Extrusion

Subjects of interest

- *Introduction/objectives*
- *Classification of extrusion processes*
- *Extrusion equipment (Presses, dies and tools)*
- *Hot extrusion*
- *Deformation, lubrication, and defects in extrusion*
- *Analysis of the extrusion process*
- *Cold extrusion and cold-forming*
- *Hydrostatic extrusion*
- *Extrusion of tubing*
- *Production of seamless pipe and tubing*

Objective

• This chapter aims to provide useful information on different extrusions processes, which can be mainly divided into direct and indirect extrusion processes. This also includes basic background on hydrostatic extrusion, extrusions of tubing and production of seamless pipe and tubing.

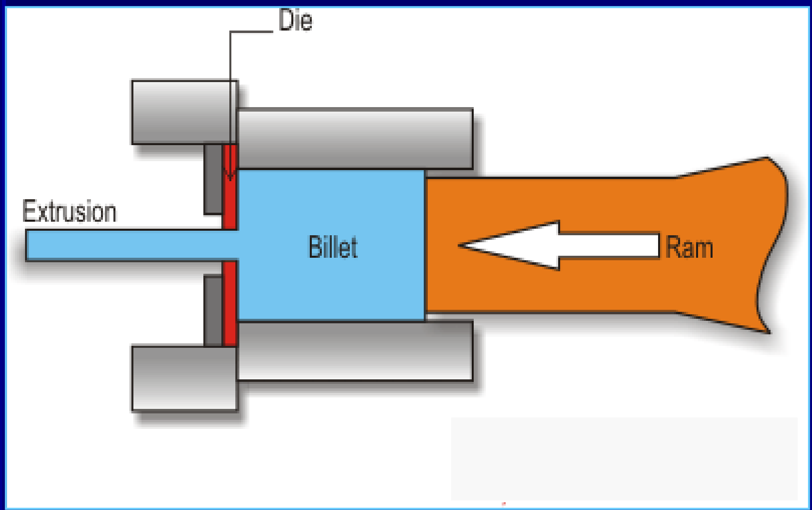
• Principal background and concept of extrusion will be addressed along with the utilisation of mathematical approaches to understand the calculation of extrusion load.

• The role of lubricants on the deformation process which results in the improvement in extrusion products will be provided.

• Finally, defects and its solutions occurring in the extrusion process will be emphasised.

What is extrusion?

Extrusion is the process by which a block/billet of metal is reduced in cross section by forcing it to ***flow through a die*** orifice under ***high pressure***.

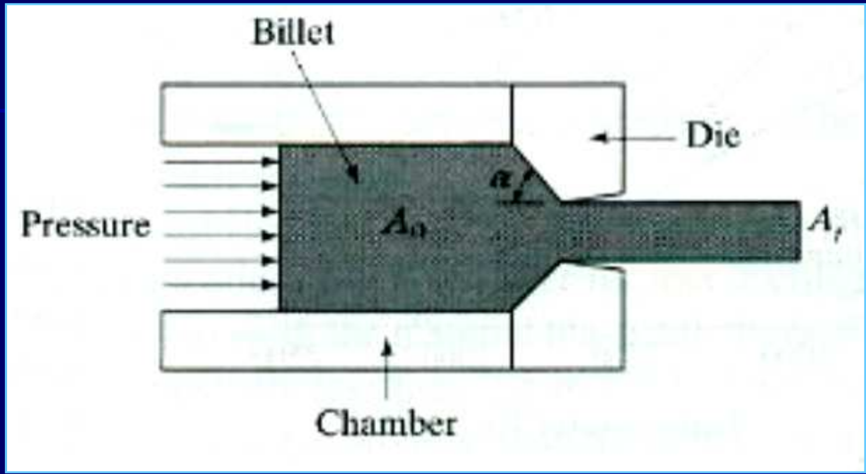


- In general, ***extrusion*** is used to produce cylindrical bars or hollow tubes or for the starting stock for drawn rod, cold extrusion or forged products.

- Most metals are ***hot extruded*** due to ***large amount of forces*** required in extrusion. Complex shape can be extruded from the more readily extrudable metals such as aluminium.

** The products obtained are also called* ***extrusion.***

• The reaction of the extrusion billet with the container and die results in ***high compressive stresses*** which are effective in ***reducing cracking*** of materials during primary breakdown from the ingot.



• This helps to increase the utilisation of extrusion in the ***working of metals that are difficult to form*** like stainless steels, nickel-based alloys, and other high-temperature materials.

• Similar to forging, lower ram force and a fine grained recrystallised structure are possible in ***hot extrusion***.

• However, better surface finish and higher strengths (strain hardened metals) are provided by ***cold extrusion***.

Extrusion products

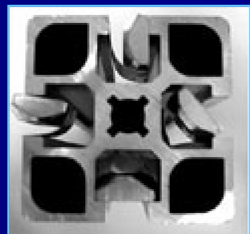
Typical parts produced by extrusion are trim parts used in automotive and construction applications, window frame members, railings, aircraft structural parts.

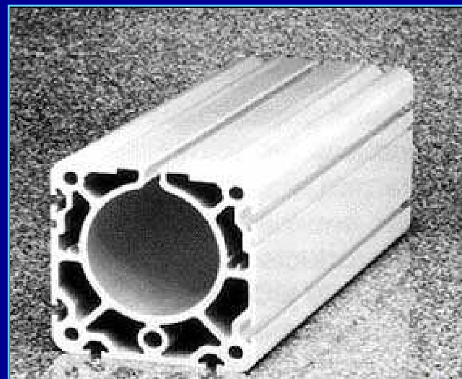
Example: Aluminium extrusions are used in commercial and domestic buildings for window and door frame systems, prefabricated houses/building structures, roofing and exterior cladding, curtain walling, shop fronts, etc. Furthermore, extrusions are also used in transport for airframes, road and rail vehicles and in marine applications.

Aluminium for windows and doors

Brass parts

Aluminium extrusions





Classification of extrusion processes

There are several ways to classify metal extrusion processes;

By direction

- Direct / Indirect extrusion
- Forward / backward extrusion

By operating temperature

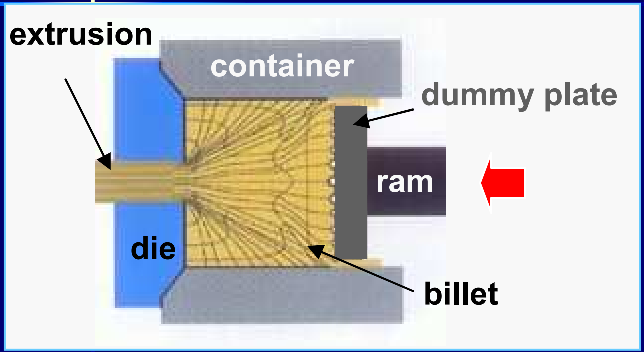
- Hot / cold extrusion

By equipment

- Horizontal and vertical extrusion

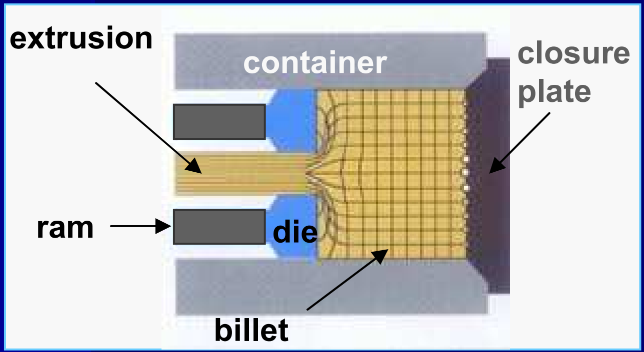
Direct and indirect extrusions

1) Direct extrusion



- The metal billet is placed in a container and driven through the die by the ***ram***.
- The ***dummy block*** or pressure plate, is placed at the end of the ram in contact with the billet.
- Friction is at the die and container wall → requires higher pressure than indirect extrusion.

2) Indirect extrusion

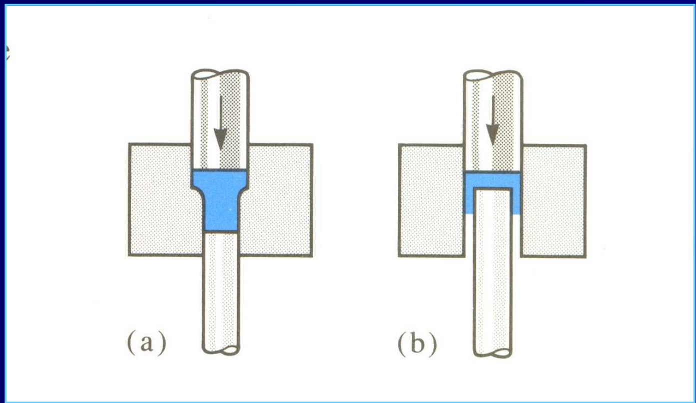


- The ***hollow ram*** containing the die is kept stationary and the ***container with the billet*** is caused to move.
- ***Friction*** at the die only (no relative movement at the container wall) → requires roughly constant pressure.
- Hollow ram ***limits*** the applied load.

Forward and backward extrusion

Extrusion can also be divided to:

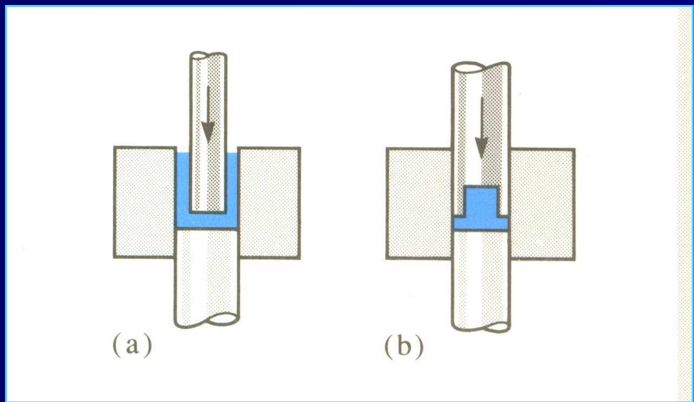
1) Forward extrusion



• Metal is forced to ***flow in the same direction*** as the punch.

• The punch closely fits the die cavity to prevent backward flow of the material.

2) Backward extrusion



• Metal is forced to ***flow in the direction opposite*** to the punch movement.

• Metal can also be forced to flow into recesses in the punch, see *Fig*.

Cold extrusion

Cold extrusion is the process done at room temperature or slightly elevated temperatures. This process can be used for most materials-subject to designing robust enough tooling that can withstand the stresses created by extrusion.

Cold extrusion

Examples of the metals that can be extruded are ***lead, tin, aluminium alloys, copper, titanium, molybdenum, vanadium, steel***. Examples of parts that are cold extruded are collapsible tubes, aluminium cans, cylinders, gear blanks.

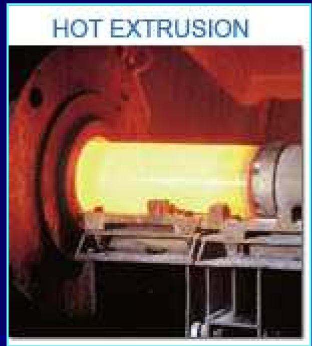
Advantages

- No oxidation takes place.
- Good mechanical properties due to severe cold working as long as the temperatures created are below the re-crystallization temperature.
- Good surface finish with the use of proper lubricants.

Collapsible tubes

Aluminium cans

Hot extrusion

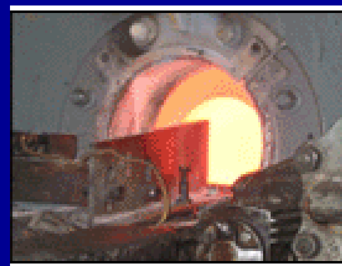


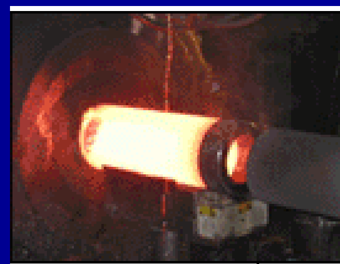
www.gspsteelprofiles.com

Hot extrusion is done at ***fairly high temperatures***, approximately 50 to 75 % of the melting point of the metal. The pressures can range from 35-700 MPa (5076 - 101,525 psi).

• The most commonly used extrusion process is the ***hot direct process***. The cross-sectional shape of the extrusion is defined by the shape of the die.

• Due to the high temperatures and pressures and its ***detrimental effect on the die life*** as well as other components, ***good lubrication*** is necessary. Oil and graphite work at lower temperatures, whereas at higher temperatures glass powder is used.





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Tube extrusion

Tubes can be produced by extrusion by attaching a ***mandrel*** to the end of the ram. The clearance between the mandrel and the die wall determines the wall thickness of the tube.

Tubes are produced either by starting with a ***hollow billet*** or by a two-step extrusion in which a solid billet is first pierced and then extruded.

Carbide Mandrel Insert for 6mMM Enhanced Tubing

Impact extrusion

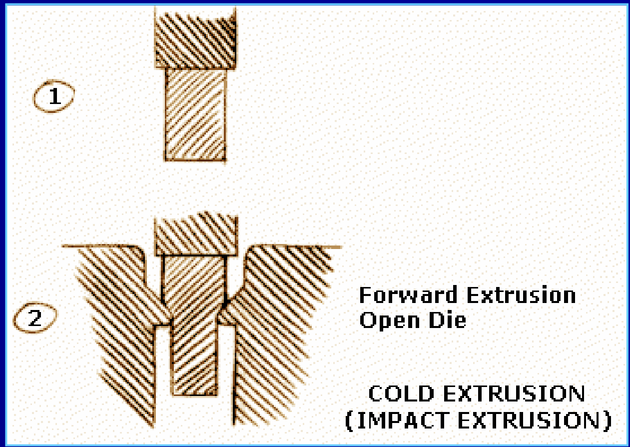
- Produce ***short lengths of hollow shapes***, such as collapsible toothpaste tubes or spray cans.

- Requires ***soft materials*** such as aluminium, lead, copper or tin are normally used in the impact extrusion.

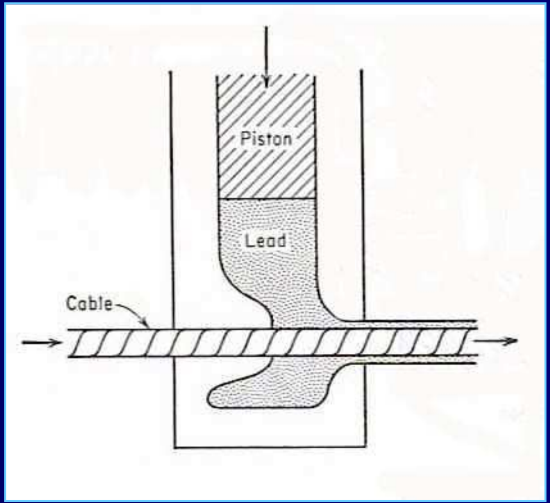
- A small shot of solid material is placed in the die and is impacted by a ram, which causes cold flow in the material. It may be either direct or indirect extrusion and it is usually performed on a ***high-speed mechanical press***.

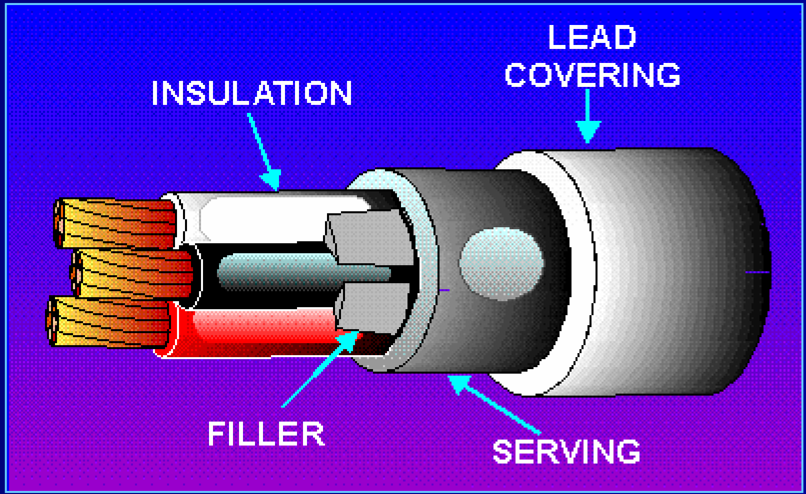
- Although the process is generally performed cold, considerable heating results from the the ***high speed deformation***.

** Small objects, soft metal, large numbers, good tolerances*.*



Extrusion was originally applied to the making of lead pipe and later to the lead sheathing on electrical cable.





Extrusion of lead sheath on electrical cable.

Extrusion equipment (Presses, dies and tools)

Extrusion equipment mainly includes presses, dies and tooling.

1) Presses

- Most extrusions are made with ***hydraulic presses***.
- These can be classified based on the direction of travel of the ram.

1) ***Horizontal presses***

2) ***Vertical presses***

2) Extrusion dies

Die design, Die materials

3) Tools

Typical arrangement of extrusion tools.

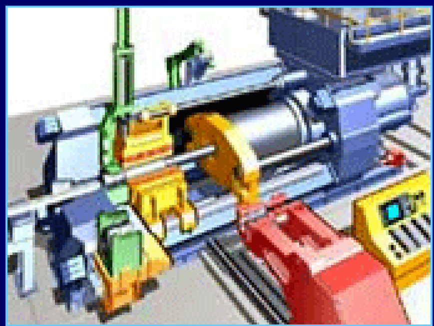
Horizontal extrusion presses

(15- 50 MN capacity or upto 140 MN)

• Used for most commercial extrusion of bars and shapes.

Disadvantages:

• deformation is non-uniform due to different temperatures between top and bottom parts of the billet.



600 Tonne, DUISBURG, HYDRAULIC EXT PRESS

Vertical extrusion presses (3- 20 MN capacity)

Chiefly used in the production of thin-wall tubing.

Advantages:

- Easier alignment between the press ram and tools.
- Higher rate of production.
- Require less floor space than horizontal presses.
- uniform deformation, due to uniform cooling of the billet in the container.

Requirements:

- Need considerable headroom to make extrusions of appreciable length.
- A floor pit is necessary.

Vertical extrusion machine

Ram speed

• Require ***high ram speeds*** in high-temperature extrusion due to heat transfer problem from billet to tools.

• ***Ram speeds*** of 0.4-0.6 m s^{-1} for refractory metals → requires a hydraulic accumulator with the press.

• ***Ram speeds*** of a few mm s^{-1} for aluminium and copper due to hot shortness → requires direct-drive pumping systems to maintain a uniform finishing temperature.

Die design

- ***Die design*** is at the heart of efficient extrusion production.
- Dies must withstand considerable amount of stresses, thermal shock, and oxidation.

Die design

Die design → **CAD/CAM** → **Milling** → **Wire sparkling erosion** → **Finishing** → **Inspection**

Die design consideration

- ***Wall thickness:*** different wall thicknesses in one section should be avoided.
- ***Simple shapes:*** the more simple shape the more cost effective.
- ***Symetrical:*** more accurate.
- ***Sharp or rounded corners***: sharp corners should be avoided.
- ***Size to weight ratio:***
- ***Tolerlances:*** tolerances are added to allow some distortions (industrial standards).

Die materials

- Dies are made from ***highly alloy tools steels*** or ***ceramics*** ***(zirconia, Si_3N_4)***. (for cold extrusion → offering longer tool life and reduced lubricant used, good wear resistance).
- ***Wall thickness*** as small as 0.5 mm (on flat dies) or 0.7 mm (on hollow dies) can be made for aluminium extrusion.
- ***Heat treatments*** such as nitriding are required (several times) to increase hardness (1000-1100 H_v or 65-70 HRC). This improves die life. → avoiding unscheduled press shutdown.

Ceramic extrusion dies

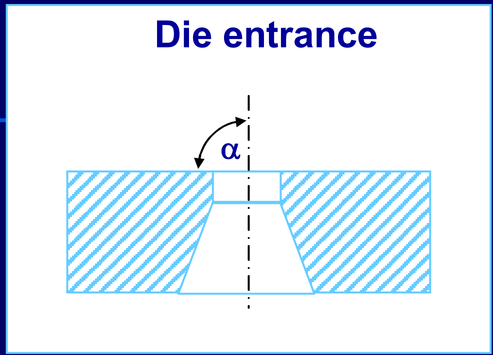
steel extrusion dies

There are two general types of extrusion dies:

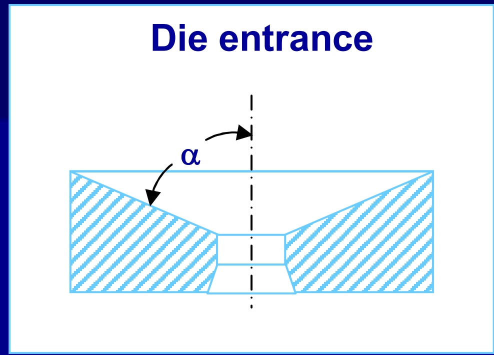
1) Flat-faced dies

2) Dies with conical entrance angle.

1) Flat-faced dies



2) Dies with conical entrance angle

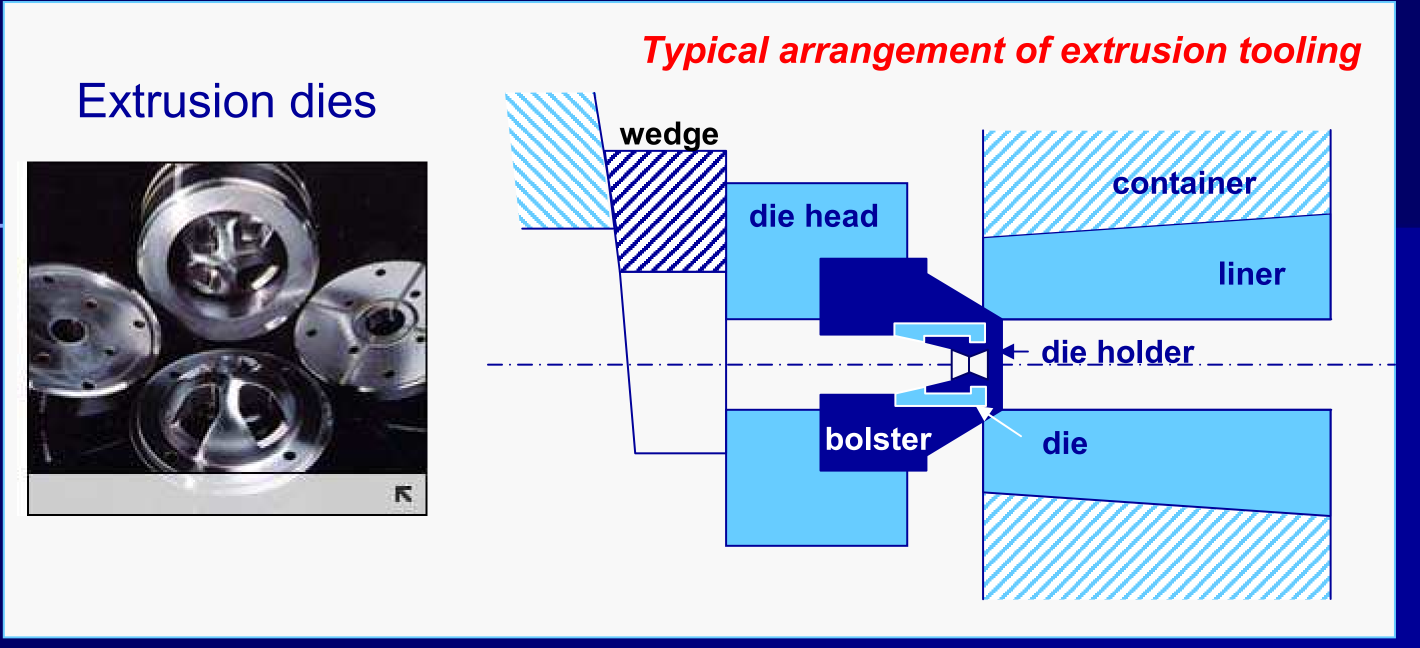


- Metal entering the die will form a dead zone and shears internally to form its own die angle.
- A parallel land on the exit side of the die helps strengthen the die and allow for ***reworking*** of the flat face on the entrance side of the die without increasing the exit diameter.

- requires good lubricants.
- decreasing ***die angle*** → , increasing ***homogeneity***, lower ***extrusion pressure*** (but beyond a point the friction in the die surfaces becomes too great.
- for most operation, $45^o < \alpha < 60^o$

Remarks; transfer equipment (for hot billets) is required.
prior heating of the container.

Typical arrangement of extrusion tooling



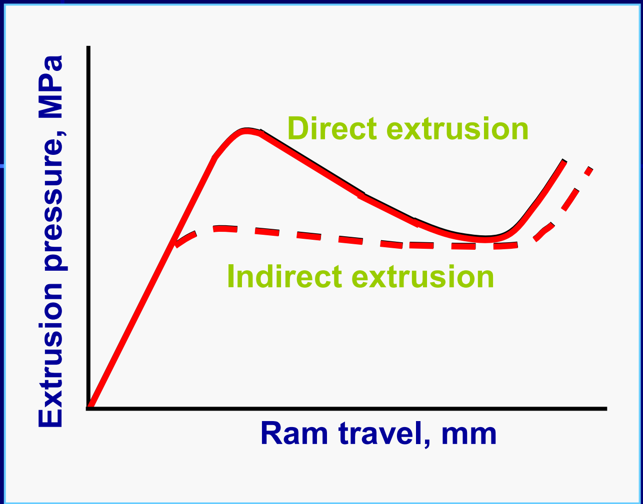
- The die stack consists of the ***die***, which is supported by a ***die holder*** and a ***bolster***, all of which are held in a ***die head***.
- The entire assembly is sealed against the container on a conical seating surface by pressure applied by a ***wedge***.
- A ***liner*** is shrunk in a more massive container to withstand high pressures.
- The ***follower pad*** is placed between the ***hot billet*** and the ***ram*** for protection purpose. Follower pads are therefore replaced periodically since they are subject to many cycles of thermal shock.

Hot extrusion

The principal variables influencing the force required to cause extrusion;

1) Type of extrusion (direct / indirect)
2) Extrusion ratio
3) Working temperature
4) Deformation
5) Frictional conditions at the die and the container wall.

Extrusion pressure = extrusion force /cross sectional area



Extrusion pressure vs. ram travel

- The rapid rise in pressure during ***initial ram travel*** is due to the initial compression of the billet to fill the extrusion container.
- ***For direct extrusion***, the metal begins to flow through the die at the maximum pressure, the ***breakthrough pressure***.
- As the billet extrudes through the die the pressure required to ***maintain flow*** progressively decreases with decreasing length of the billet in the container.
- At the ***end of the stroke***, the pressure rises up rapidly and it is usual to stop the ram travel so as to leave a small discard in the container.
- ***For indirect extrusion***, ***extrusion pressure*** is ~ constant with ***increasing ram travel*** and represent the stress required to deform the metal through the die.
- Since ***hollow ram*** is used in ***indirect extrusion***, size of the extrusions and extrusion pressure are limited.

Extrusion ratio

Extrusion ratio, R, is the ratio of the ***initial cross-sectional area***, A_o, of the billet to the ***final cross-sectional area***, A_f, after extrusion.

$$R = \frac{A_o}{A_f} \quad \text{...Eq.1}$$

R ~ 40:1 for hot extrusion of steels.
R ~ 400:1 for aluminium.

Fractional reduction in area, r

$$r = 1 - \frac{A_f}{A_o} \quad \text{...Eq.2}$$

and

$$R = \frac{1}{(1-r)} \quad \text{...Eq.3}$$

Note: R is more descriptive at large deformations!
Ex: R = 20:1 and 50:1 → r = 0.95 and 0.98 respectively.

Extrusion ratio, R, of steel could be 40:1 whereas R for aluminium can reach 400:1.

The ***velocity of the extruded product*** is given by

Velocity of the extruded product = ram velocity x R ...*Eq.4*

Extrusion force may be expressed as

$$P = kA_o \ln \frac{A_o}{A_f} \qquad \text{...Eq.5}$$

where ***k*** = extrusion constant, an overall factor which accounts for the flow stress, friction, and inhomogeneous deformation.

Effects of temperature on hot extrusion

- Decreased flow stress or deformation resistance due to increasing extrusion temperature.
- Use minimum temperature to provide metal with suitable plasticity.
- The top working temperature should be safely below the melting point or hot-shortness range.
- Oxidation of billet and extrusion tools.
- Softening of dies and tools.
- Difficult to provide adequate lubrication.

The temperature of the workpiece in metal working depends on;

1) The initial temperature of the tools and the materials
2) Heat generated due to plastic deformation
3) Heat generated by friction at the die/material interface (highest)
4) Heat transfer between the deforming material and the dies and surrounding environment.

Note: Working temperature in extrusion is normally higher than used in forging and rolling due to relatively large compressive stresses in minimising cracking.

• Usually the temperature is highest at the ***material/tool interface*** due to friction.

• If we neglect the temperature gradients and the deforming material is considered as a thin plate, the ***average instantaneous temperature*** of the deforming material at the interface is given by

$$T = T_1 + (T_o - T_1)\exp\left(\frac{-ht}{\rho c \delta}\right) \quad \text{...Eq.6}$$

Where

	T_o	= temperature at the workpiece
	T_1	= temperature at the die
	h	= heat transfer coefficient between the material and the dies
	δ	= material thickness between the dies.

If the temperature increase due to deformation and friction is included, the ***final average material temperature*** T_m at a time t is

$$T_m = T_d + T_f + T \quad \text{...Eq.7}$$

Dieter p.524-526

T_d = Temp for frictionless deformation process

T_f = Temp increase due to friction

Ram speed, extrusion ratio and temperature

- A ***tenfold*** increase in the ***ram speed*** results in about a ***50%*** increase in the ***extrusion pressure***.

- ***Low extrusion speeds*** lead to ***greater cooling of the billet***.

- ***The higher the temperature of the billet, the greater the effect of low extrusion speed on the cooling of the billet.***

- Therefore, high extrusion speeds are required with high-strength alloys that need high extrusion temperature.

- The selection of the ***proper extrusion speed and temperature*** is best determined by ***trial and error*** for each alloy and billet size.

Relationships between extrusion ratio, temperature and pressure

- For a given ***extrusion pressure***, ***extrusion ratio*** ***R*** increases with increasing ***Extrusion temperature***.
- For a given ***extrusion temperature***, a larger ***extrusion ratio*** ***R*** can be obtained with a higher extrusion ***extrusion pressure.***

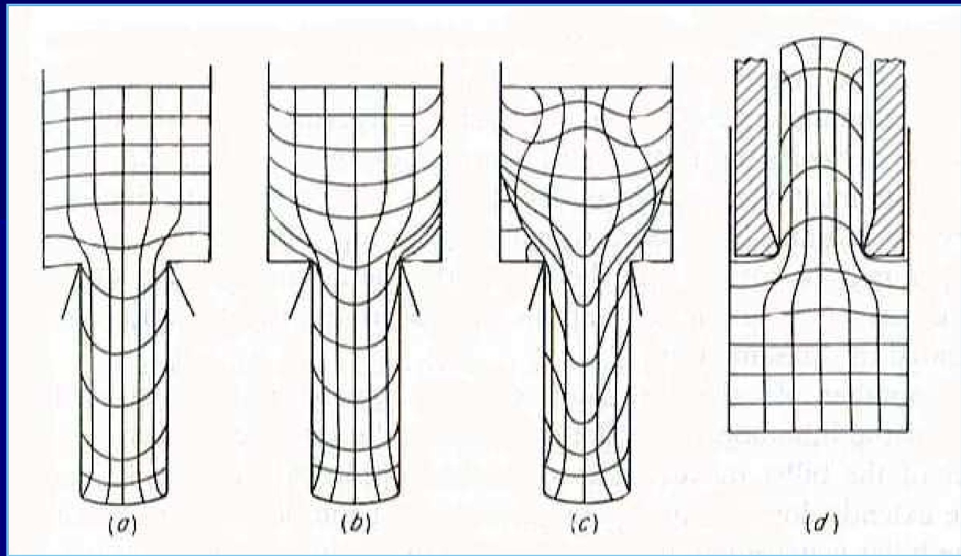
Extrusion temperature ↑ **Extrusion ratio (R)** ↑

Extrusion pressure ↑

Relationships between extrusion speed and heat dissipation

- extrusion speeds ↑, heat dissipation ↓
- extrusion speeds ↓, heat dissipation ↑ , allowable extrusion ratio ↑

Deformation in extrusion, lubrication and defects



(a) ***Low container friction and a well-lubricated billet*** – nearly homogeneous deformation.

b) Increased container wall friction, producing a dead zone of stagnant metal at corners which undergoes little deformation.

Essentially pure elongation in the centre and extensive shear along the sides of the billet. The latter leads to ***redundant work***

c) For ***high friction*** at the container-billet interface, metal flow is concentrated toward the centre and an internal shear plane develops – due to cold container. In the ***sticky friction***, the metal will separate internally along the shear zone. A thin skin will be left in a container and a new metal surface is obtained.

d) ***Low container friction and a well lubricated billet in indirect extrusion***.

Hot extrusion lubricants

• Low shear strength.

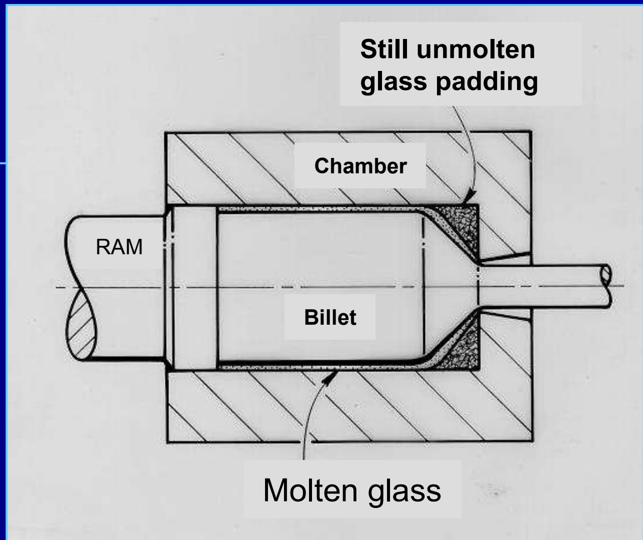
• Stable enough to prevent breakdown at high temperature.

• ***Molten glass*** is the most common lubricant for steel and nickel based alloys (high temp extrusion).

Ugine-Sejournet process

• ***Graphite-based lubricants*** are also be used at high extrusion temperature.

Ugine-Sejournet process



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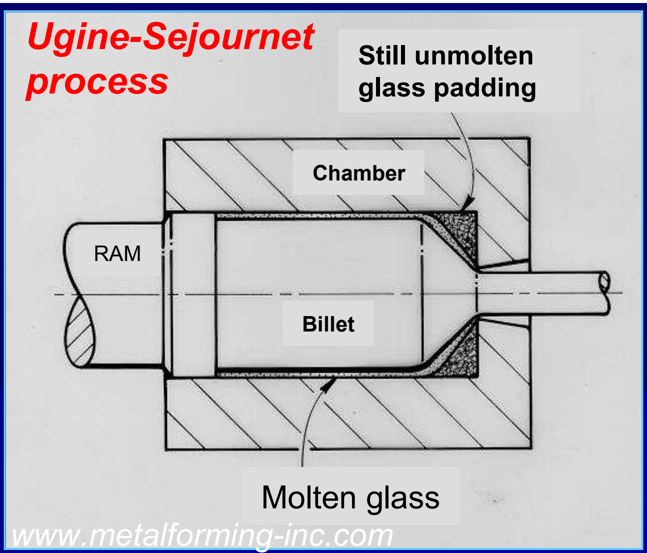
Ugine-Sejournet process



• The ***billet*** is heated in an inert atmosphere and coated with ***glass powder*** before being pressed. The glass pad placed between the die and the billet provide the main source of lubricant.

• This glass coating is soften during extrusion to provide a lubricant film (~25 μm thick), which serves not only as a ***lubricant*** but also a ***thermal insulator*** to reduce heat loss to the tools.

• The ***coating thickness*** depends on a complex interaction between the ***optimum lubricant***, the ***temperature*** and the ***ram speed.***

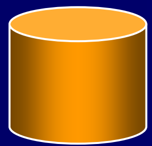
• Lubricant film must be ***complete*** and ***continuous*** to be successful, otherwise defects such as ***surface crack*** will results.

too low ram speed → thick lubricant coatings with low initial extrusion pressure → limit the length of extrusions.

too high ram speed → dangerously thin coatings.

Example: *Extrusion of aluminium*

- Aluminium billet is heated to around 450-500^{o}C and pressed through flat die to produce solid sections such as bars, rods, hollow shapes, tubes.
- Aluminium ***heat treatments*** may be required for higher strength in some applications.



Hot aluminum billet (450-500^{o}C)

↓

Press through dies — *Dies are preheated*

↓

Length cutting

↓

Stretching both ends — *Reorientation of grains*

↓

Heat treatment — *Improve mechanical properties*

↓

Finishing and inspection

Aluminium extrusion process

Aluminium extrusion part

Extrusion defects

1) Inhomogeneous deformation in direct extrusion provide the ***dead zone*** along the outer surface of the billet due to the movement of the metal in the centre being higher than the periphery.

• After 2/3 of the billet is extruded, the outer surface of the billet (normally with ***oxidised skin***) moves toward the centre and extrudes to the through the die, resulting in internal oxide stringers. - transverse section can be seen as an ***annular ring of oxide***.

Container wall friction ⬆ ***extrusion defects*** ⬆

Container wall temp ⬇ ***extrusion defects*** ⬆

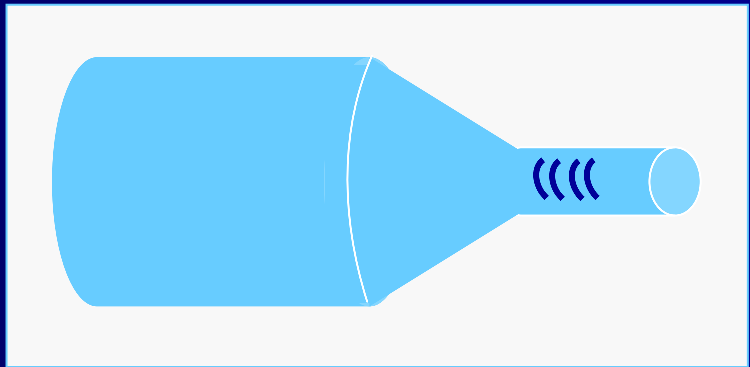
• If lubricant film is carried into the interior of the extrusion along the shear bands, this will show as longitudinal laminations in a similar way as oxide.

Solutions:

• discard the remainder of the billet (~30%) where the surface oxide begins to enter the die → not economical.

• use a follower block with a smaller diameter of the die to scalps the billet and the oxidised layer remains in the container (in brass extrusion).

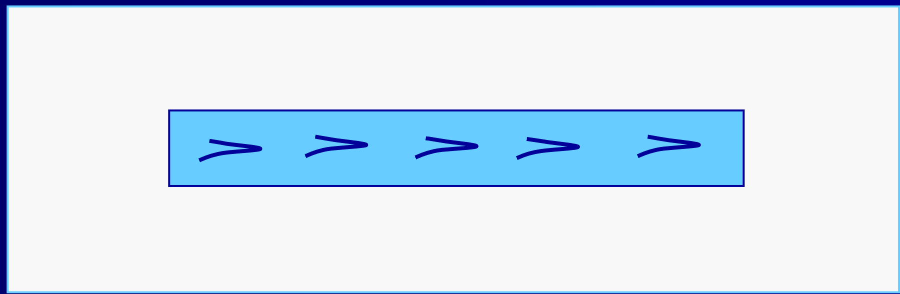
2) Surface cracking, ranging from a badly roughened surface to repetitive transverse cracking called ***fir-tree cracking***, see *Fig.* This is due to longitudinal tensile stresses generated as the extrusion passes through the die.



Surface cracks from heavy die friction in extrusion

- In hot extrusion, this form of cracking usually is intergranular and is associated with hot shortness.
- The most common case is too high ram speed for the extrusion temperature.
- At ***lower temperature***, sticking in the die land and the sudden building up of pressure and then breakaway will cause ***transverse cracking***.

3) Centre burst or chevron cracking, see *Fig*, can occur at ***low extrusion ratio*** due to ***low frictional conditions*** on the zone of deformation at the extrusion die.



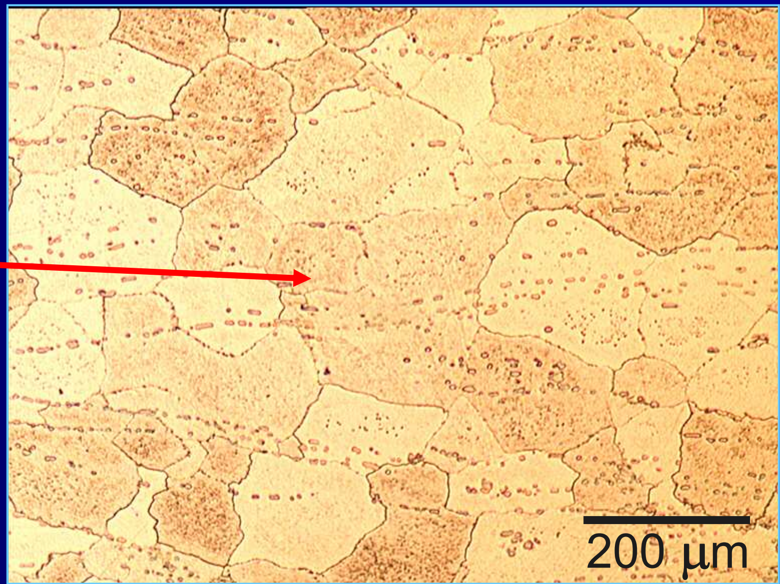
Centre burst or chevron cracks

- ***High friction*** (at a the tool-billet interface) → a sound product.
- ***Low friction*** → centre burst.

4) Variations in structure and properties within the extrusions due to non-uniform deformation for example at the front and the back of the extrusion in both longitudinal and transverse directions.

• Regions of exaggerated grain growth, see *Fig*, due to high hot working temperature.

Grain growth



Extrusion direction

5) Hot shortness (in aluminium extrusion).

Hot shortness

High temperatures generated cause incipient melting, which causes cracking.

Analysis of the extrusion process

Using the uniform deformation energy approach, the ***plastic work of deformation per unit volume*** can be expressed for direct extrusion as

$$U_p = \bar{\sigma}\int d\varepsilon = \bar{\sigma}\int_{A_o}^{A_f} d\ln A = \bar{\sigma}\ln\frac{A_f}{A_o} = -\bar{\sigma}\ln R \qquad \text{...Eq.8}$$

The work involved is

$$W = U_p V = V\bar{\sigma}\ln R = pAL = force \times dis\tan ce \qquad \text{...Eq.9}$$

Where $\bar{\sigma}$ is the ***effective flow stress in compression*** so that

** Neither friction nor redundant deformation.*

$$p = \frac{V}{AL}\bar{\sigma}\ln R = \bar{\sigma}\ln R \qquad \text{...Eq.10}$$

The ***actual extrusion pressure*** $\boldsymbol{p_e}$ is given by

Where the efficiency of the process η is the ratio of the ideal to actual energy per unit volume.

$$p_e = \frac{p}{\eta} = \frac{\bar{\sigma}}{\eta}\ln R \qquad \text{...Eq.11}$$

DePierre showed that the total extrusion force P_e is the summation of the forces below;

$$P_e = P_d + P_{fb} + P_{ff}$$

Where

P_d is the die force

P_{fb} is the frictional force between the container and the upset billet.

P_{ff} is the frictional force between the container liner and the follower ~0.

Assuming the billet ***frictional stress*** is equal to $\tau_i \sim k$, the ***ram pressure required by container friction*** is

$$p_f \frac{\pi D^2}{4} = \pi D \tau_i L$$

and

$$p_e = p_d + p_f = p_d + \frac{4\tau_i L}{D} \qquad \text{…Eq.12}$$

Where τ_i = uniform interface shear stress between billet and container liner

L = length of billet in the container liner

D = inside diameter of the container liner.

Using a ***slab analysis*** to account for friction on extruding through a conical die, ***Sash*** has performed the analysis for ***Coulomb sliding friction***,

$$p_d = \sigma_{xb} = \sigma_o\left(\frac{1+B}{B}\right)\left(1-R^B\right) \quad \text{...Eq.13}$$

Where **B** = $\mu \cot \alpha$

α = semi die angle

R = extrusion ratio = A_o/A

* *This analysis includes die friction but excludes redundant deformation.*

Using ***slip-line field theory*** for ***plane-strain condition*** without considering ***friction***, the solution is as follows;

$$p_d = \sigma_o\left(a + b\ln R\right) \quad \text{...Eq.14}$$

Where typically ***a*** = 0.8 and ***b*** = 1.5 for axisymmetric extrusion.

Using ***upper-bound analysis***, ***Kudo*** found the following expression for extrusion through rough square dies (***2α = 180°***)

$$p_d = \sigma_o\left(1.06 + 1.55\ln R\right) \qquad \textit{…Eq.15}$$

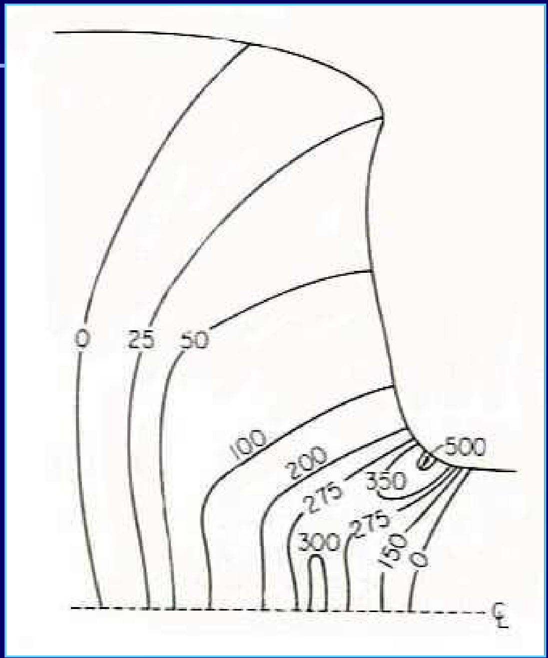
Using ***upper-bound analysis*** based on a ***velocity field***, ***Depierre*** use the following equation to describe ***die pressure*** in hydrostatic extrusion;

$$p_d = \sigma_o\left(a + b\ln R\right) + mk\cot\alpha\ln R \qquad \textit{…Eq.16}$$

Where ***m*** = τ_i/k and ***a*** and ***b*** are evaluated as follows:

α	***a***	***b***
30	**0.419**	**1.006**
45	**0.659**	**1.016**
60	**0.945**	**1.034**

Variation of local strain rate



Strain rate distribution in a partially extruded steel billet.
R = 16.5, ram speed = 210 mm.s^{-1},
Temp =1440 K.

• Using the ***technique of visioplasticity*** to map out the distribution of strain and strain rate and to calculate the variation of temperature and flow stress within the extrusion.

• There are ***local maxima*** near the exit from the die on the surface, and along the centre line of the extrusion.

The ***average strain rate*** for extrusion is usually defined by the time for material to transverse through a truncated conical volume of deformation zone, which is defined by the ***billet diameter*** **D_b** and the ***extrusion diameter*** **D_e**.

For a <u>45</u> ° semicone angle,

$$V = \frac{\pi h}{3}\left(\frac{D_b^2}{4} + \frac{D_e^2}{4} + \frac{D_b D_e}{4}\right)$$

where

$$h = \frac{(D_b - D_e)}{2}$$

so

$$V = \frac{\pi}{24}\left(D_b^3 - D_e^3\right)$$

For a ***ram velocity*** ν, the volume extruded per unit time is $\upsilon \dfrac{\pi D_b^2}{4}$

And the ***time*** to fill the volume of the deformation zone is

$$\frac{V}{\upsilon\left(\pi D_b^2 / 4\right)} = \frac{D_b^3 - D_e^3}{6\upsilon D_b^2}$$

$$\frac{D_b^3 - D_e^3}{D_b^2} \approx D_b, D_b >> D_e$$

then

$$t = \frac{D_b}{6\upsilon}$$

The ***time average mean strain rate*** is given by

For a 45 º semicone angle,

$$\dot{\varepsilon}_t = \frac{\bar{\varepsilon}}{t} = \frac{6\upsilon \ln R}{D_b}$$

…Eq.17

For the general semidie angle α,

$$\dot{\varepsilon}_t = \frac{6\upsilon D_b^2 \ln R \tan\alpha}{D_b^2 - D_e^3}$$

…Eq.18

Example: *An aluminium alloy is hot extruded at 400°C at 50 mm.s^{-1} from 150 mm diameter to 50 mm diameter. The flow stress at this temperature is given by* $\bar{\sigma} = 200(\varepsilon)^{0.15}$ *(MPa). If the billet is 380 mm long and the extrusion is done through square dies without lubrication, determine the force required for the operation.*

The ***extrusion load*** is $P = p_e A$ and from *Eq.12* and *Eq.13*

$$p_e = p_d + \frac{4\tau_i L}{D}$$

$$p_d = \sigma_o \left(\frac{1+B}{B}\right)\left(1 - R^B\right)$$

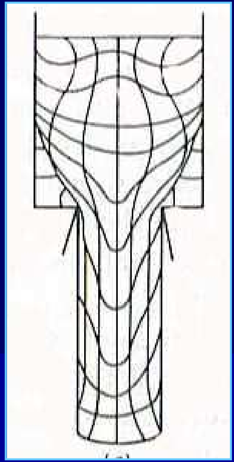
We need to know, p_e, p_d, τ_i, $\dot{\varepsilon}$, $\bar{\sigma}$ and R

$$R = \frac{150^2}{50^2} = 9$$

$$\dot{\varepsilon} = \frac{6\upsilon \ln R}{D_b} = \frac{6(50)\ln 9}{150} = 4.39 s^{-1}$$

$$\bar{\sigma} = 200(4.39)^{0.15} = 200(1.25) = 250 MPa$$

Since we use ***square dies without lubrication***, see *Fig,* a dead-metal zone will form in the corners of the container against the die. We can assume that this is equivalent to a semi ***die angle*** α = 60 °. Therefore the ***extrusion pressure*** due to flow through the die is



$$p_d = \sigma_o \left(\frac{1+B}{B} \right) \left(1 - R^B \right)$$

$$B = \mu \cot \alpha = 0.0577$$

$$p_d = 250(18.33)(1-1.174) = 797 MPa$$

, μ **is assumed ~ 0.1**

The ***maximum pressure*** due to ***container wall friction*** will occur at break-through when ***L*** = 380 mm. Aluminium will tend to stick to the container and shear internally.

$$\tau_i \cong k = \frac{\sigma_o}{\sqrt{3}} = \frac{250}{\sqrt{3}} = 144 MPa$$

then

$$p_e = p_d + \frac{4\tau_i L}{D} = 797 + \frac{4(144)(380)}{150} = 2{,}256 MPa$$

finally

$$P = p_e A = 2256 \frac{\pi}{4} (0.15)^2 = 39.9 MN$$

Cold extrusion and cold forming

Cold extrusion is concerned with the cold forming from rod and bar stock of small machine parts, such as spark plug bodies, shafts, pins and hollow cylinders or cans.

Cold forming also includes other processes such as upsetting, expanding and coining.

Precision cold-forming can result in high production of parts with good dimensional control and good surface finish.

DIES FOR EXTRUSION OF HELICAL GROOVES

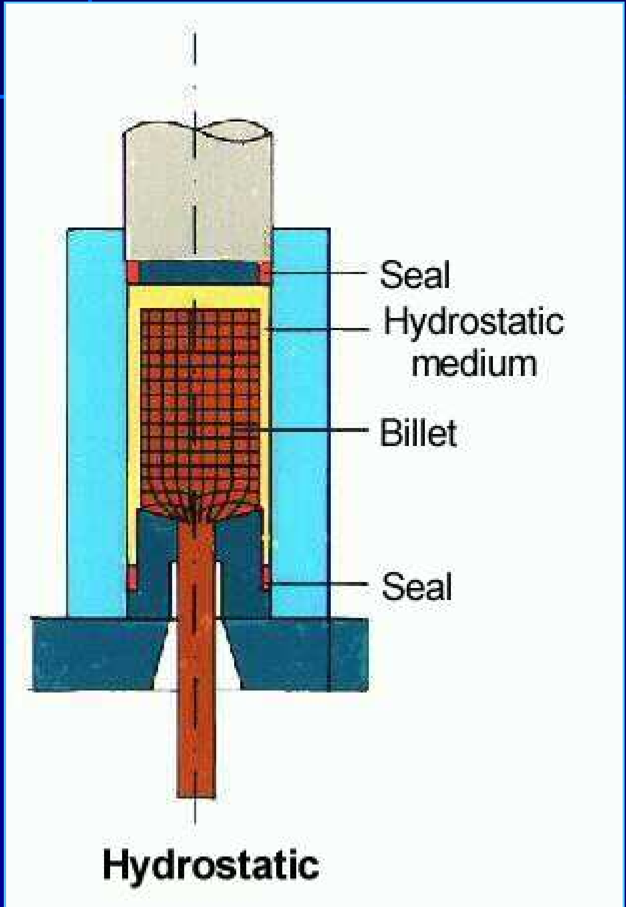
Cold extrusion products

Dies for cold extrusion

• Because of extensive strain hardening, it is often possible to use cheaper materials with lower alloy content.

• The materials should have high resistance to ductile fracture and the design of the tooling to minimise tensile-stress concentrations.

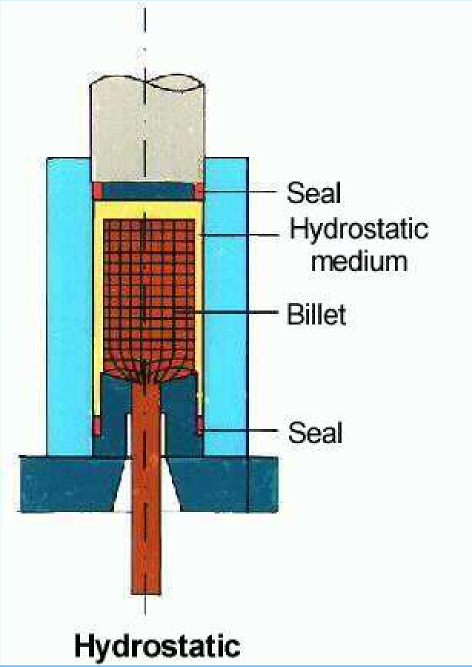
Hydrostatic extrusion



Hydrostatic extrusion

- The billet in the container is surrounded with fluid media, is also called ***hydrostatics medium.***
- The billet is forced through the die by a high hydrostatic fluid pressure.
- The rate, with which the billet moves when pressing in the direction of the die, is thus not equal to the ram speed, but is ***proportional to the displaced hydrostatics medium volume***.
- The billet should may have ***large length-to-diameter ratio*** and may have an irregular cross section.

Advantages and disadvantages in hydrostatic extrusion



Advantages:

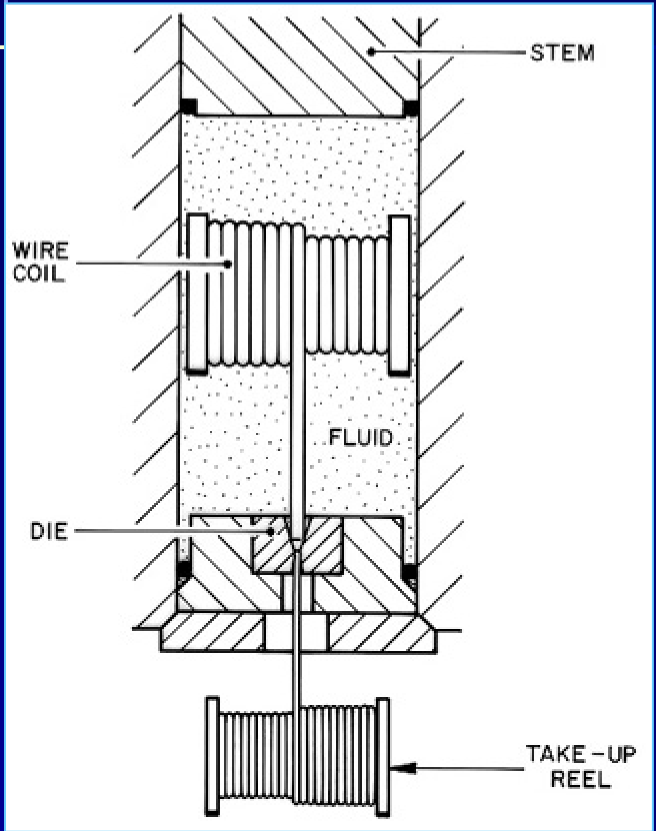
- Eliminating the large ***friction force*** between the billet and the container wall. → extrusion pressure vs ram travel curve is nearly flat.
- Possible to use dies with a very low ***semicone angle*** (α ~ **20 º**)
- Achieving of hydrodynamic lubrication in the die.

Limitations:

- Not suitable for hot-working due to pressurised liquid.
- A practical limit on ***fluid pressure*** of around 1.7 GPa currently exists because of the strength of the container.
- The liquid should not solidify at high pressure → this limits the ***obtainable extrusion ratios,***

Mild steel	***R*** should be less than 20:1
Aluminium	***R*** can achieve up to 200:1.

Augmented hydrostatic extrusion



- Due to the large amount of ***stored energy*** in a ***pressurised liquid***, the control of the extrusion on the exit form die maybe a problem.

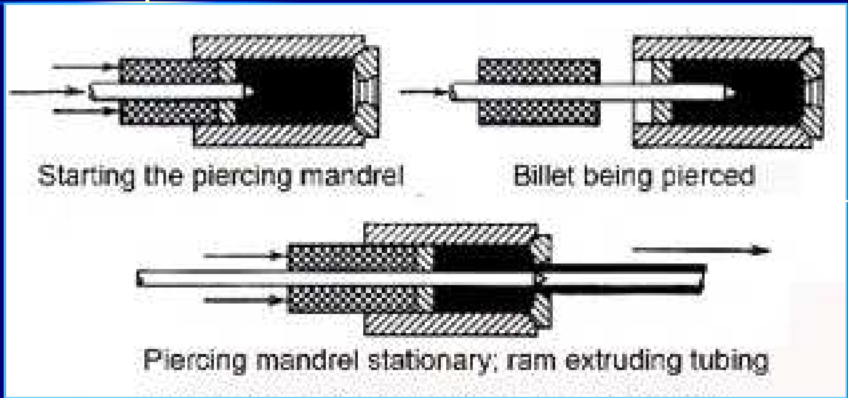
- This is however solved by ***augmented hydrostatic extrusion*** in which the axial force is applied either to the billet or to the extrusion.

- The ***fluid pressure*** is kept at less than the value required to cause extrusion and the balance is provided by the augmenting force → much better control over the movement of the extrusion.

Extrusion of tubing

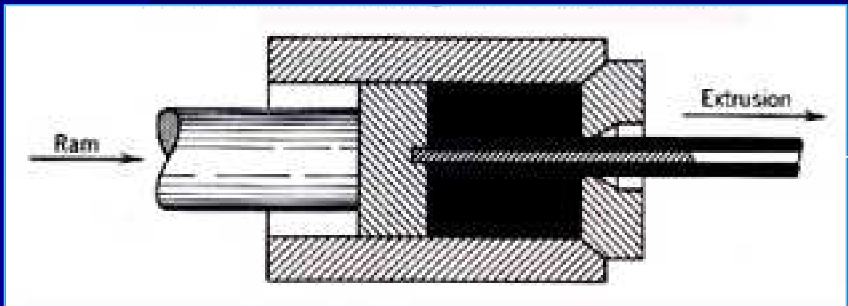
Anodized aluminium extrusions: square tubing.

Extrusion of tubing from a solid billet



• To produce tubing by extrusion from a ***solid billet***, the ram may also be fitted with a ***piercing mandrel***. As the ram moves forward, the metal is forced over the mandrel and through the hole in the die, causing a long hollow tube. *Just like toothpaste, only hollow*.

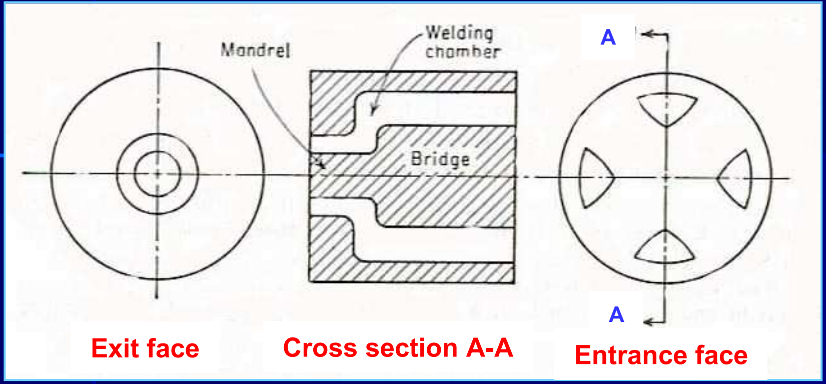
Extrusion of tubing from a hollow billet



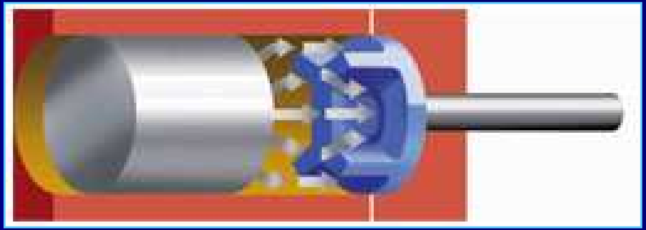
• If the billets are ***hollow***, a rod that matches the diameter of the cast hole in the billet (but slightly smaller than the hole in the die at the opposite end of the chamber) are used.

• Note: the bore of the hole will become ***oxidized*** resulting in a tube with an oxidized inside surface.

Extrusion tubing with a porthole die



A sketch of a porthole extrusion die



Porthole extrusion

Example: pyramid porthole dies

- The metal is forced to flow into separate streams and around the central bridge, which supports a short mandrel.
- The ***separate streams of metal*** which flow through the ports are brought together in a ***welding chamber*** surrounding the mandrel, and the metal exits from the die as a tube.
- Since the separate metal streams are jointed within the die, where there is no atmosphere contamination, a ***perfectly sound weld*** is obtained.
- ***Porthole extrusion*** is used to produce hollow unsymmetrical shapes in aluminium alloys.

Production of seamless pipe and tubing

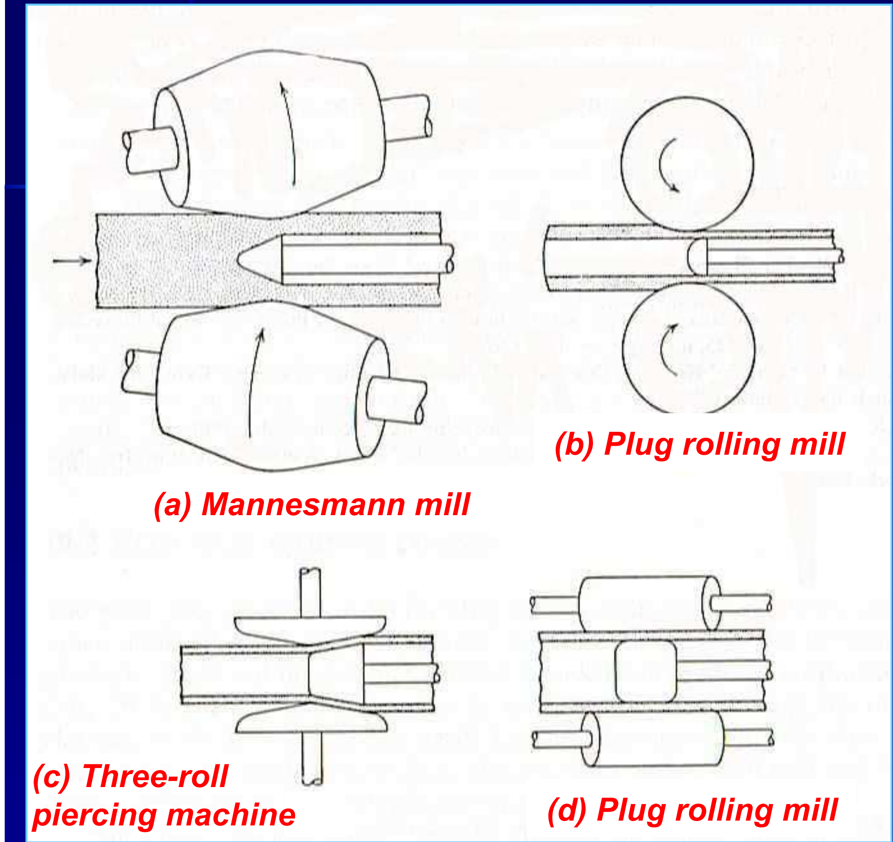
Seamless.exe

See animation

Titanium seamless pipes

Stainless steel seamless pipes

- ***Extrusion*** is suited for producing ***seamless pipe*** and ***tubing***, especially for metals which are difficult to work.
- The ***red-hot billet*** is rotated and drawn by rolls over a ***piercing rod***, or ***mandrel***. The action of the rolls causes the metal to flow over and about the mandrel to create a hollow pipe shell.
- After reheating, the ***shell is moved*** forward over a support bar and is hot-rolled in several reducing/sizing stands to the desired wall thickness and diameter.



Production of seamless pipe and tubing

(a) The ***Mannesmann mill*** is used for the rotary piercing of steel and copper billets using two barrel-shape driven rolls, which are set at an angle to each other. The axial thrust is developed as well as rotation to the billet.

(b) The ***plug rolling mills*** drive the tube over a long mandrel containing a plug.

(c) The ***three-roll piercing machine*** produces more concentric tubes with smoother inside and outside surface.

(d) The ***reeling mill*** burnishes the outside and inside surfaces and removes the slight oval shape, which is usually one of the last steps in the production of pipe or tubing.

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