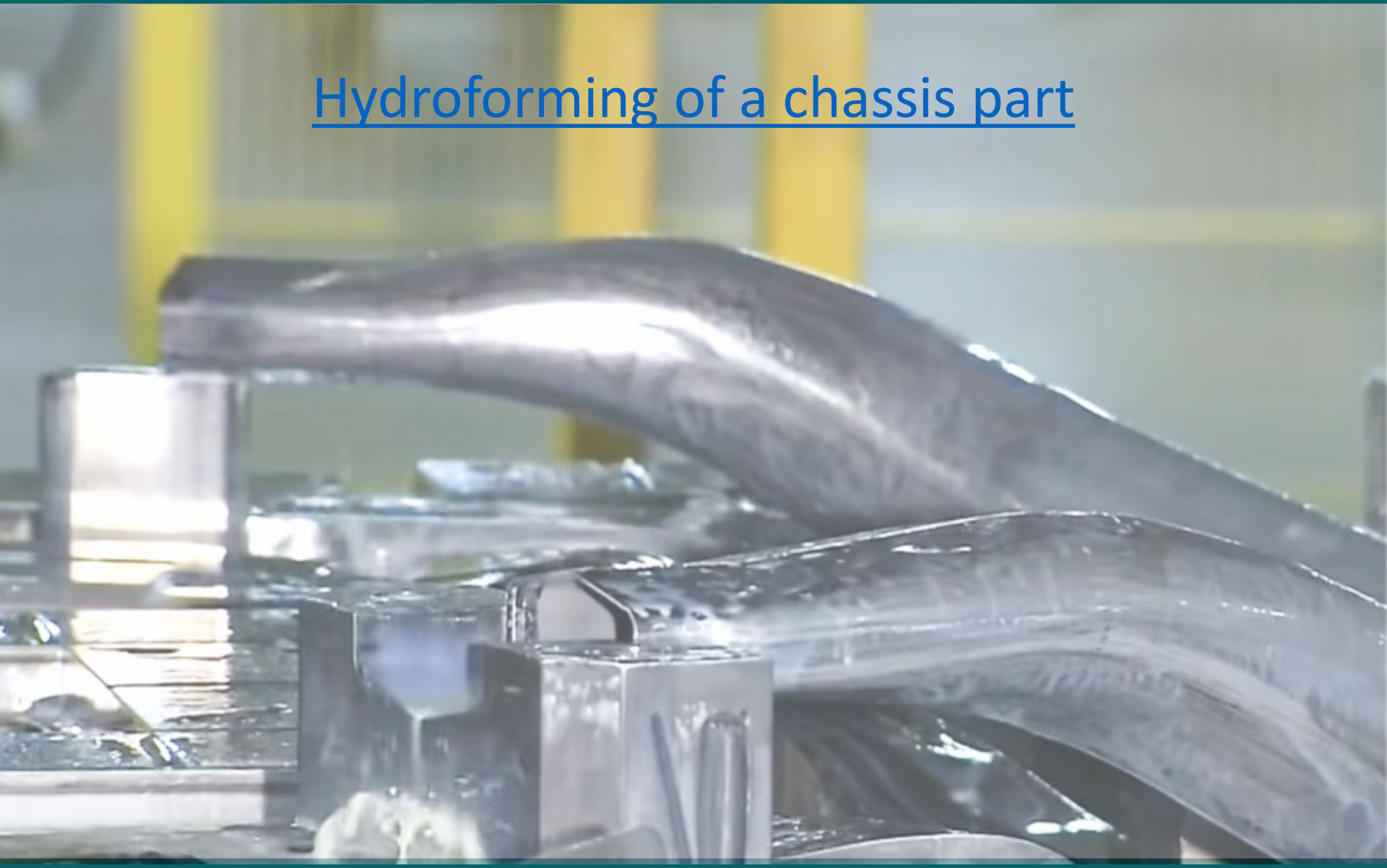
https://www.youtube.com/watch?v=M7JLO0BcI14

Hydroforming

- 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!

References

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

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=iiGlq7408ME

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

https://www.youtube.com/watch?v=zlueIHudt4k

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-WppI

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