Drawing of rods, wires and tubes

Subjects of interest

- Introduction/objectives
- Rod and wiredrawing
- Analysis of wiredrawing
- Tube drawing processes
- Analysis of tube drawing
- Residual stress in rod, wire and tubes

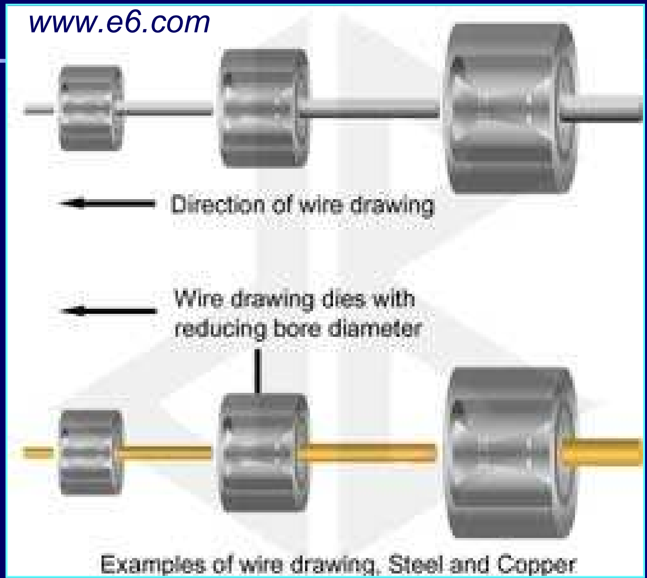
Objectives

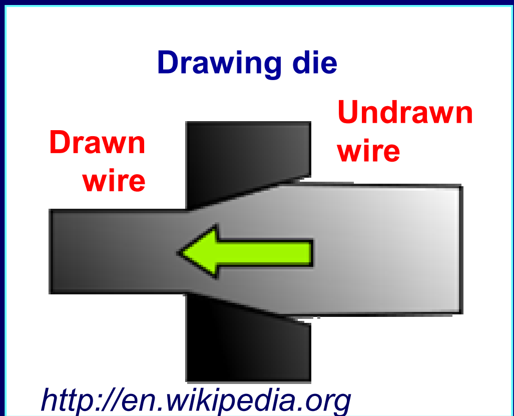
• This chapter provides fundamental background on processes of drawing of rods, wires and tubes.

• Mathematical approaches for the calculation of drawing load will be introduced.

• Finally drawing defects occurring during the process will be highlighted and its solutions will be included.

Introduction : *wire drawing*

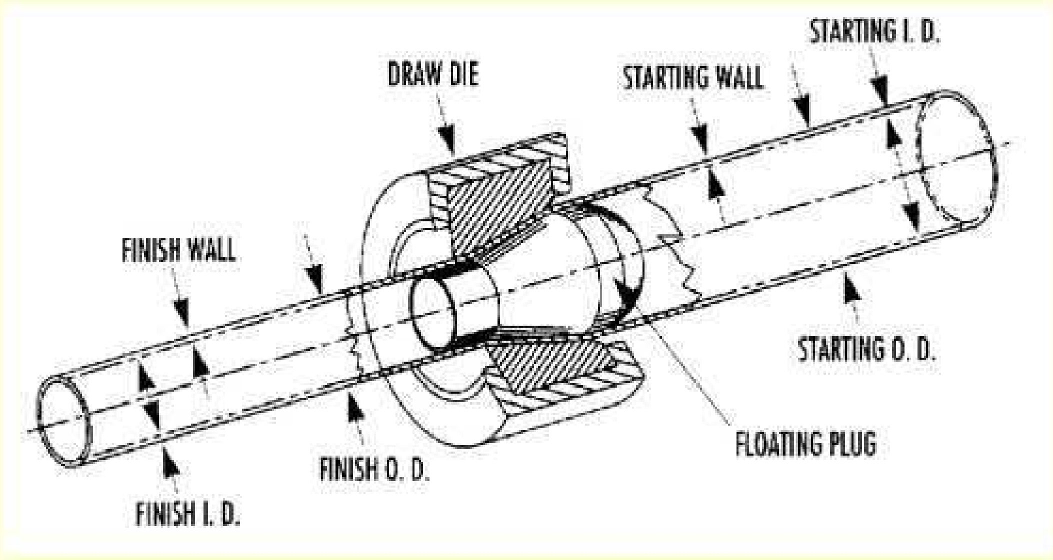




- ***Wire drawing*** involves reducing the diameter of a rod or wire by passing through a series of drawing dies or plates.
- The subsequent drawing die must have ***smaller bore diameter*** than the previous drawing die.

Introduction : *Tube drawing*

• ***Tube drawing*** involves reducing the cross section and wall thickness through a draw die.



Courtesy of Dorset Tube Company

Courtesy of Dorset Tube Company

• The ***cross section*** can be circular, square hexagonal or in any shapes.

Brass tubes for heat exchanger – cheap, strong, good corrosion resistant

Introduction

- ***Drawing*** operations involve pulling metal through a die by means of a ***tensile force*** applied to the exit side of the die.
- The ***plastic flow*** is caused by compression force, arising from the reaction of the metal with the die.
- ***Starting materials***: hot rolled stock (ferrous) and extruded (non-ferrous).
- Material should have ***high ductility*** and ***good tensile strength***.
- Bar wire and tube drawing are usually carried out at ***room temperature***, except for large deformation, which leads to considerable rise in temperature during drawing.
- The metal usually has a ***circular symmetry*** (but not always, depending on requirements).

Rod and wiredrawing

• Reducing the diameter through ***plastic deformation*** while the volume remains the same.

• ***Same principals*** for drawing bars, rods, and wire but ***equipment is different in sizes*** depending on products.

Metal rods

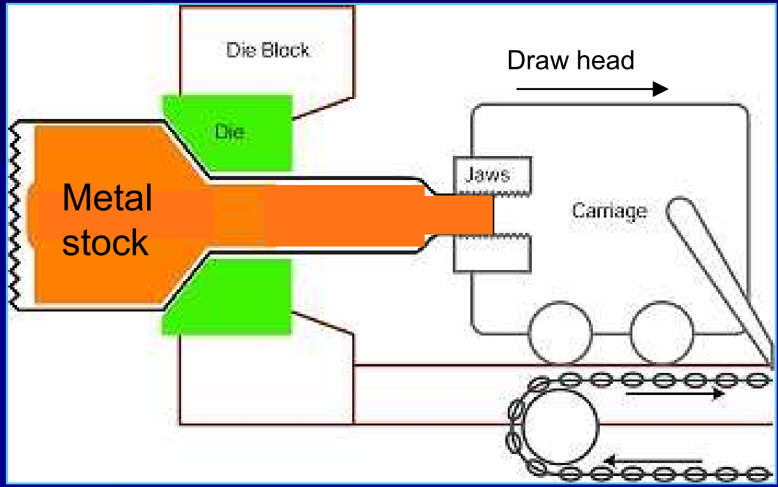
Metal wires

Rods → relatively larger diameter products.

Wires → small diameter products < 5 mm diameter.

Rod drawing

• Rods which can not be coiled, are produced on drawbenches.



Machine capacity :
- 1 MN drawbench
- 30 m of runout
- 150-1500 $mm.s^{-1}$ draw speed

Rod is swaged
↓
Insert though the die
↓
Clamped to the jaws of the drawhead
↓
The drawhead is moved by a hydraulic mechanism

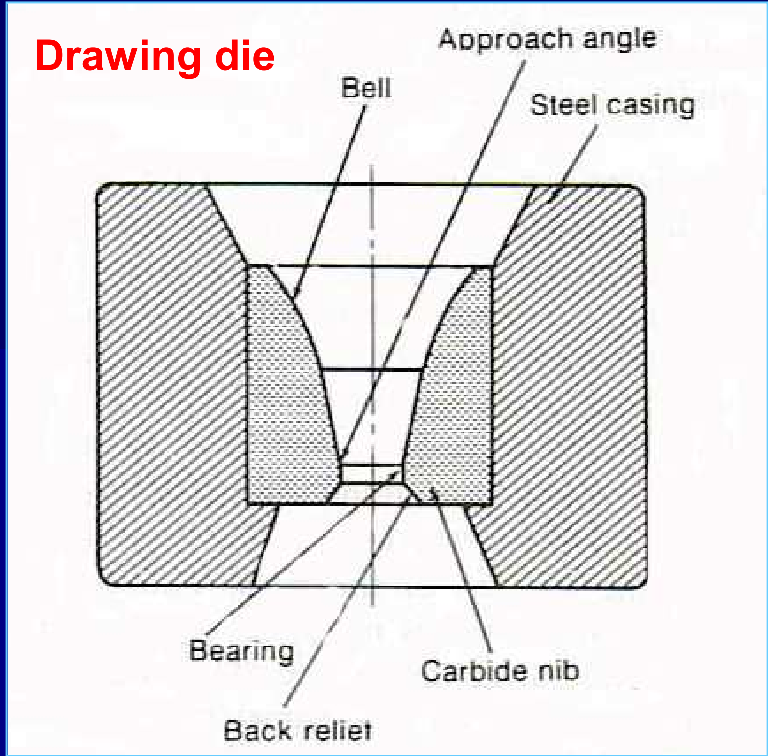
Wire drawing die

Conical drawing die

• ***Shape of the bell*** causes ***hydrostatic pressure*** to increase and promotes the ***flow of lubricant*** into the die.

• ***The approach angle*** – where the actual reduction in diameter occurs, giving the ***half die angle*** α.

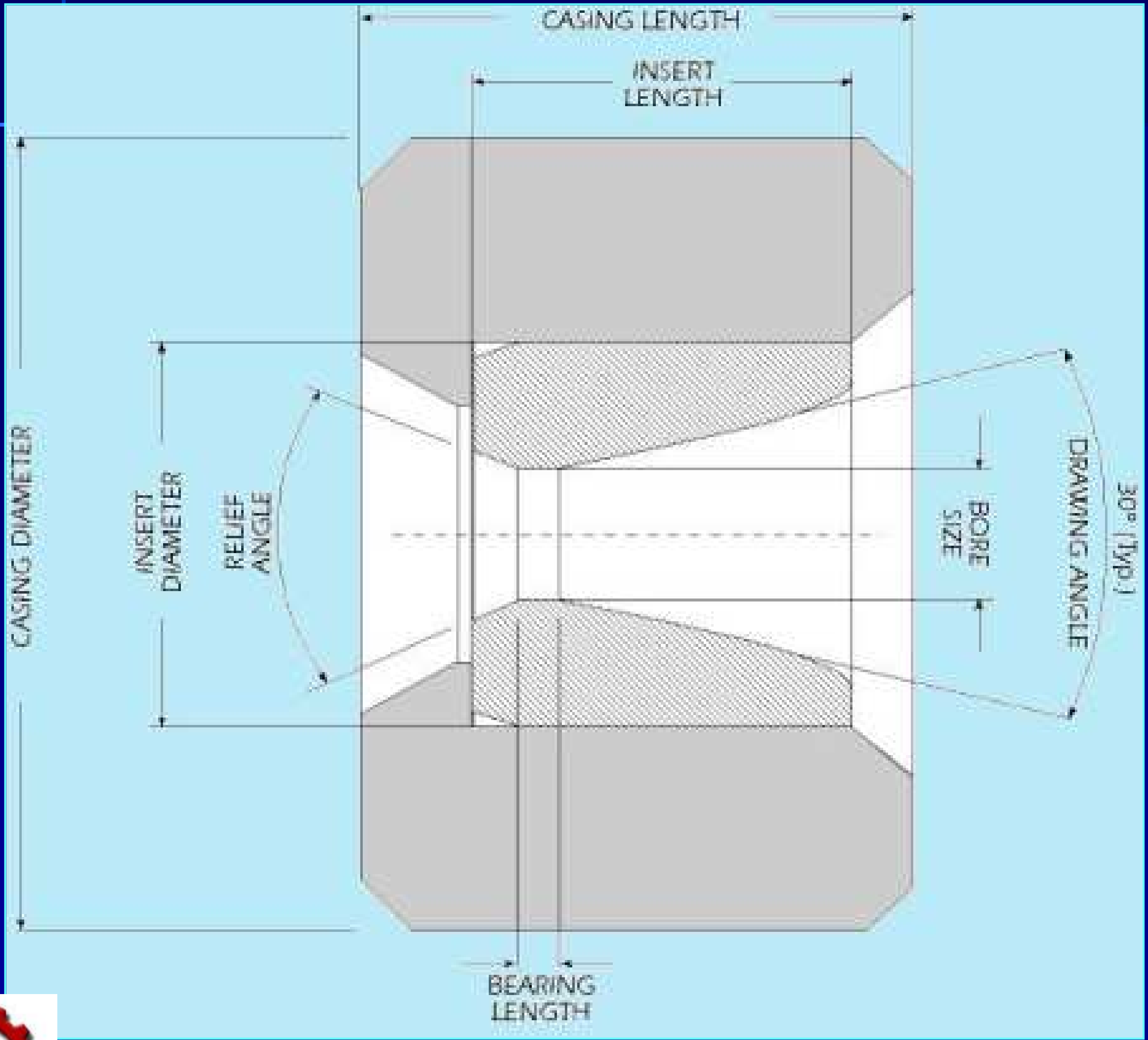
• The ***bearing region*** produces a ***frictional drag*** on the wire and also remove surface damage due to die wear, without changing dimensions.



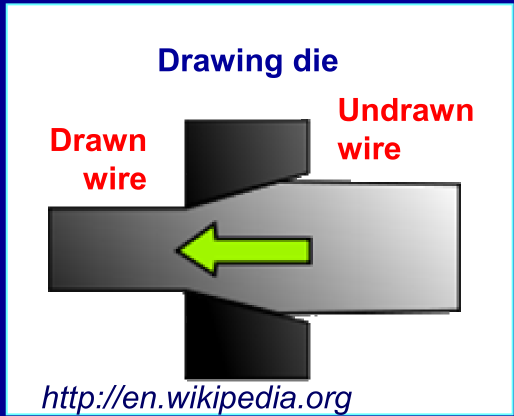
• The ***die nib*** made from ***cemented carbide*** or ***diamond*** is encased for protection in a thick steel casing.

• The ***back relief*** allows the metal to expand slightly as the wire leaves the die and also minimises abrasion if the drawing stops or the die is out of alignment.

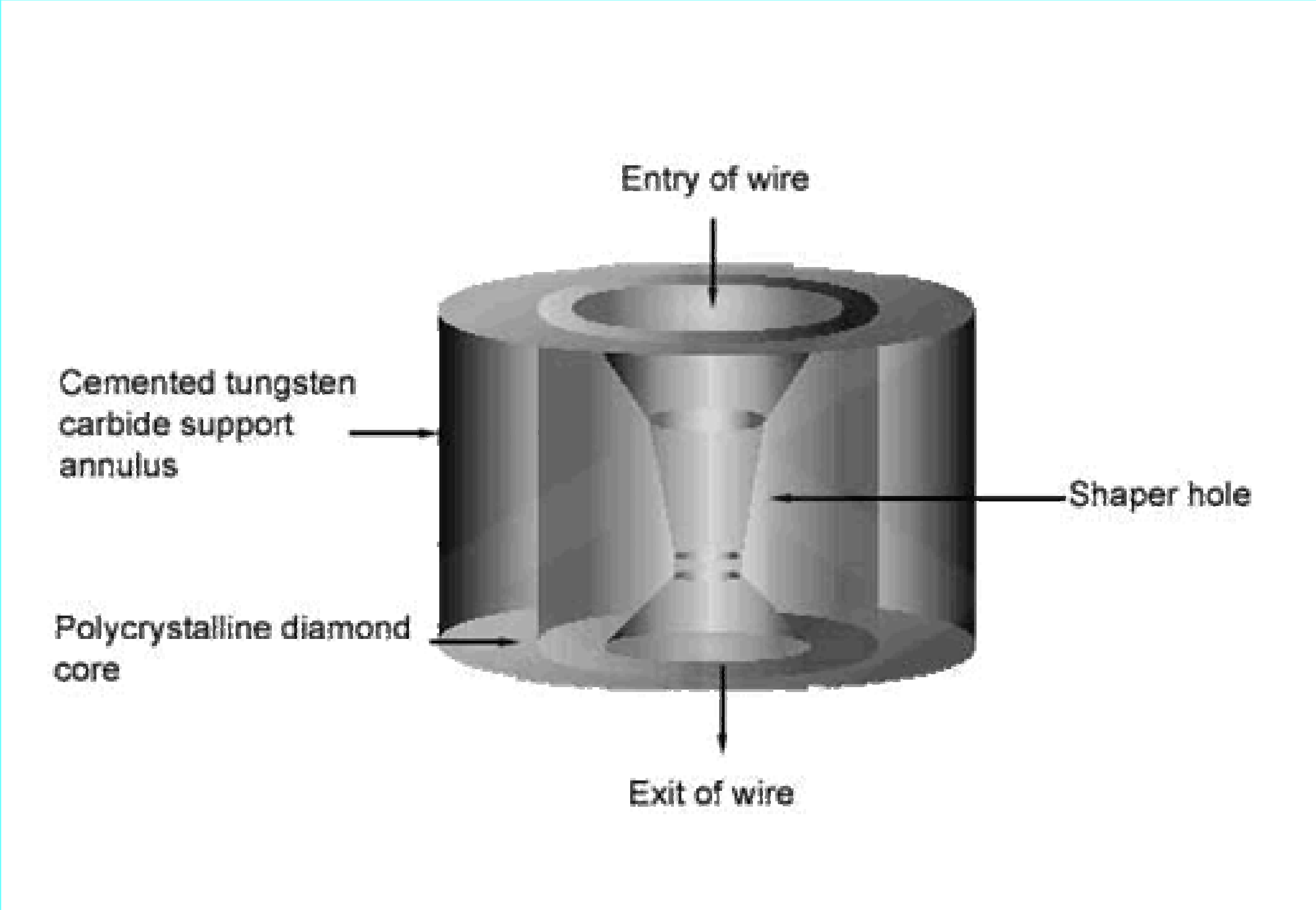
Example of wiredrawing dies



A drawing of wire drawing die



Example of wiredrawing dies



Wire drawing die made from cemented tungsten carbide with polycrystalline diamond core.

Drawing die materials

- *Cemented carbides* are the most widely used for drawing dies due to their superior strength, toughness, and wear resistance.

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- Most drawing dies are ***cemented carbide*** or ***industrial diamond*** (for fine wires).
  - ***Cemented carbide*** is composed of carbides of Ti, W, Ni, Mo, Ta, Hf.

- ***Polycrystalline Diamond (PCD)*** used for wire drawing dies – for fine wires. Longer die life, high resistance to wear, cracking or bearing.

Wire drawing equipment

Bull block drawing machines

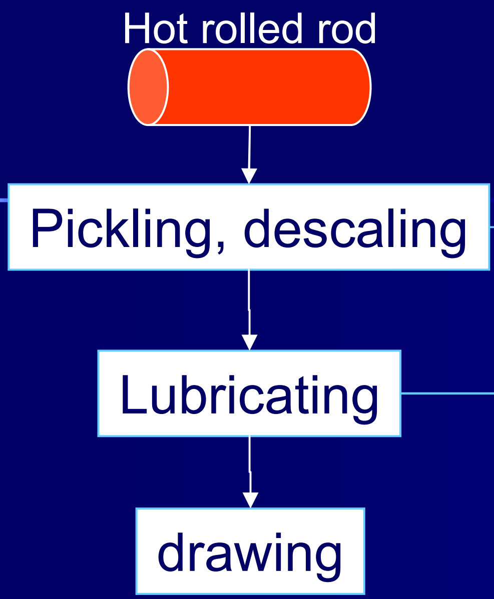
Multiple bull block machines - common

• The wire is first passed through the overhead loop and pulley, brought down and then inserted through the die of the second drum and drawn through this die for further reduction.

• Thus, the wire is drawn through all the ***wire drawing drums*** of the set in a ***continuous*** manner to get the required finished diameter of the wire. ***Speed*** of each draw block has to be ***synchronised*** to avoid ***slippage*** between the wire and the block.

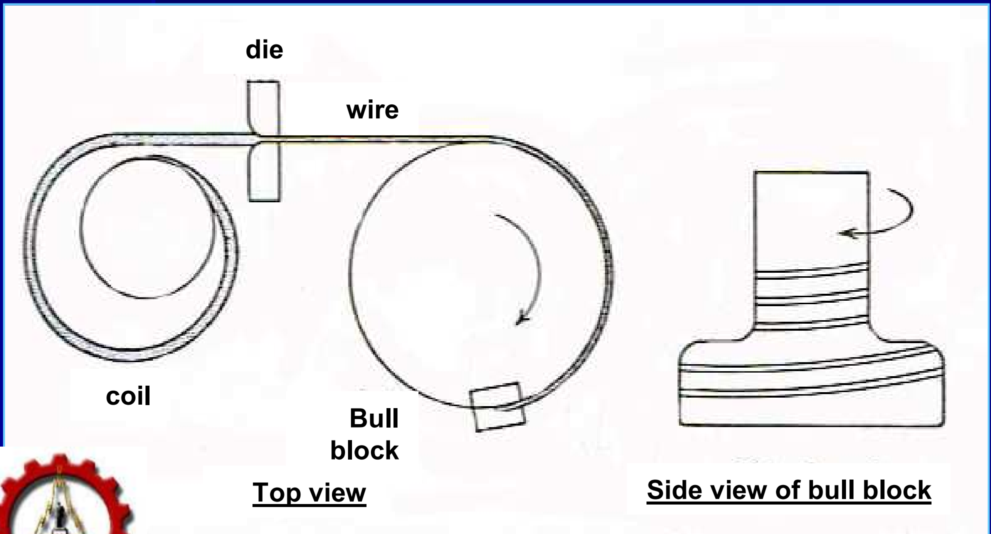
• The ***drawing speed*** ~ up to 10 $m.s^{-1}$ for **ferrous drawing**
~ up to 30 $m.s^{-1}$ for **nonferrous drawing**.

Wire drawing process



Remove ***scale*** -causing surface defects.

- **Cu** and **Sn** are used as lubricants for high strength materials. Or conversion coating such as ***sulphates*** or ***oxalates***.
- ***Oils*** and ***greases*** for wire drawing
- ***Mulsifiable oils*** for wet wire drawing
- ***Soap*** for dry drawing.

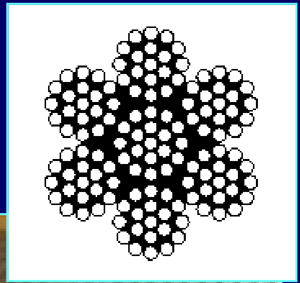


- ***Bull block*** drawing allows the generation of long lengths
- ***Area reduction*** per drawing pass is rarely greater than **30-35%.**

$$\%RA = \left[1 - \left(\frac{D_{Outlet}}{D_{Inlet}}\right)^2\right] \times 100$$

<u>Example:</u> Drawing of stainless wire

- **Stainless steels**: 304, 304L, 316, 316L
- **Applications**: redrawing, mesh weaving, soft pipe, steel rope, filter elements, making of spring.



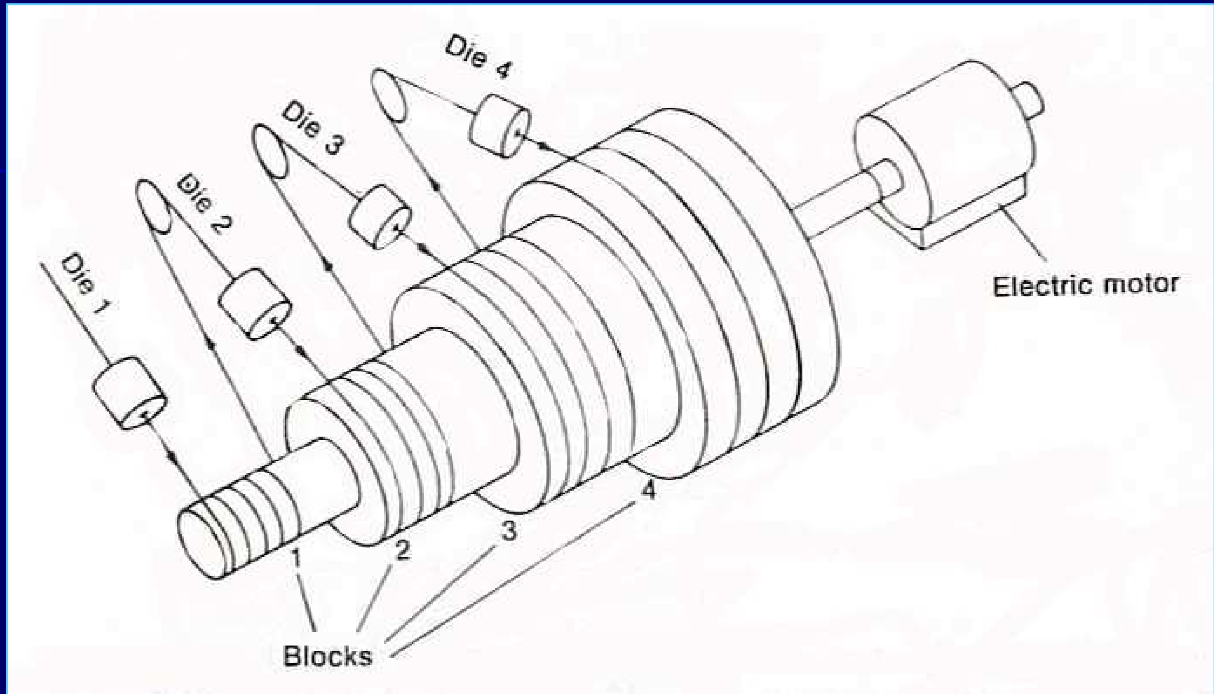
Stainless steel rope

- Larger diameter stainless wire is first ***surface examined***, tensile and hardness tested, diameter size measured.
- Surface preparation by ***pickling*** in acid (ferrictic and martensitic steels) and basic solutions (austenitic steels). The prepared skin is then coated with lubricant.
- Cold drawing is carried out through ***diamond dies*** or ***tungsten carbide dies*** till the desired diameter is obtained.

Stainless steel meshes

- Cleaning off oil/lubricant is then carried out and the wire is heat-treated (***annealing at about 1100°C or plus skin pass***).

Stepped-cone multiple-pass wiredrawing



- More ***economical design***.
- Use ***a single electrical motor*** to drive a series of stepped cones.
- The diameter of each cone is designed to produce a peripheral speed equivalent to a certain size reduction.

Heat treatments

• Nonferrous wire / low carbon steel wire → ***Tempering*** (ranging from dead soft to full hard). This also depends on the metal and the reduction involved.

• Steels (***C*** content > 0.25%) normally 0.3-0.5% require ***Patenting heat treatment*** before being drawn. Patented wire have improved reduction of area up to 90% due to the formation of very fine pearlite.

Heating above the upper critical temp ***T***~970^{o}C

↓

Cooling in a lead bath at ***T***~315^{o}C

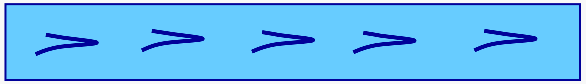
• *Provide **austenitic structure** with rather large grain size.*

• *Rapid cooling plus small cross section of wire change microstructure to **very fine pearlite** preferably with no separation of primary ferrite.*

→ Good combination of strength and ductility.

Defects in rod and wiredrawing

- Defects in the starting rod (seams, slivers and pipe).
- Defects from the deformation process, i.e., ***centre burst*** or ***chevron cracking (cupping).***



Centre burst or chevron cracks

- This defect will occur for ***low die angles*** at low reductions.
- For a given reduction and die angle, the critical reduction to prevent fracture increases with the friction.

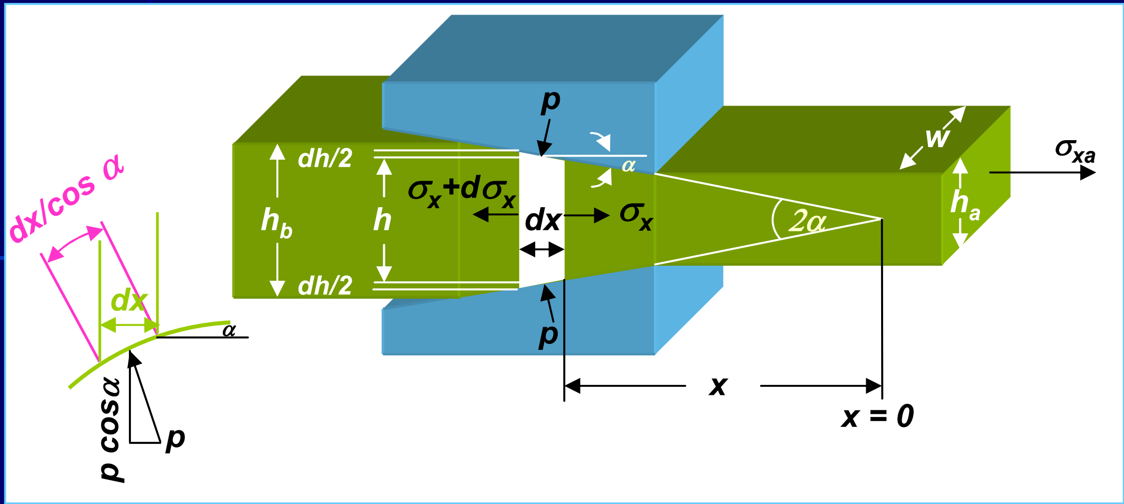
Analysis of wiredrawing

From the uniform-deformation energy method, a draw stress is given by

$$\sigma_{xa} = \bar{\sigma}_o \ln \frac{A_b}{A_a} = \sigma_o \ln \frac{1}{1-r} \qquad \text{...Eq.1}$$

(This however ignore friction, transverse stress and redundant deformation.)

Consider the problem of ***strip drawing of a wide sheet***, (*Dieter p. 509*)



- A wide strip is being drawn through a frictionless die with a total included angle of ***2α***.
- ***Plane strain condition*** is applied (no strain in the width direction.)

The ***equilibrium of forces*** in the ***x*** direction is made up of ***two*** components

1) Due to the change in longitudinal stress with x increasing positively to the left.

$$(\sigma_x + d\sigma_x)(h+dh)w - \sigma_x hw$$

2) Due to the die pressure at the two interfaces.

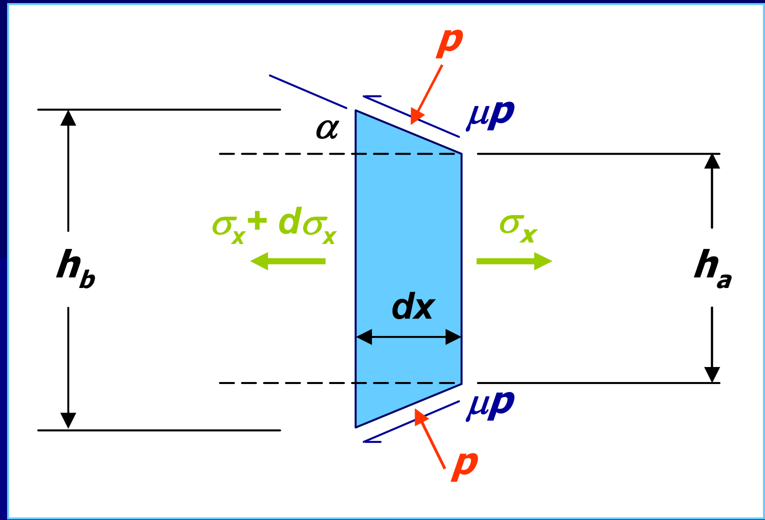
$$2p\sin\alpha\left(w\frac{dx}{\cos\alpha}\right)$$

Taking the equilibrium of force in the ***x*** direction and neglect ***$d\sigma_x dh$***

$$\sigma_x dh + hd\sigma_x + 2p\tan\alpha dx = 0 \qquad \text{...Eq.2}$$

We shall now consider the problem of ***strip drawing*** where a ***Coulomb friction coefficient*** μ exists between the strip and the die.

The equilibrium now includes $2\mu pdx$.



Taking equilibrium of forces in the ***x*** direction *Eq.2* then becomes

$$\sigma_x dh + hd\sigma_x + 2p\tan\alpha dx + 2\mu pdx = 0$$

$$\sigma_x dh + hd\sigma_x + 2pdx(\tan\alpha + \mu) = 0$$

Since ***h = 2x tan*** α, and ***dh = 2 dx tan*** α, then ***2dx = dh/tan*** α

We now have $$\sigma_x dh + hd\sigma_x + p(1 + \mu\cot\alpha)dh = 0 \qquad \text{...Eq.3}$$

Since the yield condition for plane strain is $\sigma_x + p = \sigma'_o$ and $B = \mu \cot \alpha$, the differential equation for strip drawing is

$$\frac{d\sigma_x}{\sigma_x B - \sigma'_o(1+B)} = \frac{dh}{h} \qquad \text{...Eq.4}$$

If B and σ'_o are both constant, *Eq.4* can be integrated directly to give the draw stress σ_{xa}.

$$\sigma_{xa} = \sigma'_o \frac{1+B}{B}\left[1-\left(\frac{h_a}{h_b}\right)^B\right] = \sigma'_o \frac{1+B}{B}\left[1-(1-r)^B\right]$$

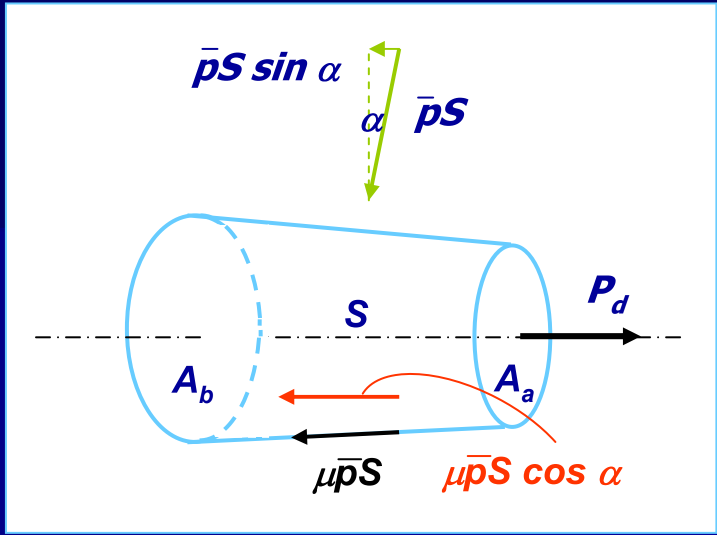
For wiredrawing conducted with conical dies,

$$\sigma_{xa} = \sigma_o \frac{1+B}{B}\left[1-\left(\frac{D_a}{D_b}\right)^{2B}\right] \qquad \text{...Eq.5}$$

Analysis for wiredrawing with friction by Johnson and Rowe

The surface area of contact between the wire and the die is given by

$$S = \frac{A_b - A_a}{\sin\alpha} \quad \text{...Eq.6}$$



$\bar{p}$ is the mean normal pressure on this area.
P_d is the draw force.

Balancing the ***horizontal components*** of the frictional force and the normal pressure.

$$P_d = \mu\bar{p}S\cos\alpha + \bar{p}S\sin\alpha$$

$$P_d = \bar{p}S(\mu\cos\alpha + \sin\alpha) = \bar{p}\frac{A_b - A_a}{\sin\alpha}(\mu\cos\alpha + \sin\alpha) \quad \text{...Eq.7}$$

$$P_d = \bar{p}(A_b - A_a)(\mu\cot\alpha + 1) = \bar{p}(A_b - A_a)(1 + B)$$

In the ***absence of friction***, ***B = 0*** and

$$P_d = \bar{p}(A_b - A_a) = \bar{\sigma}_o \, A_a \ln \frac{A_b}{A_a} \qquad \text{...Eq.8}$$

The ***draw stress*** with ***friction*** is given by

$$\sigma_{xa} = \frac{P_d}{A_a} = \bar{\sigma}_o \ln \frac{A_b}{A_a}(1+B) \qquad \text{...Eq.9}$$

Example: *Determine the draw stress to produce a 20% reduction in a 10-mm stainless steel wire. The flow stress is given by* $\sigma_o = 1300\varepsilon^{0.30}$ *(MPa). The die angle is* 12^o *and* $\mu = 0.09$.

$$B = \mu \cot\alpha = (0.09)\cot 6^o = 0.8571$$

$$\varepsilon_1 = \ln\frac{1}{1-r} = \ln\frac{1}{1-0.2} = 0.223$$

$$\bar{\sigma} = \frac{K\varepsilon_1^n}{n+1} = \frac{1300(0.223)^{0.30}}{1.30} = 637MPa$$

$$D_b = 10mm$$

$$D_a = D_b(1-r) = 10(0.8) = 8mm$$

From *Eq.5*

$$\sigma_{xa} = \bar{\sigma}\left(\frac{1+B}{B}\right)\left[1-\left(\frac{D_a}{D_b}\right)^{2B}\right] = 637\left(\frac{1.8571}{0.8571}\right)\left[1-0.8^{2\times0.8571}\right] = 438MPa$$

~ 20% difference

From *Eq.9*

$$\sigma_{xa} = \bar{\sigma}_o \ln\frac{A_b}{A_a}(1+B) = 637\ln\frac{1.0^2}{0.8^2}(1.8571) = 527MPa$$

If the wire is moving through the die at 3 m.s^{-1}, determine the ***power*** required to produce the deformation.

$$Power = force \times \frac{distance}{time}$$

Drawing force

$$P_d = \sigma_{xa} A_a = 438 \times \frac{\pi}{4}(8)^2 = 22.02 kN$$

Power

$$Power = 22.02 \times 3 = 66.06 kW$$

If ***redundant work*** is included in *Eq.9*, the expression becomes

$$\sigma_{xa} = \phi\sigma_o \ln\frac{A_b}{A_a}(1+B)$$

…Eq.10

Where ϕ is a factor for the influence of ***redundant work***, which can be defined as

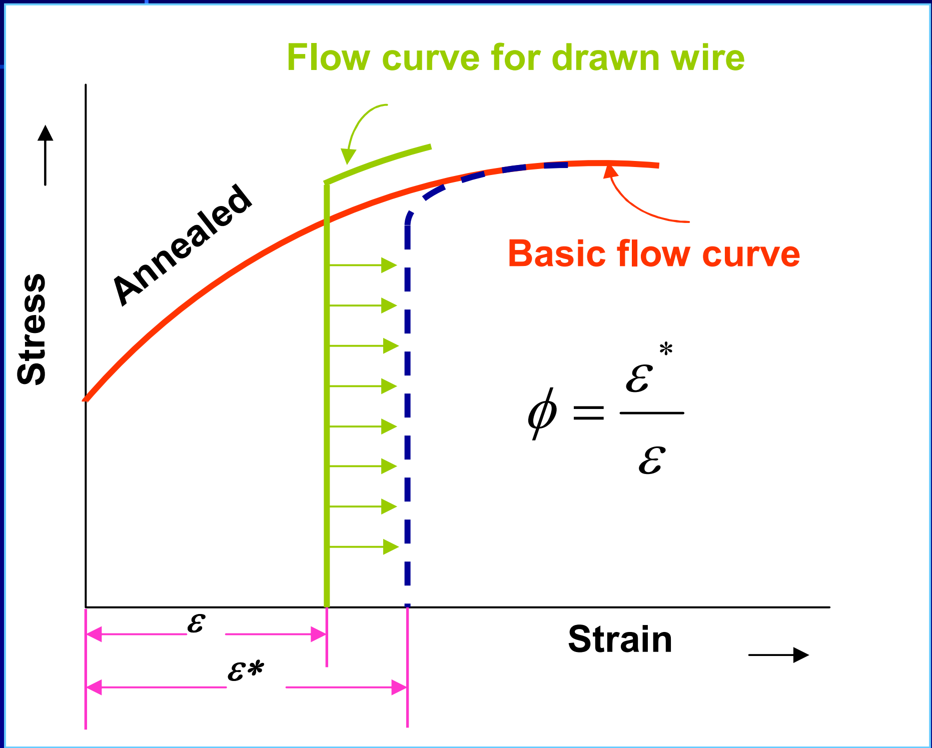
$$\phi = f(\alpha, r) = \frac{\varepsilon^*}{\varepsilon}$$

…Eq.11

Where ϕ = the ***redundant work factor***.

ε^* = the ***'enhanced strain'*** corresponding to the yield stress of the metal, which has been homogeneously deformed to a strain ε.

Procedure for determining redundant deformation of drawn wire



- The ***flow curve of a drawn wire*** is superimposed on the flow curve for the annealed metal.

- The origin of the curve for the drawn metal is displaced along the strain axis = drawing reduction,
$\varepsilon = \ln (A_b/A_a) = \ln [1/(1-r)]$.

- Due to ***redundant work***, the yield stress of the drawn metal is above the basic flow curve .

- To determine ϕ, the flow curve for the drawn metal is moved to the right to ε^* where the curves coincide.

Based on deformation-zone geometry

For drawing of round wire $\Delta = \frac{\alpha}{r}\left[1 + (1-r)^{1/2}\right]^2$ …Eq.12

Where α = the approach semi-angle, in radians

r = the drawing reduction

Commercially, α is in the range 6 to 10^o and r of about 20%.

and the ***redundant work*** ϕ is related to Δ by

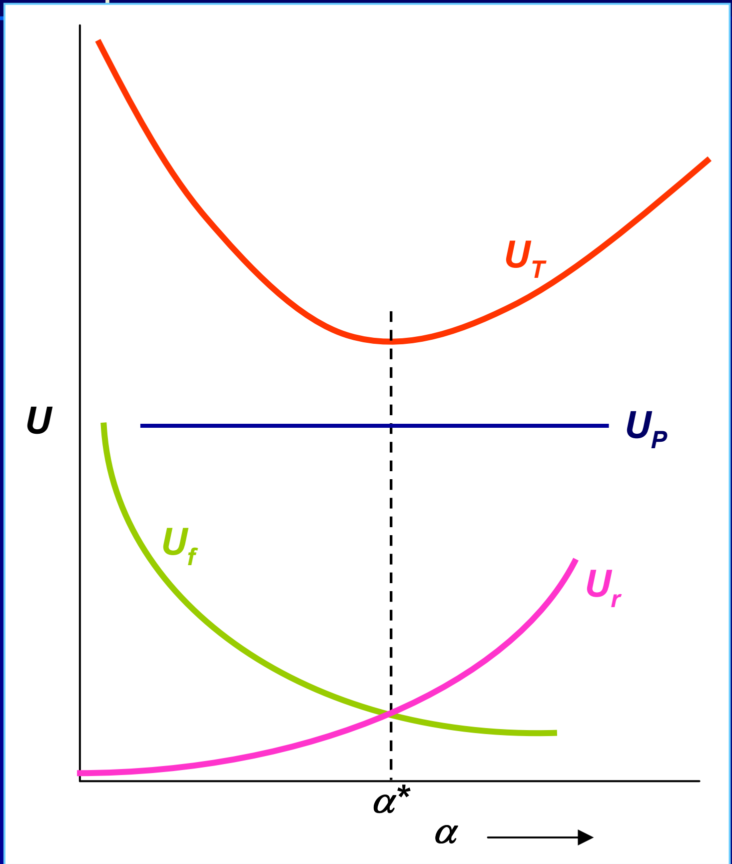
where $$\phi = C_1 + C_2\Delta \approx 0.8 + \frac{\Delta}{4.4}$$ …Eq.13

Δ = ***h/L*** = mean thickness / the length of the deformation zone

For strip, Δ_s is based on a plane-strain reduction $r_s = 1-(h_1/h_0)$

For wire or rod, Δ_w is based on an axisymmeteric reduction $r_w = 1-(d_1/d_0)$

The effect of die angle on the total energy required to cause deformation



Ideal work of plastic deformation U_P independent of die angle α.

α ↑ ***Work to overcome friction*** U_f ↓

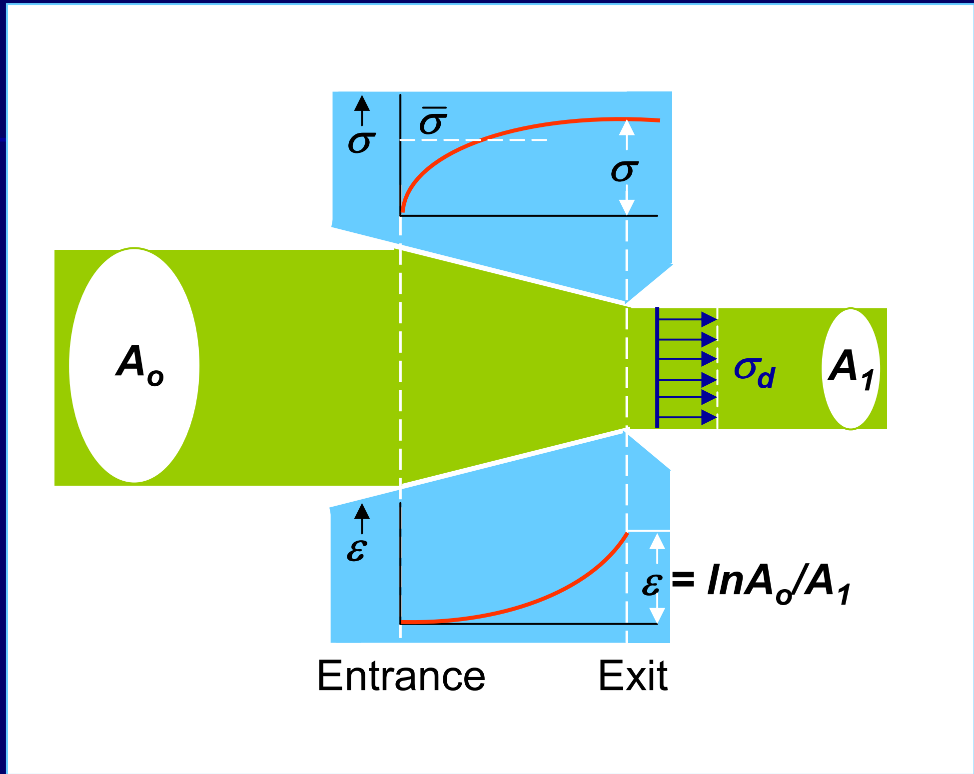
α ↑ ***Redundant work*** U_r ↑

The summation of U_p, U_f and U_r gives **the total energy** U_T.

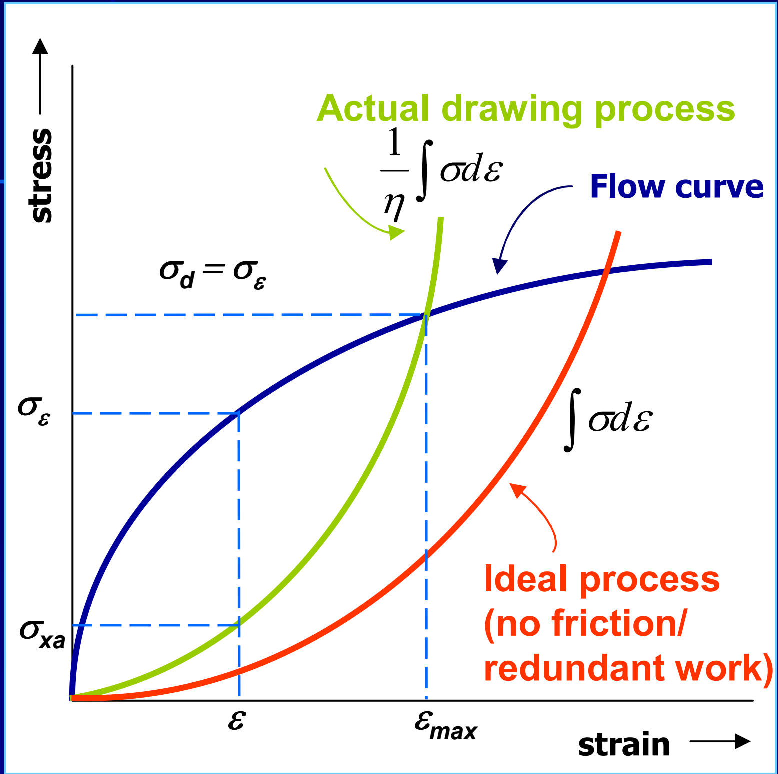
This has a minimum at some optimum die angle α^*.

The reduction and the friction ↑ α^* ↑

Components of total energy of deformation


σ
$\bar{\sigma}$
σ
A_o
σ_d
A_1
ε
$\varepsilon = lnA_o/A_1$
Entrance
Exit

Development of limit on drawability



For ***steady-state wiredrawing*** σ_{xa} can be expressed most simply by

$$\sigma_{xa} = \frac{1}{\eta}\int \sigma d\varepsilon \quad \text{...Eq.14}$$

Where the ***efficiency of the deformation process***, $\eta = U_p/U_T$

At a given strain $\varepsilon = \ln (A_b/A_a)$ → draw stress σ_{xa} and the flow stress σ_ε.

As the material is being deformed through the die, strain hardening occurs and if the material is ***severely strain-hardened*** → ***necking*** → ***fracture***.

The drawing limit is reached when $\sigma_d = \sigma_\varepsilon$

If the material follows a power-law hardening relationship $\sigma_\varepsilon = K\varepsilon^n$, then

$$\sigma_d = \frac{K\varepsilon^{n+1}}{\eta(n+1)} = \frac{\sigma_\varepsilon \varepsilon}{\eta(n+1)} \qquad \text{...Eq.15}$$

Substituting the criterion for the maximum drawing strain in a single pass, that is, $\sigma_d = \sigma_\varepsilon$,

$$\varepsilon_{\max} = \eta(n+1) \qquad \text{...Eq.16}$$

Since $\varepsilon = \ln (A_b/A_a)$,

$$\left(\frac{A_b}{A_a}\right)_{\max} = e^{\eta(n+1)} \qquad \text{...Eq.17}$$

And by the definition of the reduction $r = 1- (A_a/A_b)$

$$r_{\max} = 1 - e^{-\eta(n+1)} \qquad \text{...Eq.18}$$

For repeated reductions through a series of dies, $n \rightarrow 0$, $r \Downarrow$

$$\left(\frac{\varepsilon_{drawing}}{\varepsilon_{stretch}}\right)_{\max} = \frac{\eta(n+1)}{n} \qquad \text{...Eq.19}$$

Example: *From previous example, a 10 mm stainless steel wire is drawn using a die angle = 12°, μ = 0.09, and flow stress is given by* σ_o ***= 1300$\sigma^{0.30}$***. *Determine the largest possible reduction.*

To a first approximation the limit on drawing reduction occurs when $\sigma_{xa} = \bar{\sigma}$.

$$\sigma_{xa} = \bar{\sigma}\left(\frac{1+B}{B}\right)\left[1-(1-r)^{B}\right]$$

$$637 = 637\left(\frac{1.8571}{0.8571}\right)\left[1-(1-r)^{0.8751}\right]$$

$$r = 0.51$$

$$or$$

$$\varepsilon = \ln\frac{1}{1-r} = 0.71$$

$$\sigma_o = 1300\varepsilon^{0.30} = 1300(0.7)^{0.30} = 1{,}173MPa$$

A better estimate is to let $\sigma_{xa} = \sigma_o$ at ε = 0.71, i.e. σ_{xa} = 1173 MPa

$$\sigma_{xa} = \bar{\sigma}\left(\frac{1+B}{B}\right)\left[1-(1-r)^{B}\right]$$

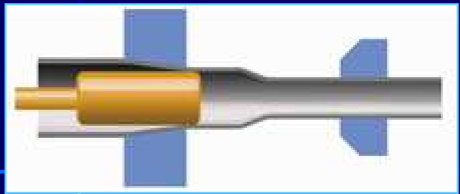
$$1173 = 673(2.167)\left[1-(1-r)^{0.8571}\right]$$

$$r = 0.89$$

Note: in the case of no friction/ redundant work, η **= 1**, no strain hardening ***(n = 0)***, we have

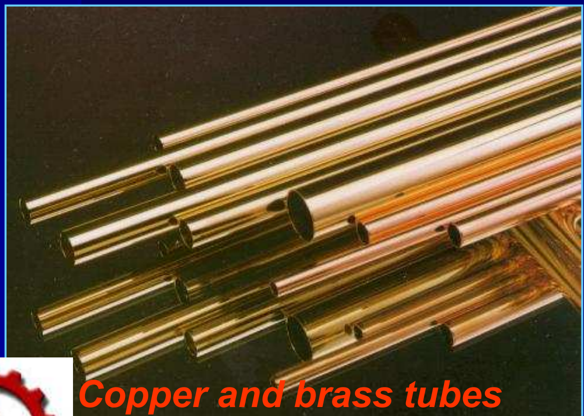
$$r_{\max} = 1 - \frac{1}{e} = 0.63$$

Tube-drawing processes



Tube drawing

Seamless stainless tubes/pipes



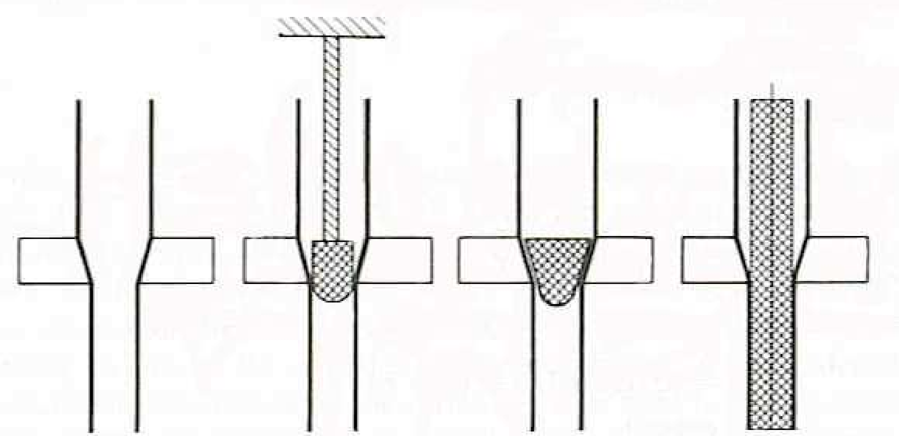
Copper and brass tubes

- Following the hot forming process, tubes are ***cold drawn*** using dies, plugs or mandrels to the required shape, size, tolerances and mechanical strength.
- provides good surface finishes.
- increase mechanical properties by strain hardening.
- can produce tubes with ***thinner walls*** or smaller diameters than can be obtained from other hot forming methods.
- can produce more irregular shapes.

Classification of tube drawing processes

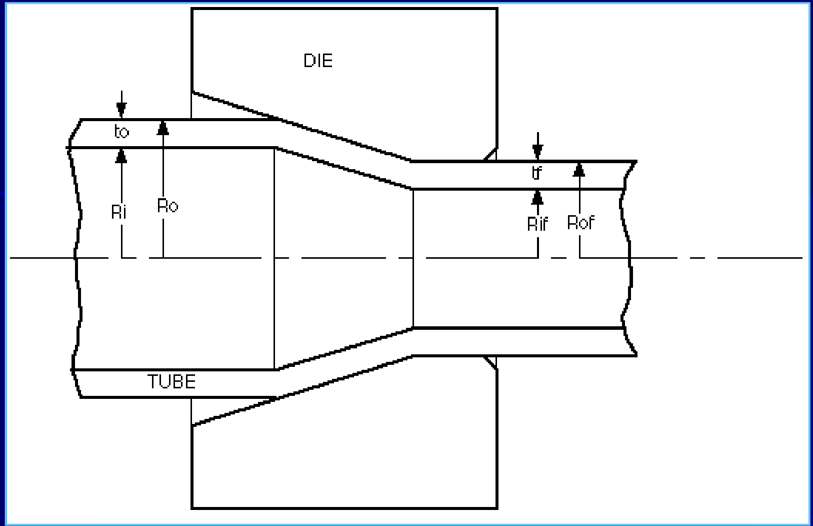
There are ***three*** basic types of ***tube-drawing*** processes

- ***Sinking***
- ***Plug drawing***
    - ***- Fixed plug***
    - ***- Floating plug***
- ***Mandrel drawing.***



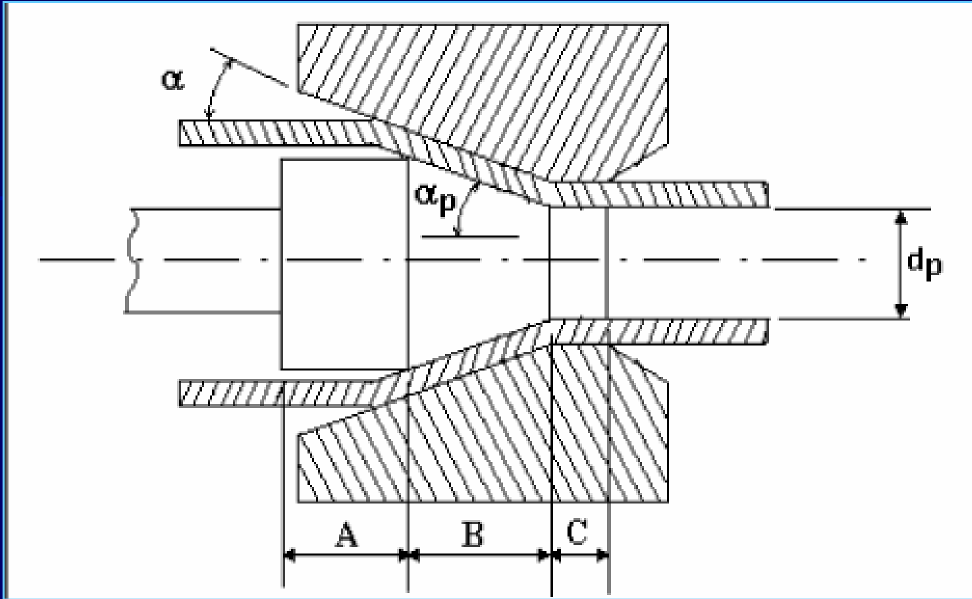
Tube sinking **Fixed plug** **Floating plug** **Moving mandrel**

Tube sinking



- The tube, while passing through the die, ***shrinks*** in outer radius from the ***original radius R_o*** to a ***final radius R_{of}***.
- No internal tooling (internal wall is not supported), the wall then thicken slightly.
- ***Uneven*** internal surface.
- The final thickness of the tube depends on original diameter of the tube, the die diameter and friction between tube and die.
- Lower limiting deformation.

Fixed plug drawing



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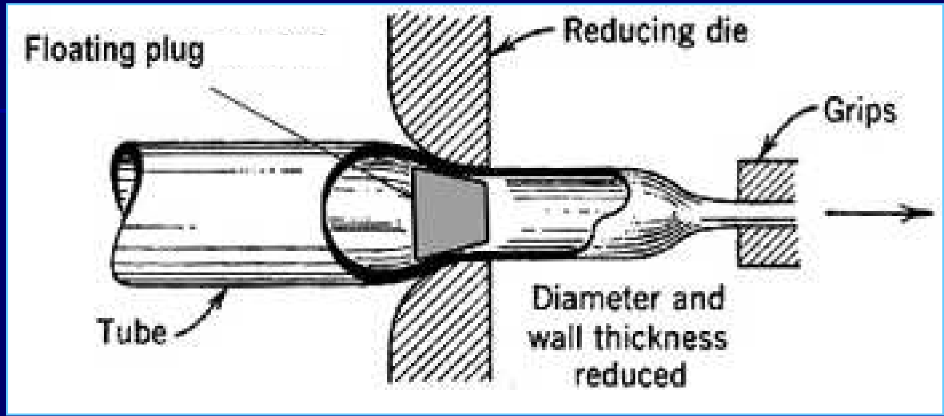
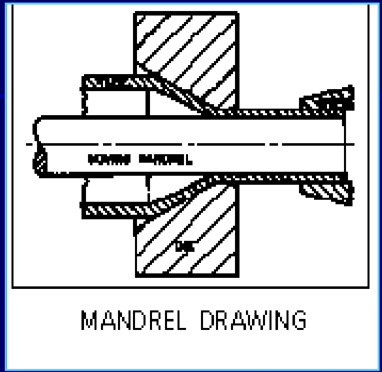
- Use cylindrical / conical plug to control size/shape of inside diameter.
- Use ***higher drawing loads*** than floating plug drawing.
- Greater dimensional accuracy than tube sinking.
- ***Increased friction*** from the plug limit the reduction in area (seldom > 30%).
- can draw and coil long lengths of tubing.

Floating plug drawing



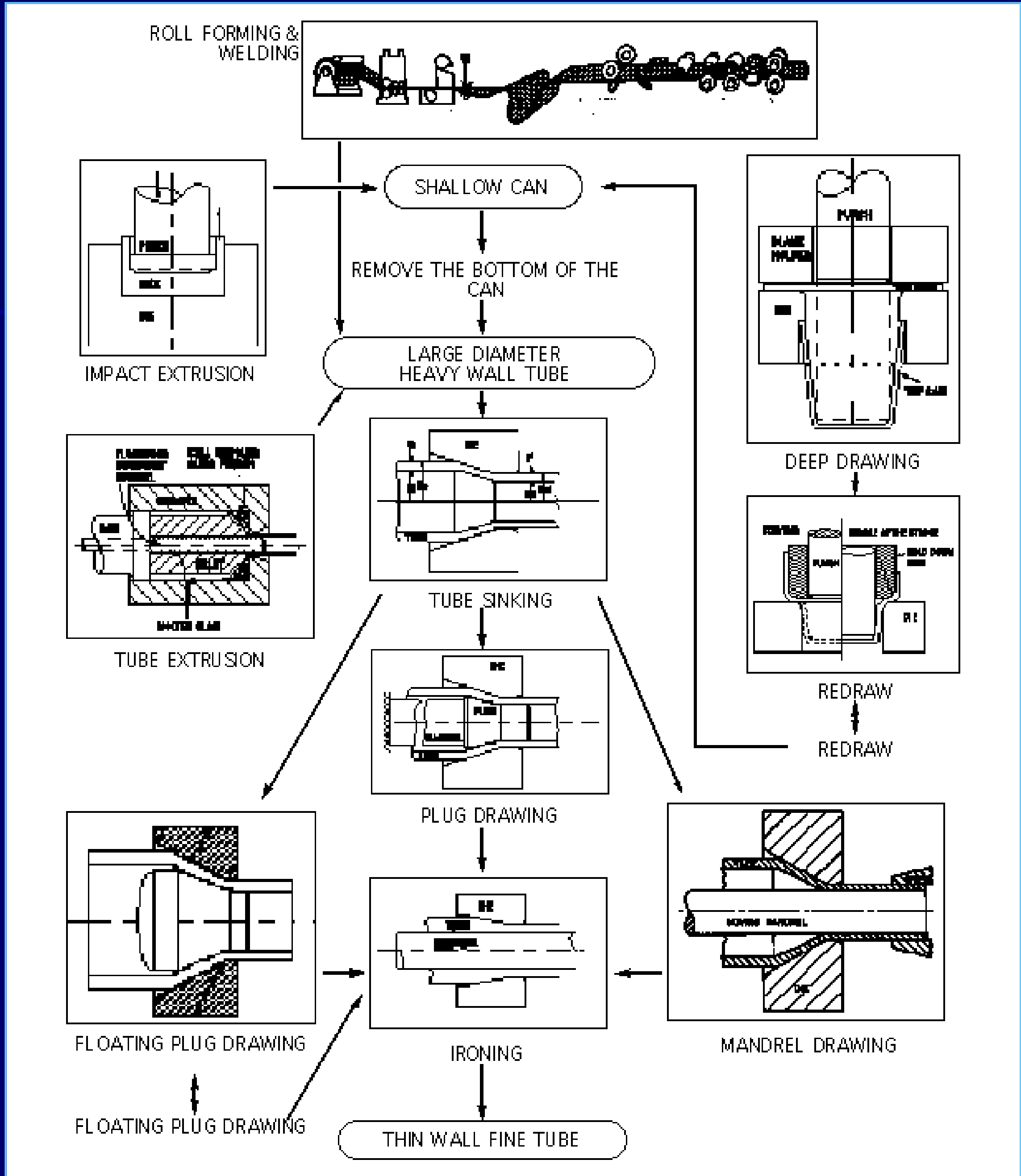
- A ***tapered plug*** is placed inside the tube.
- As the tube is drawn the plug and the die act together to reduce both the outside/inside diameters of the tube.
- Improved reduction in area than tube sinking (~ 45%).
- Lower ***drawing load*** than fixed plug drawing.
- Long lengths of tubing is possible.
- ***Tool design and lubrication*** can be very critical.

Moving mandrel drawing



- ***Draw force*** is transmitted to the metal by the pull on the exit section and by the friction forces acting along the tube -mandrel interface.
- ***minimised friction***.
- $V_{mandrel} = V_{tube}$
- The mandrel also imparts a ***smooth inside finish surface*** of the tube.
- mandrel removal disturbs dimensional tolerance.

Example: schematic alternate pass reduction schedule for tube making



Analysis of tube-drawing

- The greatest part of deformation occurs as a ***reduction in wall thickness***.
- The inside diameter is reduced by a small amount equal to dimensions of the plug or mandrel inserted before drawing.
- There is ***no hoop strain*** and the analysis can be based on ***plane-strain conditions***.

For tube drawing with a plug, the ***draw stress*** can be expressed by

$$\sigma_{xa} = \sigma_o' \frac{1+B'}{B'}\left[1-\left(\frac{h_a}{h_b}\right)^{B'}\right]$$

where

$$B' = \frac{\mu_1 + \mu_2}{\tan\alpha - \tan\beta}$$

And

μ_1 = friction coefficient between tube and die wall.

μ_2 = friction coefficient between tube and plug.

α = semi die angle of the die.

β = semi cone angle of the plug.

In ***tube drawing*** with a ***moving mandrel***, the friction forces at the mandrel-tube interface are directed toward the exit of the die. For a moving mandrel, ***B'*** can be expressed as

$$B' = \frac{\mu_1 - \mu_2}{\tan\alpha - \tan\beta} \qquad \ldots Eq.20$$

If $\mu_1 = \mu_2$, which is often be the case, then ***B' = 0***. The differential equation of equilibrium for this simple case is

$$\boxed{\begin{aligned} h\,d\sigma_x + (\sigma_x + p)\,dh &= 0 \\ h\,d\sigma_x + \sigma_o'\,dh &= 0 \end{aligned}} \qquad \ldots Eq.21$$

Integration of this equation and by using ***Boundary condition*** $\sigma_{xb} = 0$ and $h = h_b$, the ***draw stress*** becomes

Ideal homogeneous deformation

$$\sigma_{xa} = \sigma_o' \ln\frac{h_b}{h_a} = \sigma_o' \ln\frac{1}{1-r} \qquad \ldots Eq.22$$

It is possible that $\mu_2 > \mu_1$, → ***B*** is ***negative***, the draw stress is there for less than required by frictionless ideal deformation.

The ***stresses*** in ***tube sinking*** have been analysed by ***Sachs*** and ***Baldwin***.

Assumption: the wall thickness of the tube remains constant.

The ***draw stress*** at the die exit is similar to wiredrawing. The cross sectional area of the tube is related to the mid-radius ***r*** and the wall thickness ***h*** by $A \sim 2\pi rh$.

$$\sigma_{xa} = \sigma_o^{"} \frac{1+B}{B}\left[1-\left(\frac{A_f}{A_b}\right)^B\right] \qquad \text{...Eq.23}$$

Where $\sigma''_o \sim 1.1\sigma_o$ to account for the complex stresses in tube sinking.

Residual stresses in rod, wire and tubes

Two distinct types of ***residual-stress*** patterns in cold-drawn rod and wire:

Small reduction
(<1% reduction per pass)

- Longitudinal residual stresses
  - Surface → compressive
  - Axis → tensile
- Radial stresses
  - Surface → drop off to zero
  - Axis → tensile
- Circumferential stresses
  - Surface → compressive
  - Axis → tensile

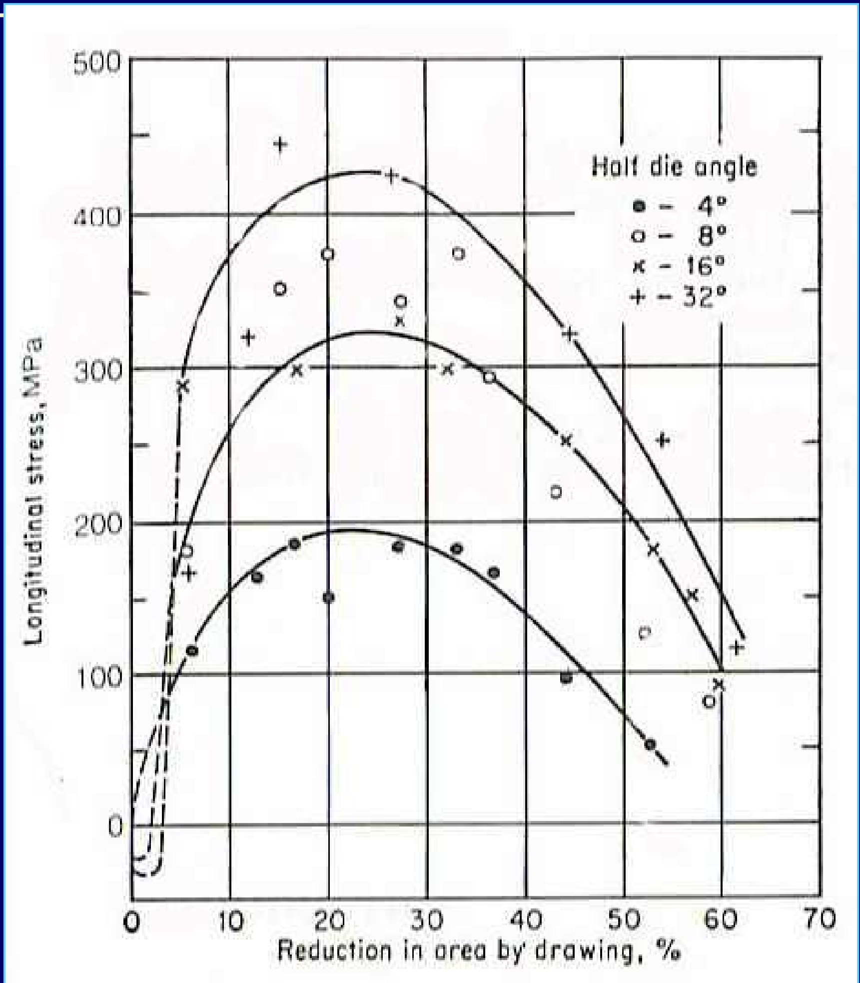
Deformation is localised in the surface layers.

Large reduction
(Commercial significance)

- Longitudinal residual stresses
  - Surface → tensile
  - Axis → compressive
- Radial stresses
  - Axis → compressive
- Circumferential stresses
  - Surface → tensile
  - Axis → compressive

Effects of semi die angle and reduction per pass on longitudinal residual stress in cold-drawn brass wire

(by Linicus and Sachs)



- At a given reduction, α ⇧ longitudinal stress ⇧
- Maximum values of longitudinal residual stress ~ 15-35% reduction in area.

Defects in cold drawn products

- ***Longitudinal scratches*** (scored die, poor lubrication , or abrasive particles)
- ***Slivers*** (swarf drawn into the surface).
- Long fissures (originating in ingot).
- ***Internal cracks*** (pre-existing defects in starting material or ruptures in the centre due to overdrawing).
- ***Corrosion induced cracking*** due to internal residual stresses.

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