K. K. College of Engineering and Management

At:-Nairo, Bagsuma, Govindpur, Dhanbad

Course code :-

Subject : **MANUFACTURING PROCESSES I**

Course Objectives :--

To motivate and challenge students to understand and develop an appreciation of the processes in correlation with material properties which change the shape, size and form of the raw materials into the desirable product by conventional or unconventional manufacturing methods.

Course Contents :-

Module-I (5hrs)

Conventional Manufacturing Processes:
Casting and moulding: Metal casting processes and equipment, Heat transfer and solidification, shrinkage, riser design, casting defects and residual stresses.

Module-II (8hrs)

Introduction to bulk and sheet metal forming, plastic deformation and yield criteria.

fundamentals of hot and cold working processes; load estimation for bulk forming (forging, rolling, extrusion, drawing) and sheet forming (shearing, deep drawing, bending) principles of powder metallurgy.
Metal Cutting: Single and multi-point cutting; Orthogonal cutting, various force components: Chip formation, Tool wear and tool life. Surface finish and integrity, Machinability, Cutting tool materials, cutting fluids coating; Turning, Drilling, Milling and finishing processes, Introduction to CNC machining

Module-III (3hrs)

Additive manufacturing: Rapid prototyping and rapid tooling.

Module-IV (3hrs)

Joining/ fastening processes: Physics of welding, brazing and soldering; design considerations in welding. Solid and liquid state joining processes; Adhesive bonding

Module-V (5hrs)

Unconventional Machining Processes:
Abrasive Jet Machining, Water Jet Machining Abrasive Water Jet Machining, Ultrasonic Machining principles and process parameters

Module-VI (8hrs)

Electrical Discharge Machining principle and processes parameters, MRR, surface finish tool wear, dielectric, power and control circuits, wire EDM; Electro-chemical machining (ECM), etchant & maskant, process parameters, MRR and surface finish.

Module-VII (3hrs)

Laser Beam Machining (LBM), Plasma Arc Machining (PAM) and Electron Beam Machining

Books and References:

1. Kalpakjian and Schmid, Manufacturing processes for engineering materials (5th Edition)- Pearson India, 2014.
2. Mikell P. Groover, Fundamentals of Modern Manufacturing: Materials, Processes, and Systems.
3. Manufacturing Technology by P.N. Rao., MCGRAW HILL INDIA.
4. Materials and Manufacturing by Paul Degarmo.
5. Manufacturing Processes by Kaushish, PHI.
6. Principles of Foundry Technology, Jain, MCGRAW HILL INDIA
7. Production Technology by RK Jain.
8. Degarmo, Black &Kohser, Materials and Processes in Manufacturing.

Course Outcomes:

Upon completion of this course, students will be able to understand the different conventional and unconventional manufacturing methods employed for making different products Objectives:

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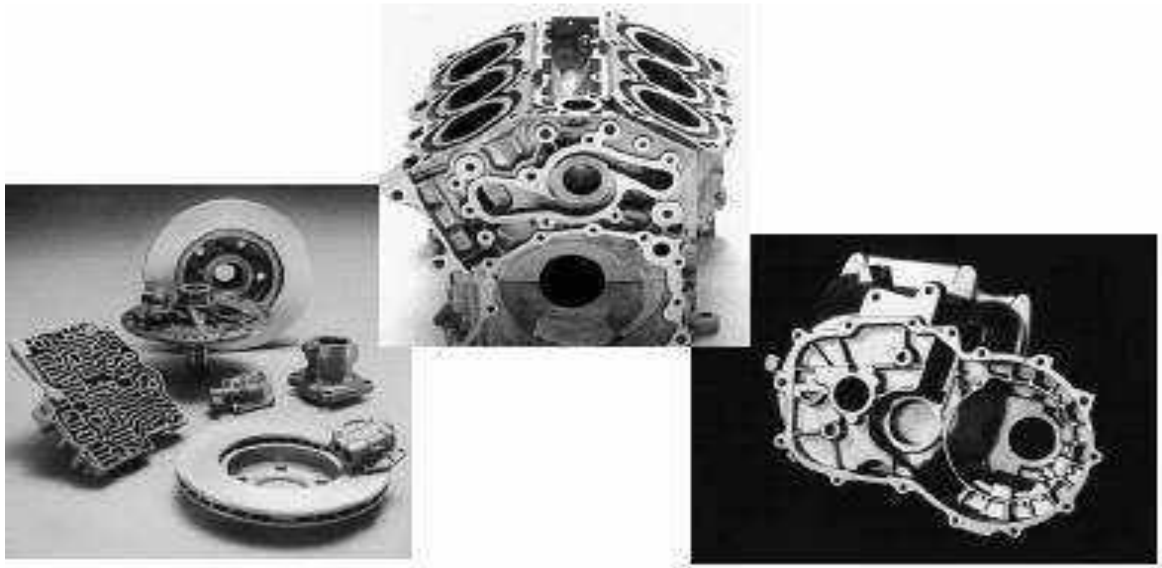
Module 1

Metal casting processes

• Casting is one of the oldest manufacturing process. It is the first step in making most of the products.

• Steps:
- Making mould cavity
- Material is first liquefied by properly heating it in a suitable furnace.
- Liquid is poured into a prepared mould cavity
- allowed to solidify
- product is taken out of the mould cavity, trimmed and made to shape

We should concentrate on the following for successful casting operation:
(i)Preparation of moulds of patterns
(ii)Melting and pouring of the liquefied metal
(iii)Solidification and further cooling to room temperature
(iv)Defects and inspection



Advantages

• Molten material can flow into very small sections so that intricate shapes can be made by this process. As a result, many other operations, such as machining, forging, and welding, can be minimized.

• Possible to cast practically any material: ferrous or non-ferrous.

• The necessary tools required for casting moulds are very simple and inexpensive. As a result, for production of a small lot, it is the ideal process.

• There are certain parts (like turbine blades) made from metals and alloys that can only be processed this way. Turbine blades: Fully casting + last machining.

• Size and weight of the product is not a limitation for the casting process.

Limitations

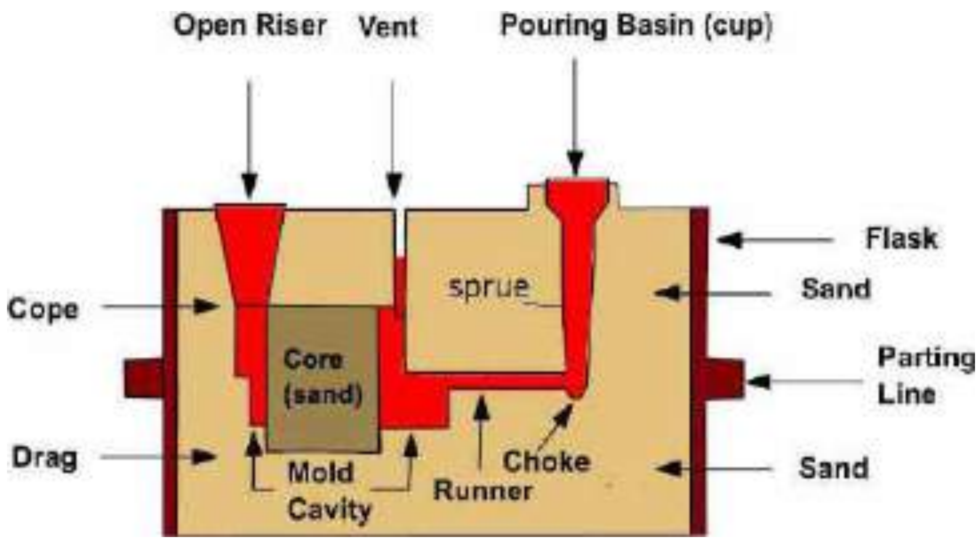
• Dimensional accuracy and surface finish of the castings made by sand casting processes are a limitation to this technique.

• Many new casting processes have been developed which can take into consideration the aspects of dimensional accuracy and surface finish. Some of these processes are die casting process, investment casting process, vacuum-sealed moulding process, and shell moulding process.

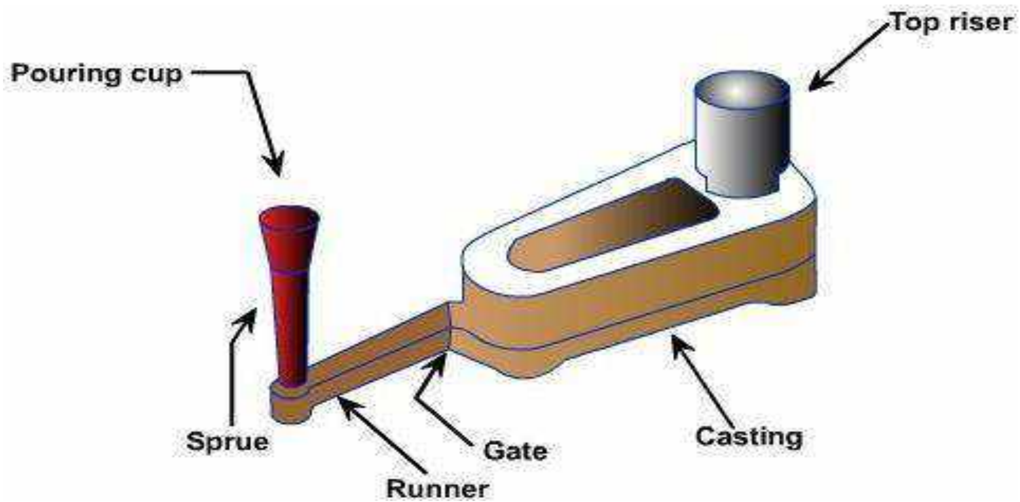
• Metal casting is a labour intensive process

• Automation: a question

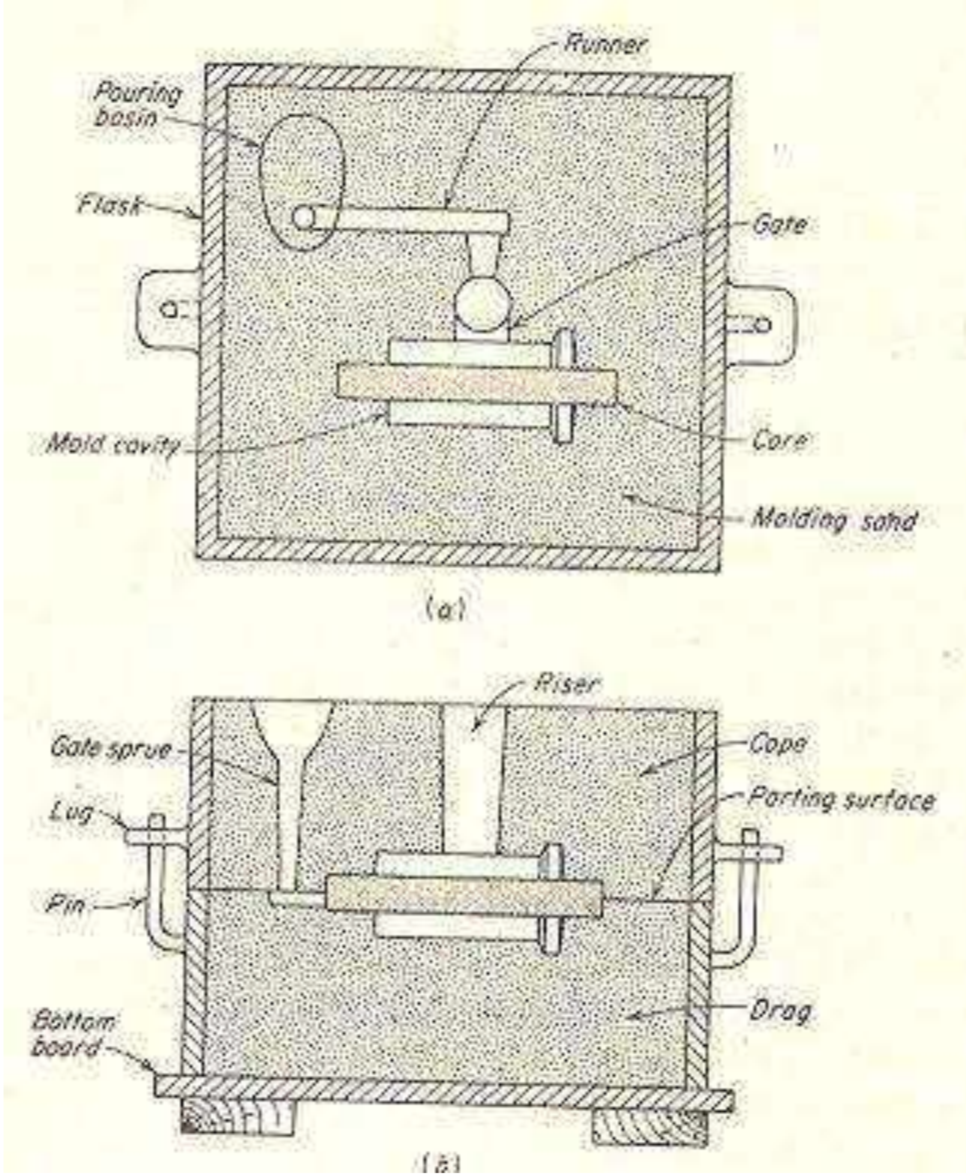
Typical sand mould



Mould Section and casting nomenclature

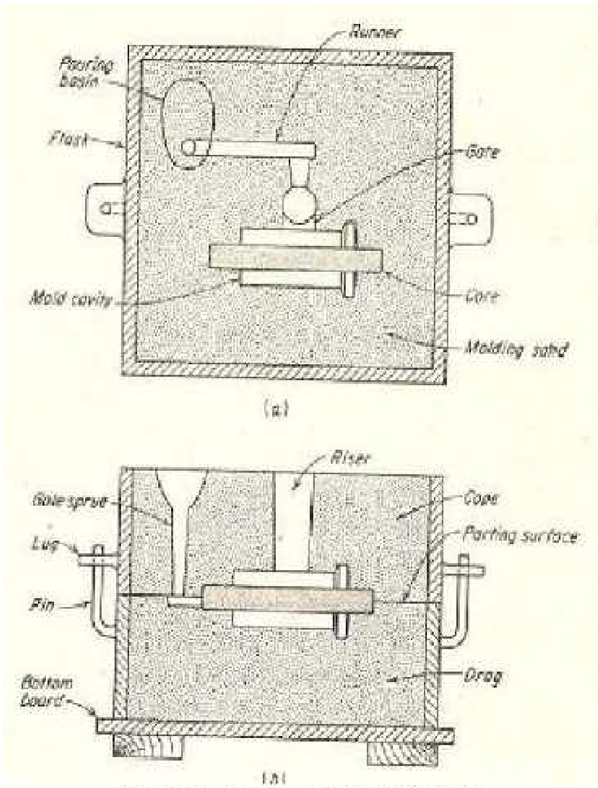


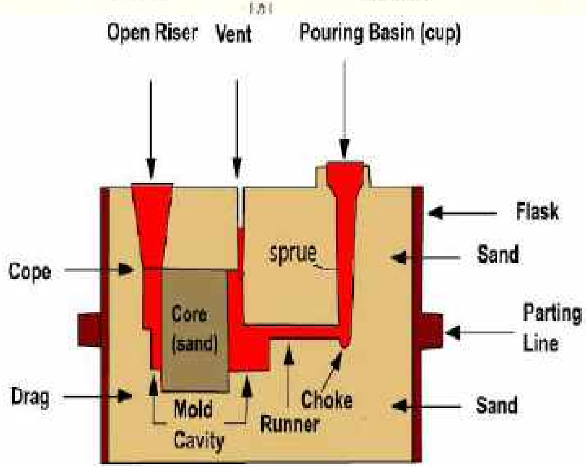
pattern attached with gating and risering system



Mould Section and casting nomenclature, (a) top view, (b) front view

Important casting terms





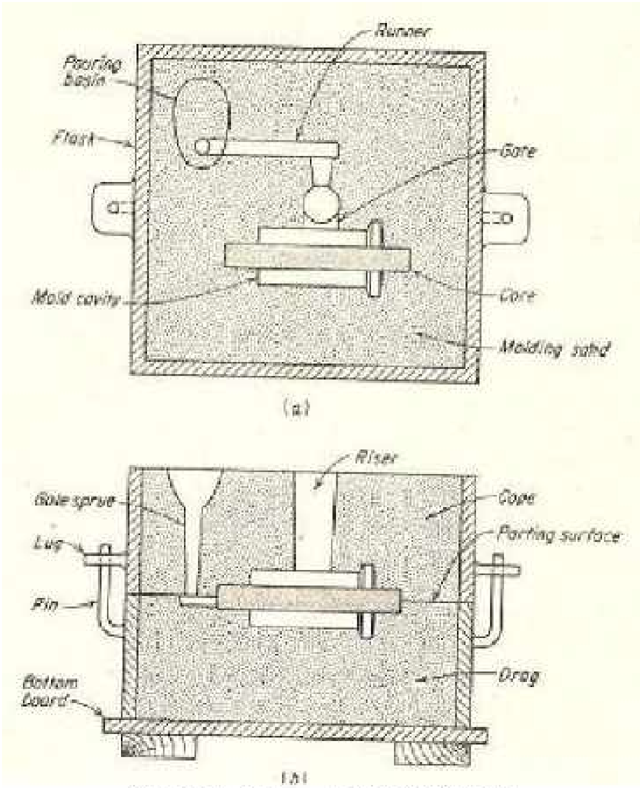
Flask: A metal or wood frame, without fixed top or bottom, in which the mould is formed. Depending upon the position of the flask in the moulding structure, it is referred to by various names such as drag – lower moulding flask, cope – upper moulding flask, cheek – intermediate moulding flask used in three piece moulding.

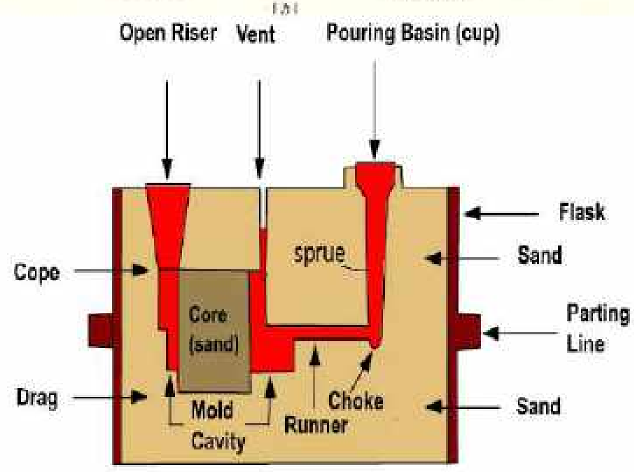
Pattern: It is the replica of the final object to be made. The mould cavity is made with the help of pattern.

Parting line: This is the dividing line between the two moulding flasks that makes up the mould.

Moulding sand: Sand, which binds strongly without losing its permeability to air or gases. It is a mixture of silica sand, clay, and moisture in appropriate proportions.

Facing sand: The small amount of carbonaceous material sprinkled on the inner surface of the mould cavity to give a better surface finish to the castings.





Core: A separate part of the mould, made of sand and generally baked, which is used to create openings and various shaped cavities in the castings.

Pouring basin: A small funnel shaped cavity at the top of the mould into which the molten metal is poured.

Sprue: The passage through which the molten metal, from the pouring basin, reaches the mould cavity. In many cases it controls the flow of metal into the mould.

Runner: The channel through which the molten metal is carried from the sprue to the gate.

Gate: A channel through which the molten metal enters the mould cavity.

Chaplets: Chaplets are used to support the cores inside the mould cavity to take care of its own weight and overcome the metallostatic force.

Riser: A column of molten metal placed in the mould to feed the castings as it shrinks and solidifies. Also known as “feed head”.

Vent: Small opening in the mould to facilitate escape of air and gases.

Steps in making sand castings

The six basic steps in making sand castings are,
(i) Pattern making, (ii) Core making, (iii) Moulding, (iv) Melting and pouring, (v) Cleaning

Pattern making

- Pattern: Replica of the part to be cast and is used to prepare the mould cavity. It is the physical model of the casting used to make the mould. Made of either wood or metal.

-The mould is made by packing some readily formed aggregate material, such as moulding sand, surrounding the pattern. When the pattern is withdrawn, its imprint provides the mould cavity. This cavity is filled with metal to become the casting.

- If the casting is to be hollow, additional patterns called ‘cores’, are used to form these cavities.

Core making

Cores are placed into a mould cavity to form the interior surfaces of castings. Thus the void space is filled with molten metal and eventually becomes the casting.

Moulding

Moulding is nothing but the mould preparation activities for receiving molten metal.
Moulding usually involves: (i) preparing the consolidated sand mould around a pattern held within a supporting metal frame, (ii) removing the pattern to leave the mould cavity with cores.

Mould cavity is the primary cavity.

The mould cavity contains the liquid metal and it acts as a negative of the desired product.

The mould also contains secondary cavities for pouring and channeling the liquid material in to the primary cavity and will act a reservoir, if required.

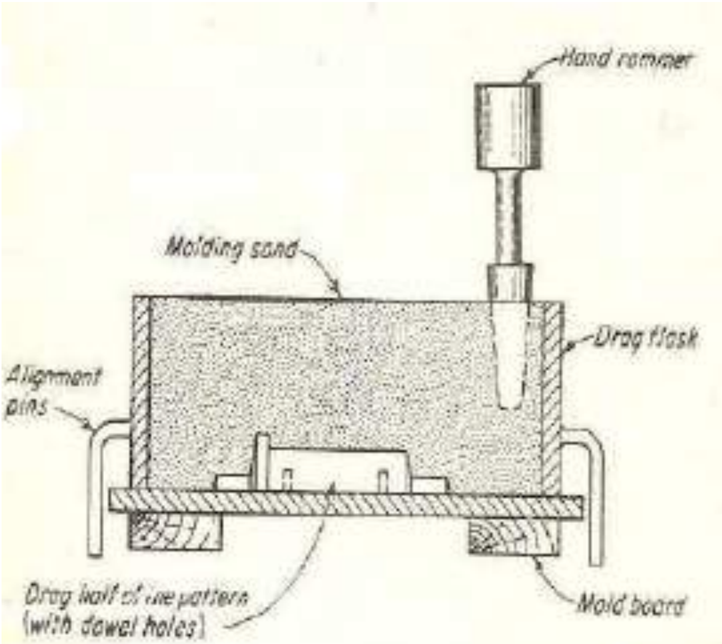
Melting and Pouring

The preparation of molten metal for casting is referred to simply as melting. The molten metal is transferred to the pouring area where the moulds are filled.

Cleaning

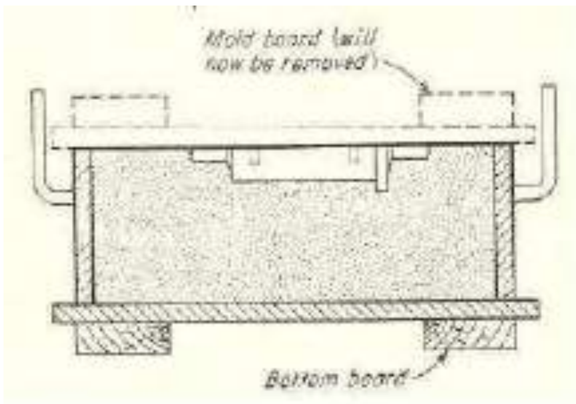
Cleaning involves removal of sand, scale, and excess metal from the casting. Burned-on sand and scale are removed to improved the surface appearance of the casting. Excess metal, in the form of fins, wires, parting line fins, and gates, is removed. Inspection of the casting for defects and general quality is performed.

Making a simple sand mould



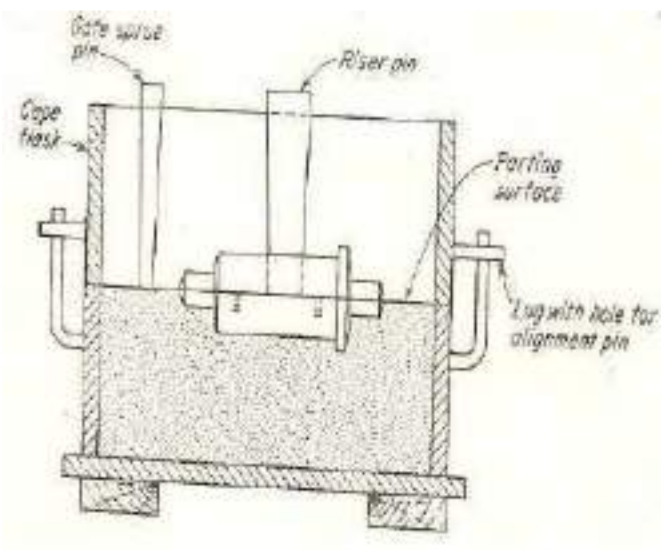
1) The drag flask is placed on the board
2) Dry facing sand is sprinkled over the board
3) Drag half of the pattern is located on the mould board. Dry facing sand will provide a non-sticky layer.
4) Molding sand is then poured in to cover the pattern with the fingers and then the drag is filled completely
5) Sand is then tightly packed in the drag by means of hand rammers. Peen hammers (used first close to drag pattern) and butt hammers (used for surface ramming) are used.

6) The ramming must be proper i.e. it must neither be too hard or soft. Too soft ramming will generate weak mould and imprint of the pattern will not be good. Too hard ramming will not allow gases/air to escape and hence bubbles are created in casting resulting in defects called 'blows'. Moreover, the making of runners and gates will be difficult.
7) After the ramming is finished, the excess sand is leveled/removed with a straight bar known as strike rod.



8) Vent holes are made in the drag to the full depth of the flask as well as to the pattern to facilitate the removal of gases during pouring and solidification. Done by vent rod.

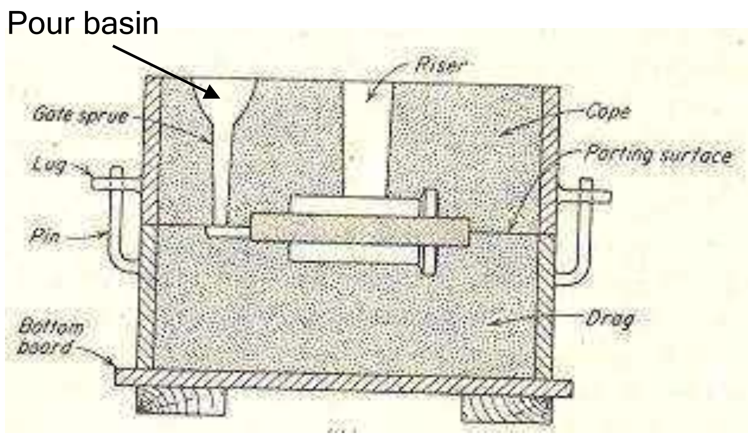
9) The finished drag flask is now made upside down exposing the pattern.



10) Cope half of the pattern is then placed on the drag pattern using locating pins. The cope flask is also located with the help of pins. The dry parting sand is sprinkled all over the drag surface and on the pattern.

11) A sprue pin for making the sprue passage is located at some distance from the pattern edge. Riser pin is placed at an appropriate place.

12) Filling, ramming and venting of the cope is done in the same manner.



13) The sprue and riser are removed and a pouring basin is made at the top to pour the liquid metal.

14) Pattern from the cope and drag is removed.

15) Runners and gates are made by cutting the parting surface with a gate cutter. A gate cutter is a piece of sheet metal bent to the desired radius.

16) The core for making a central hole is now placed into the mould cavity in the drag. Rests in core prints.

17) Mould is now assembled and ready for pouring.

Pattern

The pattern and the part to be made are not same. They differ in the following aspects.

1.A pattern is always made larger than the final part to be made. The excess dimension is known as Pattern allowance.

Pattern allowance => shrinkage allowance, machining allowance

2.Shrinkage allowance: will take care of contractions of a casting which occurs as the metal cools to room temperature.

Liquid Shrinkage: Reduction in volume when the metal changes from liquid state to solid state. Riser which feed the liquid metal to the casting is provided in the mould to compensate for this.
Solid Shrinkage: Reduction in volume caused when metal looses temperature in solid state. Shrinkage allowance is provided on the patterns to account for this.

Shrink rule is used to compensate solid shrinkage depending on the material contraction rate.

Cast iron: One foot (=12 inches) on the **1/8-in-per-foot shrink rule** actually measures 12-1/8 inches.

So, **4 inch** will be **4-1/24 inch** for considering shrinkage allowance.

Shrink rule for other materials

Material	Dimension	Shrinkage allowance (inch/ft)
Grey Cast Iron	Up to 2 feet	0.125
	2 feet to 4 feet	0.105
	over 4 feet	0.083
Cast Steel	Up to 2 feet	0.251
	2 feet to 6 feet	0.191
	over 6 feet	0.155
Aluminum	Up to 4 feet	0.155
	4 feet to 6 feet	0.143
	over 6 feet	0.125
Magnesium	Up to 4 feet	0.173
	Over 4 feet	0.155

2. The shrinkage allowance depends on the coefficient of thermal expansion of the material (**α**). A simple relation indicates that higher the value of ***α***, more is the shrinkage allowance.
3. For a dimension 'l', shrinkage allowance is $\alpha l\,(\theta_f - \theta_0)$. Here θ_f is the freezing temperature and θ_0 is the room temperature.
4. Machining allowance: will take care of the extra material that will be removed to obtain a finished product. In this the rough surface in the cast product will be removed. The machining allowance depends on the size of the casting, material properties, material distortion, finishing accuracy and machining method.

Machining allowances of various metals

Metal	Dimension (inch)	Allowance (inch)
Cast iron	Up to 12	0.12
	12 to 20	0.20
	20 to 40	0.25
Cast steel	Up to 6	0.12
	6 to 20	0.25
	20 to 40	0.30
Non ferrous	Up to 8	0.09
	8 to 12	0.12
	12 to 40	0.16

5. Draft allowance:

All the surfaces parallel to the direction in which the pattern will be removed are tapered slightly inward to facilitate safe removal of the pattern. This is called ‘draft allowance’.

General usage:

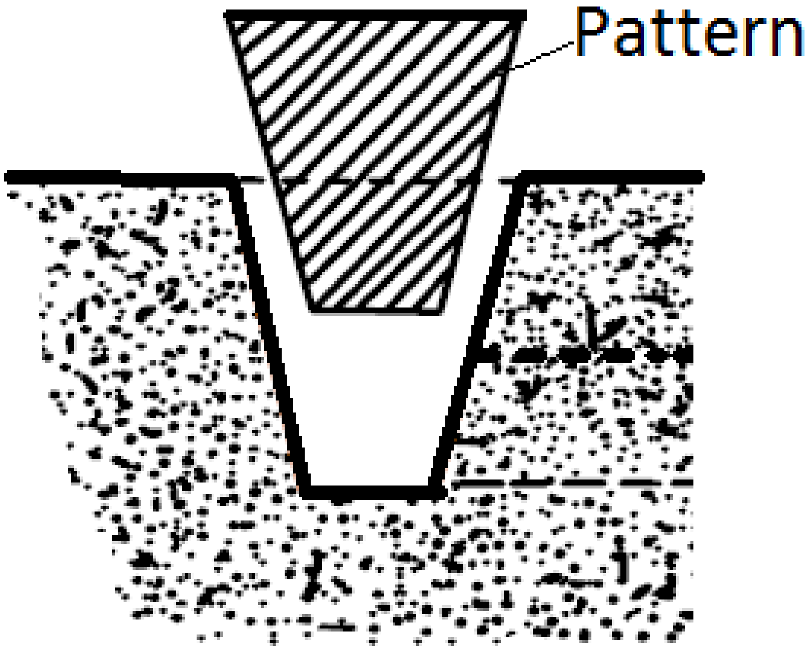
External surfaces ; Internal surfaces, holes, pockets

Typical Draft Allowances

Pattern material	Height of the given surface (inch)	**Draft angle (External surface)**	**Draft angle (Internal surface)**
Wood	1	3.00	3.00
	1 to 2	1.50	2.50
	2 to 4	1.00	1.50
	4 to 8	0.75	1.00
	8 to 32	0.50	1.00
Metal and plastic	1	1.50	3.00
	1 to 2	1.00	2.00
	2 to 4	0.75	1.00
	4 to 8	0.50	1.00
	8 to 32	0.50	0.75

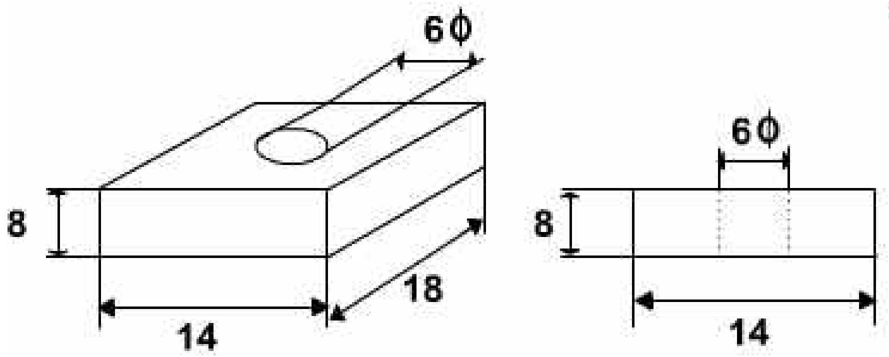
cracks

Pattern having no draft on vertical surfaces



Pattern having draft allowance on vertical surfaces

The casting shown is to be made in CI using a wooden pattern. Assuming only shrinkage allowance, calculate the dimensions of the pattern. All dimensions are in inches



Material	Dimension	Shrinkage allowance (inch/ft)
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	2 feet to 4 feet	0.105
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	4 feet to 6 feet	0.143
	over 6 feet	0.125
Magnesium	Up to 4 feet	0.173
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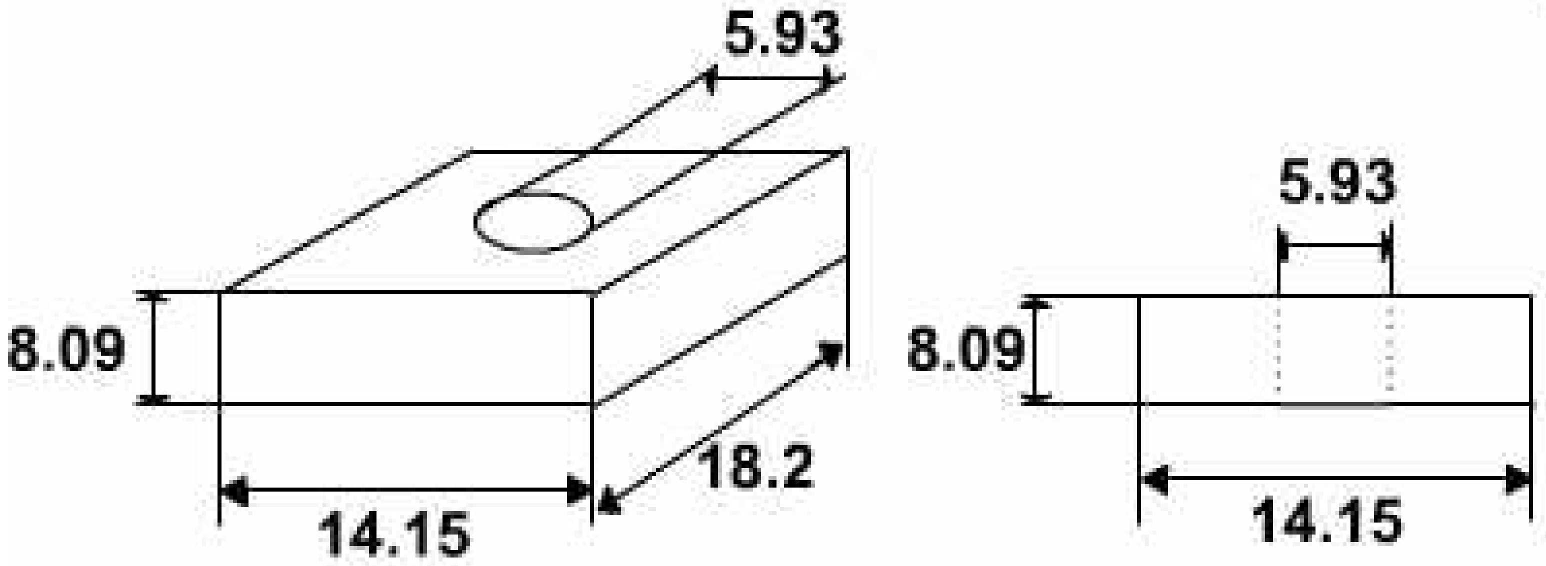
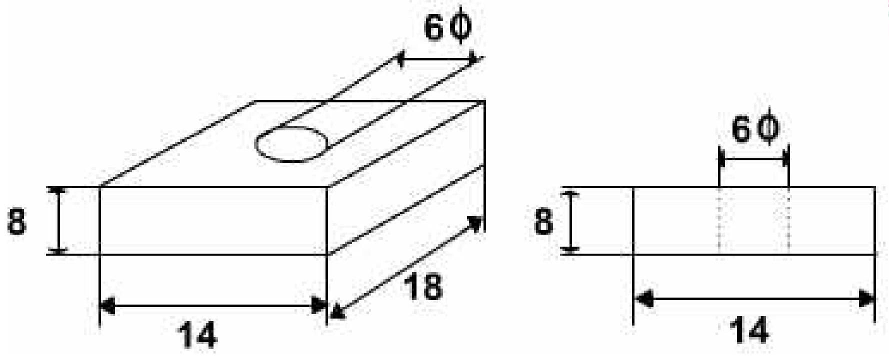
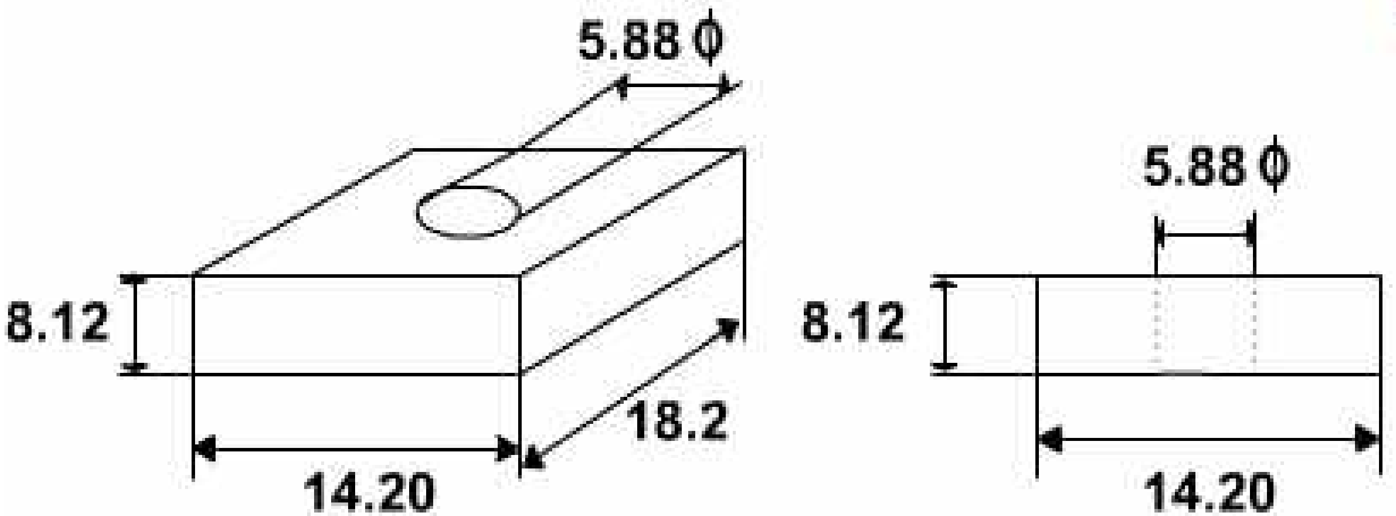

5.93
8.09
18.2
14.15
5.93
8.09
14.15

The casting shown is to be made in CI using a wooden pattern. Assuming only machining allowance, calculate the dimension of the pattern. All dimensions are in Inches



Metal	Dimension (inch)	Allowance (inch)
Cast iron	Up to 12 12 to 20 20 to 40	0.12 0.20 0.25
Cast steel	Up to 6 6 to 20 20 to 40	0.12 0.25 0.30
Non ferrous	Up to 8 8 to 12 12 to 40	0.09 0.12 0.16



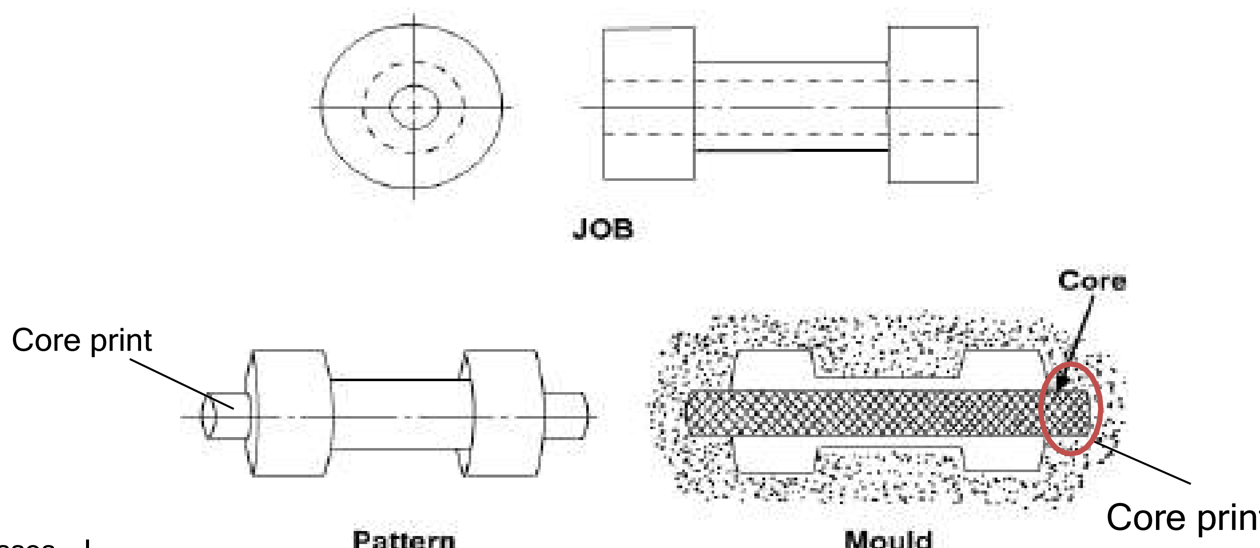
5.88 ϕ
8.12
18.2
14.20
5.88 ϕ
8.12
14.20

6. Core and core print:

- Cores are used to make holes, recesses etc. in castings

- So where coring is required, provision should be made to support the core inside the mould cavity. Core prints are used to serve this purpose. The core print is an added projection on the pattern and it forms a seat in the mould on which the sand core rests during pouring of the mould.

- The core print must be of adequate size and shape so that it can support the weight of the core during the casting operation.

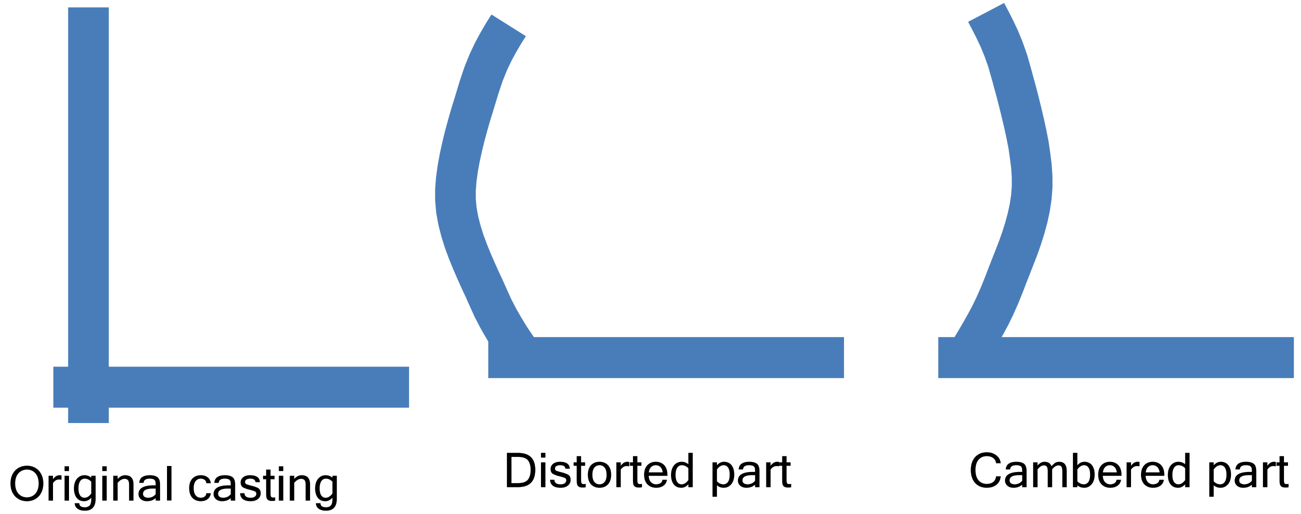


7. Distortion allowance (camber)

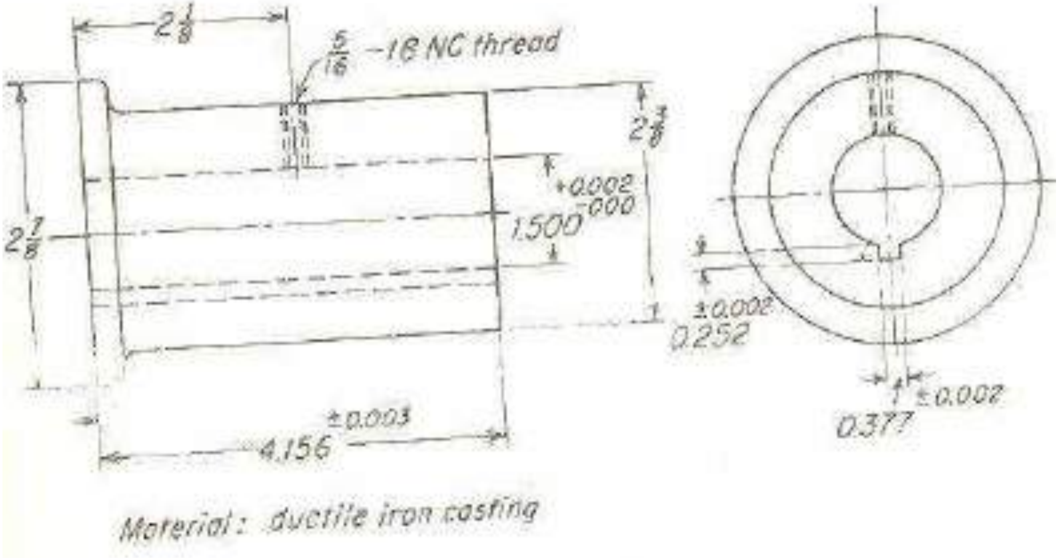
- Vertical edges will be curved or distorted
- This is prevented by shaped pattern converge slightly (inward) so that the casting after distortion will have its sides vertical
- The distortion in casting may occur due to internal stresses. These internal stresses are caused on account of unequal cooling of different sections of the casting and hindered contraction.

Prevention:

- providing sufficient machining allowance to cover the distortion affect
- Providing suitable allowance on the pattern, called camber or distortion allowance (inverse reflection)



8. The tapped hole and slot will not be sand cast. They will be made by machining operations.
9. The pattern shown is made in two halves which are located by dowel pins. This is called ‘split pattern’.
10. Pattern material: wood => light, easily workable, minimum tendency for checking and warping



Pattern materials

- Patterns for sand castings are subjected to considerable wear and tear due to ramming action that is required and the abrasive action of the sand
- Should be impervious to moisture because of changing surroundings
- Made of: wood, metal, plastics, plaster and synthetic materials
- Woods => white pine, sugar pine; The wood should be straight grain, light, easy to work, little tendency to develop crack and warp.
- More durable: Mahogany
- For large castings: metal such as cast iron or aluminium
- When metal pattern are cast from the wooden master pattern, double shrinkage must be provided on the wooden master pattern
- Assume metal pattern is made of aluminium and castings are made of CI, the shrinkage allowance for the wooden master pattern is:

5/32 inch per foot for Al+ 1/8 inch per foot CI = 9/32 inch per foot

Solid shrinkage for cast metals

Material	Dimension	Shrinkage allowance (inch/ft)
Grey Cast Iron	Up to 2 feet	0.125
	2 feet to 4 feet	0.105
	over 4 feet	0.083
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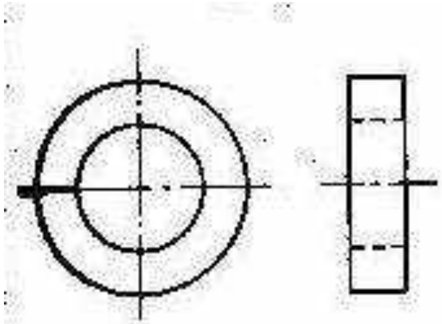
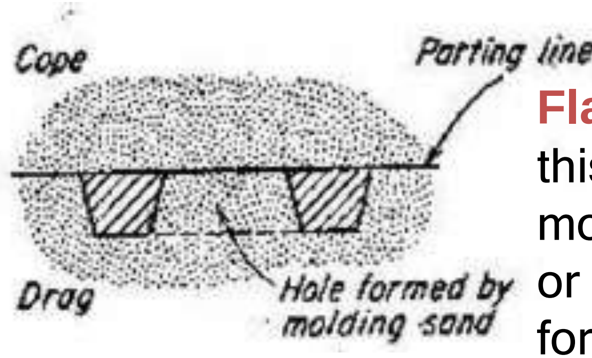
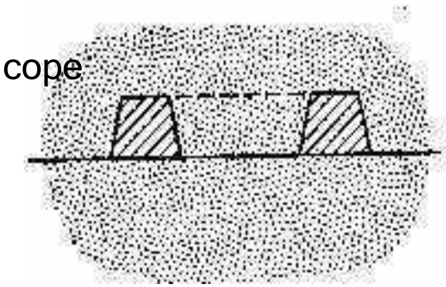
Different ways for making a casting mold

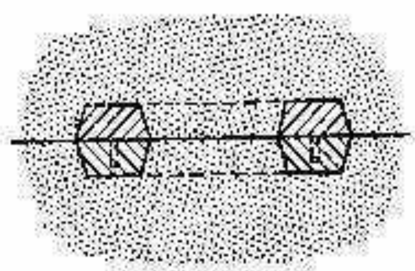


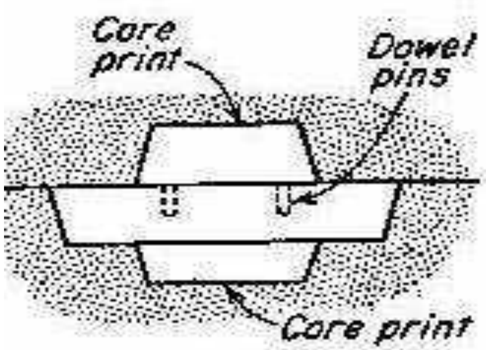
Simple bushing:
Sand casting to be molded

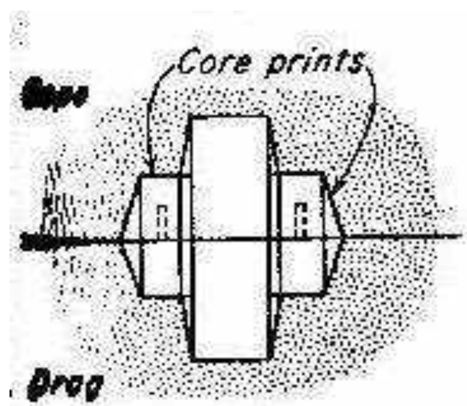


Flat back pattern can be used for this. In this after completing, the mold cavity is either in the drag side or in cope side or in both. The hole is formed by the molding sand.
The outside edge around the flat back is the parting line and it is the starting place for draft.
This is the simplest and easiest method.





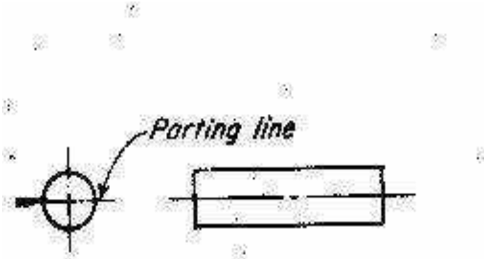




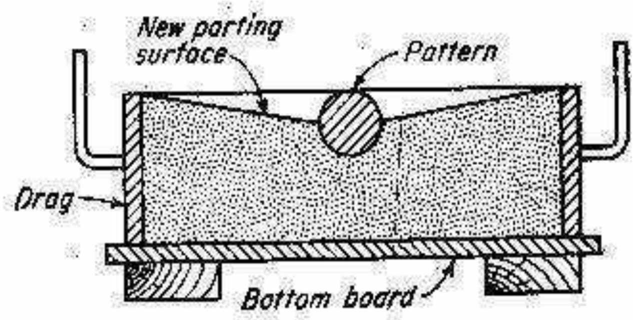
Using a dry sand core to obtain the core and this is split pattern. The axis of the hole (and core print) is vertical in first case.

The second case is same as first, except that the hole axis is horizontal.

J S Campbell, *Principles Of Manufacturing Materials And Processes*

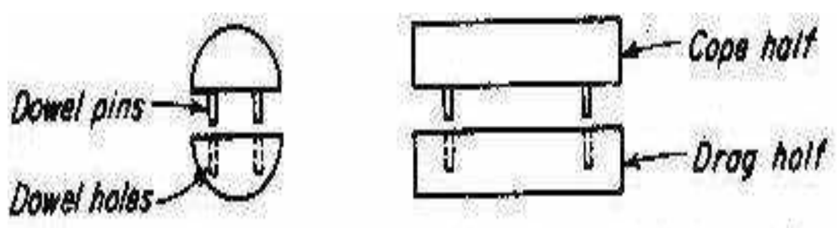


solid cylindrical pattern



Consider a solid cylindrical pattern as shown above. The pattern is placed on the molding board, rammed and rolled over. In order to withdraw the pattern from the sand, some of the sand is removed and smoothened as shown. This creates a new parting surface. Thus a parting line is made which joins parting line around the pattern. The operation of removing the sand and making a new parting surface is called 'Coping down'.

The mold is completed by ramming up the cope in a usual manner.

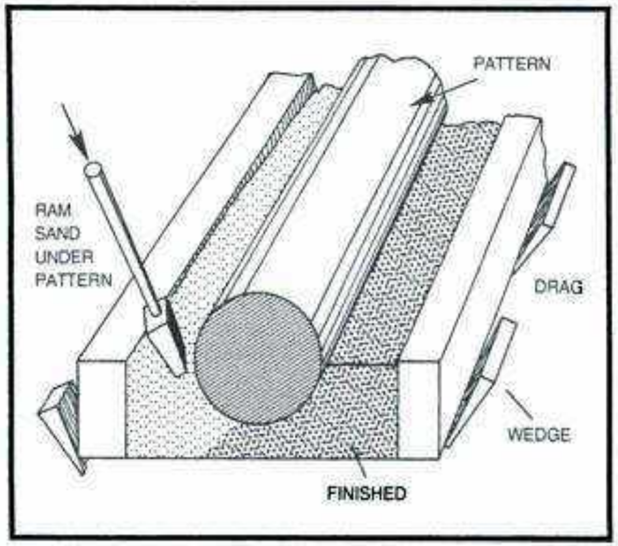


Split pattern for molding cylindrical casting

Other methods:

- cylindrical pattern standing on the end, if it were not too long
- cylindrical pattern can be molded using split pattern/mold also as shown in above figure.

Bedding-in method

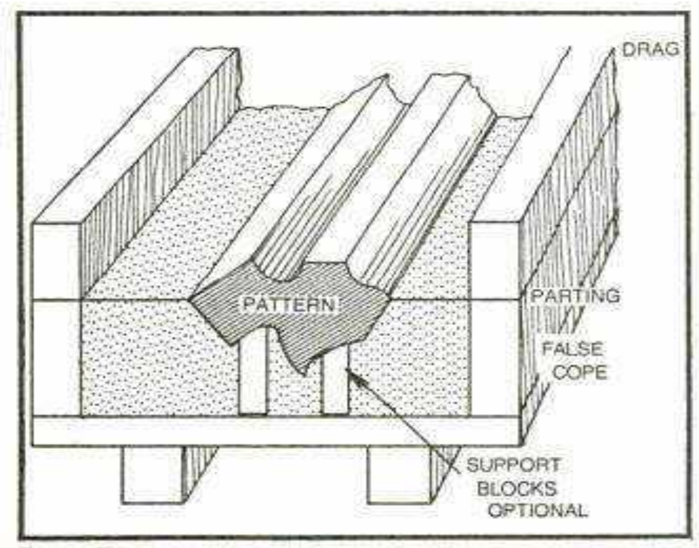


A complete handbook of sand casting, C.W. Ammen

- The solid cylindrical pattern can also be molded using 'bedding-in method'.
- In this method, first the drag is partially filled with molding sand and rammed.
- After sufficient ramming, the pattern is pressed into the sand. In this, to have proper ramming of sand, the sand close to the pattern is tucked and rammed tightly.
- Sometimes, the pattern is removed and the sand is surface tested for soft spots. In case of soft spots, ramming is continued with additional sand till the sand is packed tightly.

- The pattern is again pressed downwards to have a properly rammed mold cavity.
- Bedding-in is done so that the parting line is about level with the surrounding flat sand surface.
- Whenever a pattern is bedded-in, the drag need not be rolled over.
- Bedding-in can be employed for making larger molds using pit molding

False cope (sometimes called ‘odd side’)



A complete handbook of sand casting, C.W. Ammen

False cope technique is another method of molding the solid cylindrical pattern.

This is similar to bedding-in method, except that it is not required to ram the sand tightly under the pattern, or the pattern shape is such that it is not possible to ram the sand tightly.

The pattern is first bedded into the cope without giving importance to the ramming of sand beneath the pattern and a smooth parting surface is made.

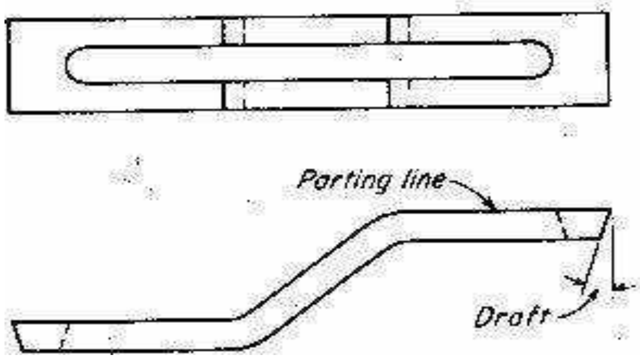
The cope and pattern is then dusted with parting sand and drag part of flask is placed on top of the cope. Ramming is then completed in a usual manner.

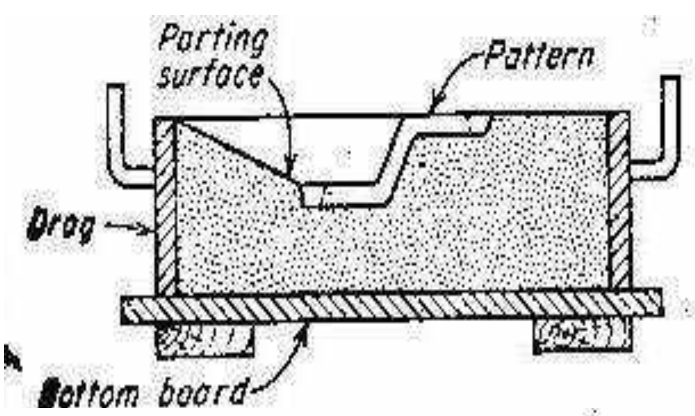
The entire assembly is clamped and rolled over on a sand bed. The clamps are removed and the cope, cope bottom board are removed and destroyed.

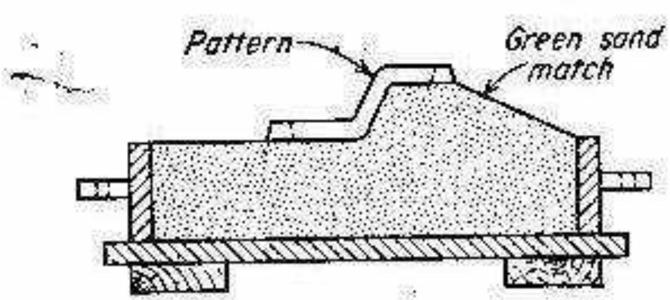
The empty cope is then placed on the drag and usual ramming is performed.

It should be observed that the cope, first used, is a dummy block for creating the drag correctly. This is called ‘FALSE COPE’.

Green sand match







Green sand match ready for further drag making

The main reason for making a green sand match is that the coping down operations can be reduced to a greater extent, reducing the costs and time.

Take an example like a pattern with a parting line not lying in one plane (shown in first figure).

This pattern should be supported on a moldboard at the elevated end by a wood piece.

Once the ramming, rolling over and coping down are completed, the drag will look like as shown in second figure.

On top of this drag, a green sand match may be rammed up extra hard without sprue and riser pins.

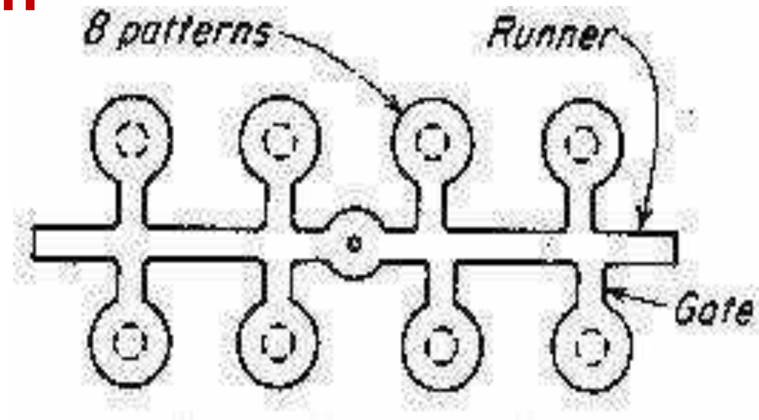
The completed **green sand match** with pattern in place is shown in last figure.

The sand match is now retained with the uneven parting surface to support pattern and for further making of rammed drags.

Also called hard sand match, POP match, cement match

J S Campbell, *Principles Of Manufacturing Materials And Processes*

Gated pattern



Gated pattern for making eight small patterns

In this, the gate is made part of the pattern.

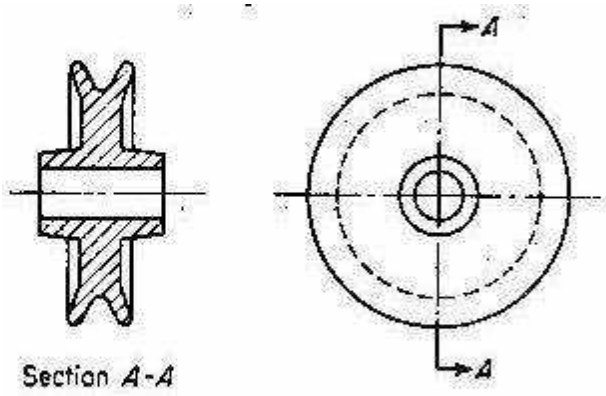
In general, a gated pattern consists of many small patterns fastened together through gating.

Since gates, runners are part of the pattern, time and cost are not spent in making them separately.

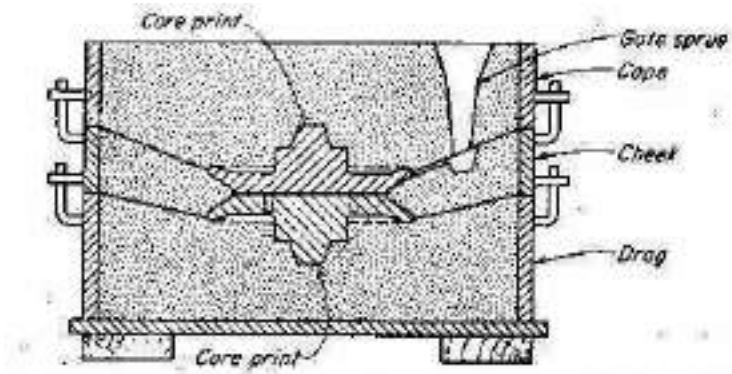
A number of patterns are rapped and drawn from the mold at the same time, saving additional time.

J S Campbell, *Principles Of Manufacturing Materials And Processes*

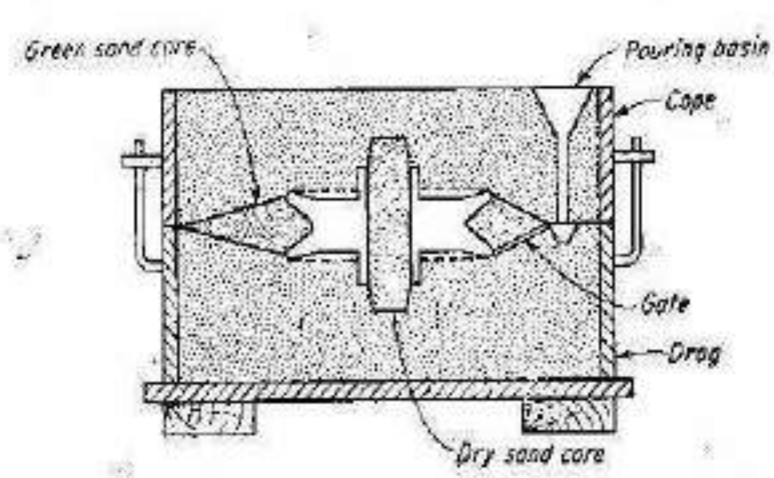
Patterns requiring two or more parting surfaces



Sheave wheel to be molded



Three part mold for sheave wheel casting



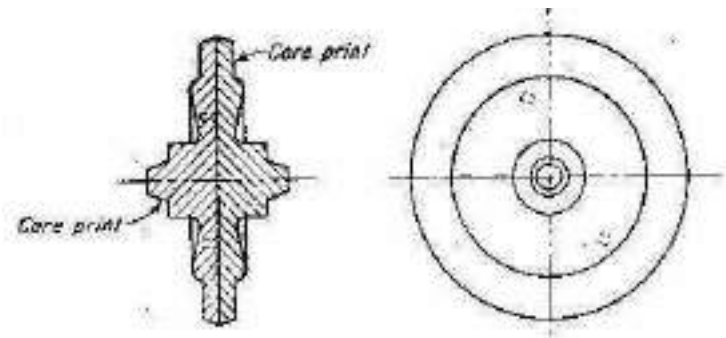
Using green sand core for making sheave wheel casting

- First method of making a sheave wheel mold is through three part flask, having a middle flask region called ‘cheek’.

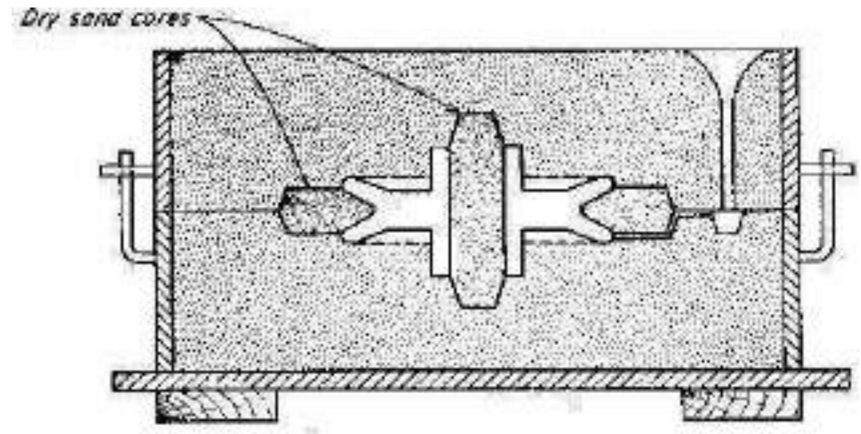
- another way is by using special green sand core.

J S Campbell, *Principles Of Manufacturing Materials And Processes*

Cores for exterior casting surfaces



Pattern for making a sheave wheel casting using a dry sand core for groove making



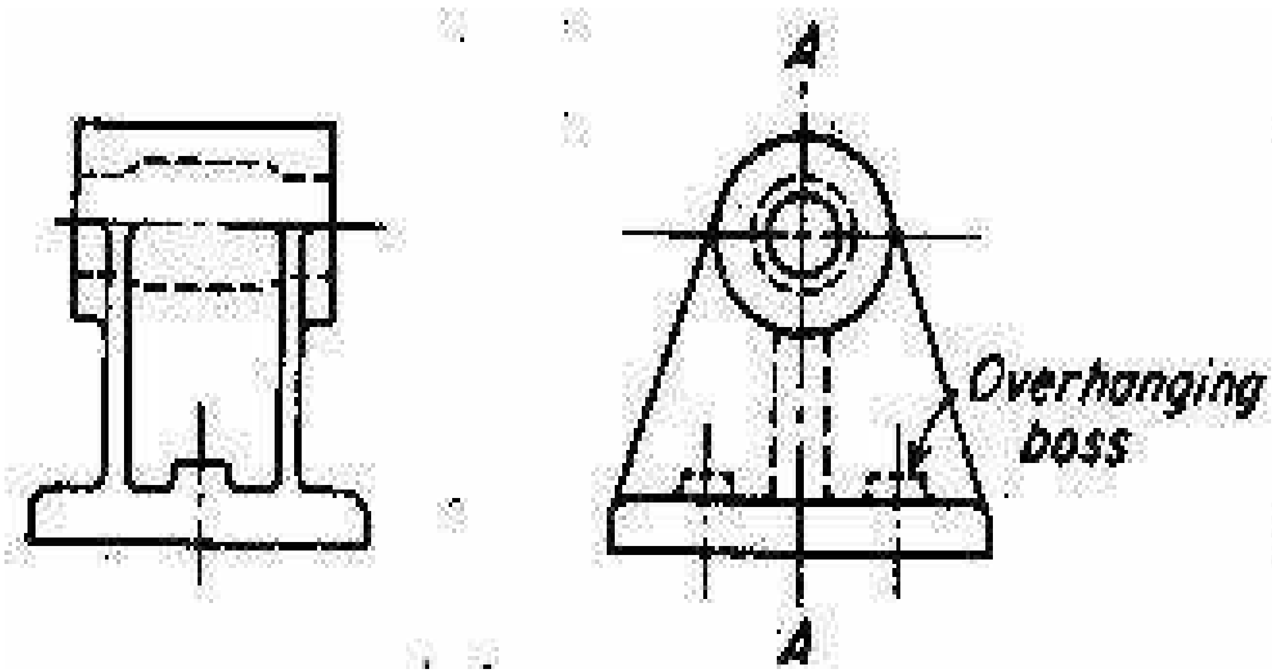
Mold with dry sand cores for making a sheave wheel casting

- Dry sand cores can be used for making the grooves

- Usage of core box is required for making core which makes this method not suitable below certain quantity

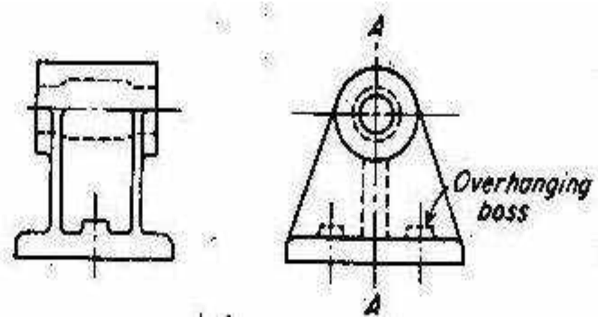
- For large quantity, this method is preferred

 J S Campbell, *Principles Of Manufacturing Materials And Processes*

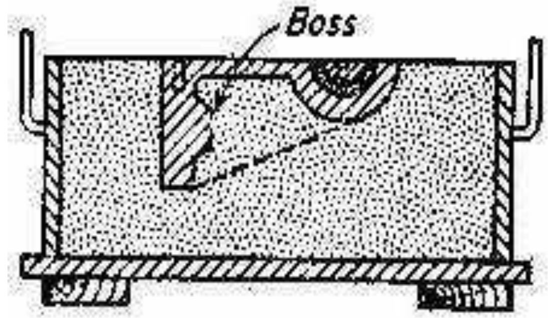


Bearing frame casting having overhanging bosses

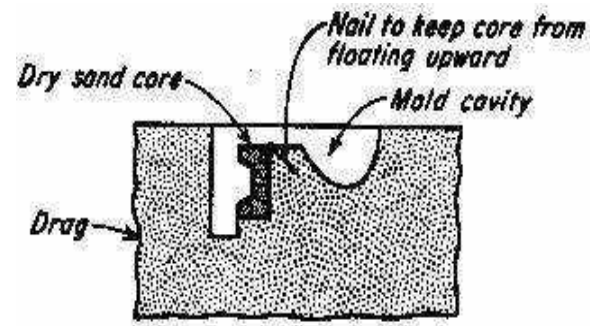
Cores for exterior casting surfaces



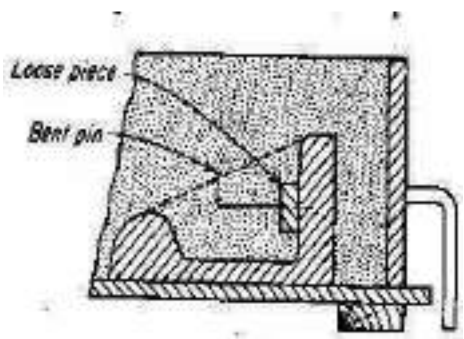
Bearing frame casting having overhanging bosses



Drag showing half of the pattern rammed up in the molding sand



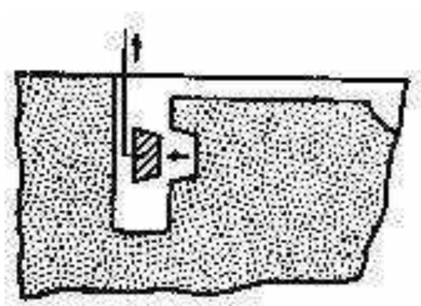
Using **a dry sand core** held using a nail to produce a boss



Using a dry core sand:

- The over-hanging bosses are made using core prints, dry sand core in place

-The dry sand core part is held in mold by using a nail to keep the core from floating upward. Chaplets can also be used (described later).

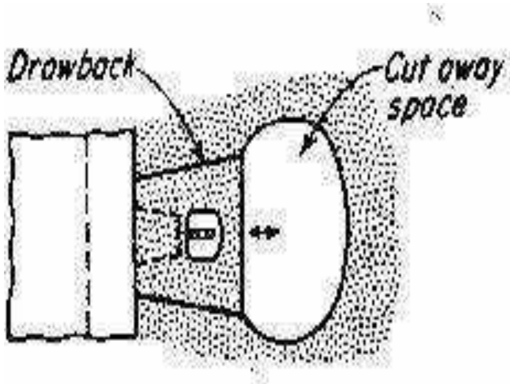


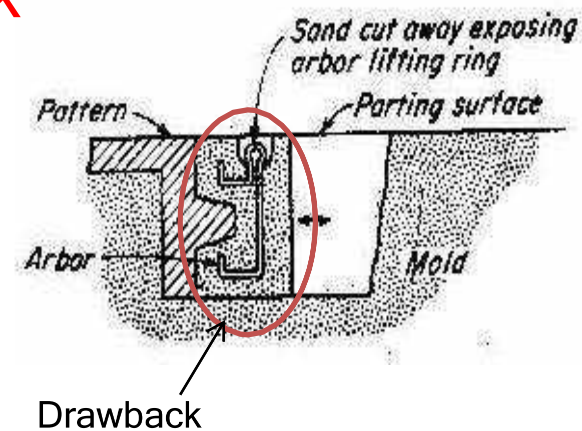
Using a loose piece

Using a loose piece:

- A loose piece is held by using a bent pin
- Ramming is done properly around the loose piece. Later pattern and pin are withdrawn carefully as shown.
- **Disadvantage:** shifting of loose piece while ramming
- Loose pieces are used in core boxes for making cores with backdraft (horizontal depression or projection)

Using Drawback





Drawback is employed for patterns with backdrafts (horizontal depression or projection).

A drawback consists of mold that can be drawn back in order to remove the pattern.

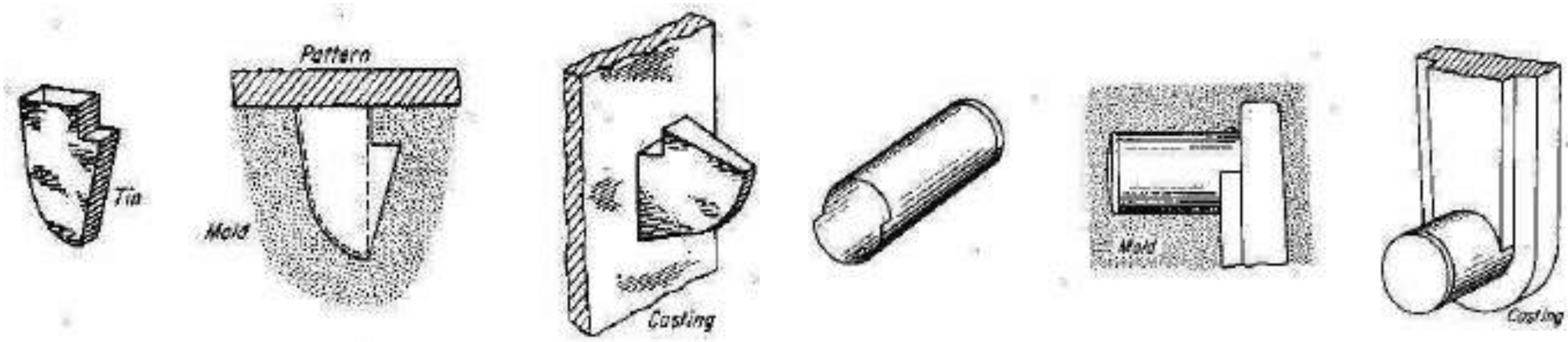
As shown in figure, a drawback is rammed around a rigid support called **'arbor'** that is used to move it.

Drawback is like a green sand core rammed up against the mold instead of making it in core box.

Once the pattern is removed, the drawback is located in the original place. It is backed up with additional sand so that it will not displace during fluid filling.

It is also used for large molds for certain castings.

Tins



• Tins are made of sheet metal shapes that are used with patterns to make certain internal and external shapes, but at the same time patterns can be removed from the mold cavity

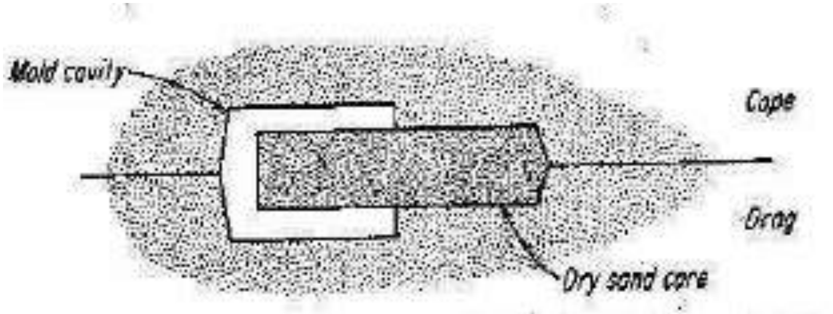
• They are thin hollow sheet metal shells that are attached to pattern before the pattern in rammed up in sand

• When the pattern is withdrawn, they remain in mold and should fuse into the casting

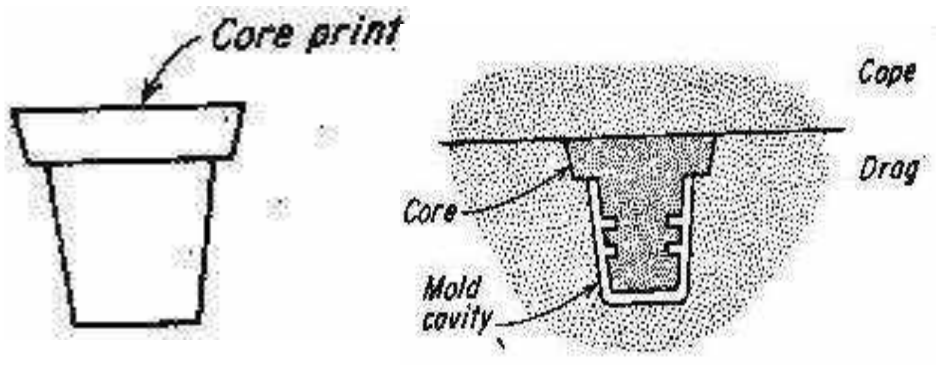
• For ferrous castings, a tin plated sheet steel of about 0.012 inch thick is used

J S Campbell, *Principles Of Manufacturing Materials And Processes*

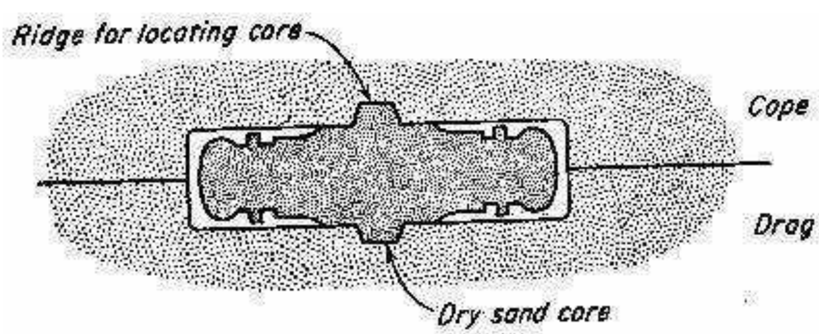
Core and core print



Where a core does not extend entirely through the casting, it should be fixed/balanced properly as shown. Too long cores can not be balanced properly.

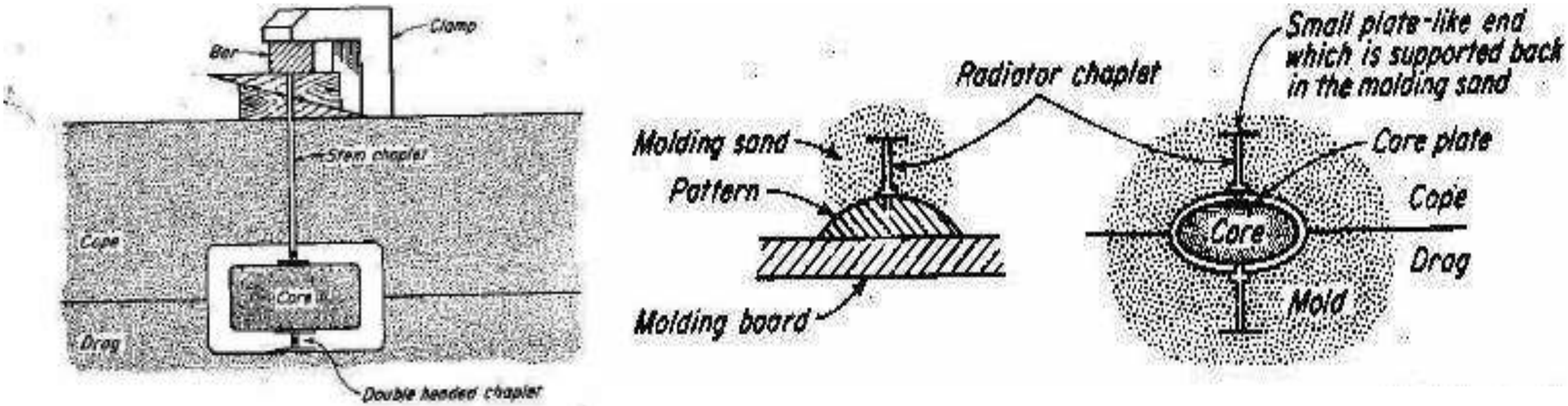


A pattern with a hanging core print is shown for making a piston. The core in the mold acts as a cover for mold cavity and hence cope is not needed.



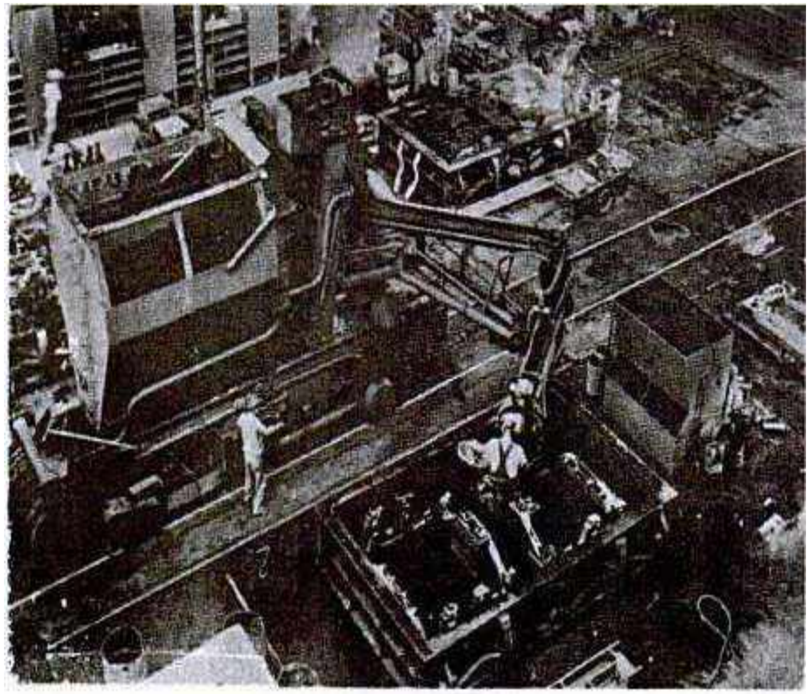
A method for molding two pistons at a time having one balanced core.

Using chaplets



- Chaplets are used to support a core and are placed between a core and the mold wall.
- As the mold is filled with molten metal, the chaplet prevents the core to float and move upwards dislocating from its position.
- The part of chaplet in mold will be fused into the casting.
- chaplets not fused properly will create mechanical weakness and mold wall leak.
- They are generally made heavier rather than lighter, such that they seldom unite with the surrounding metal.
- Tin or copper plated chaplets are used for ferrous castings to avoid rusting.
- <u>Radiator chaplets</u> having a flat square ends are fixed in the pattern itself and will provide good support to core along with rammed sand.

Ramming a large mold



- First few inches of sand over the pattern should be carefully rammed and tightly packed.
- soft spots, packets should be rammed properly
- Large mold of considerable depth should be rammed layer by layer
- Floor rammers that are heavy and measure up to 5 feet long can be used. The molder will stand on the rammed sand.
- Nowadays pneumatic rammer is operated by compressed air with a butt shaped end
- Ramming should be done as close to vertical surfaces of pattern

Pit molding

Pit mold for diesel engine

• Large castings are made in pits in foundry floor. Reinforced concrete is used to make sides and bottom of pits.

• a bed of charcoal is used at the bottom of a pit to aid the escape of gases.

• bedding-in technique may be used since rolling over of drag is not possible.

• appropriate placing of pattern is done.

• several cores can be used for making delicate shapes.

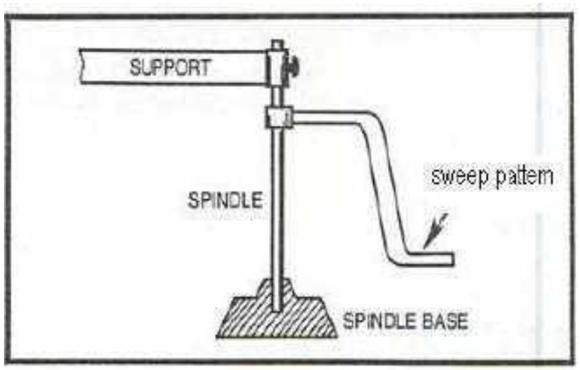
• Pit molding may take few days to weeks for completion, and hence binders are added to the molding sand which harden when air-dried.

• sometimes, the mold cavity is heated to harden with time, by placing a stove down into the mold cavity and covering the entire mold to keep the heat inside the cavity.

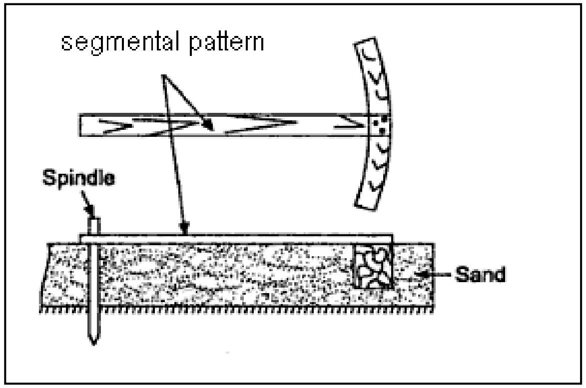
• slow cooling of molten metal is allowed so that the internal stresses can be minimized.

Low cost patterns for large molding

Meant for large, but few, castings: sweep, segmental pattern, partial pattern, skeleton pattern



Sweep pattern: A sweep pattern consists of a board having a profile of the desired mold, which is revolved around a spindle or guide produces the mold. Two are used – one for sweeping the cope and other for drag.

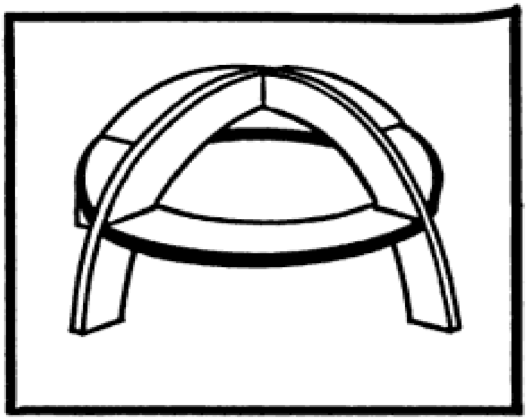


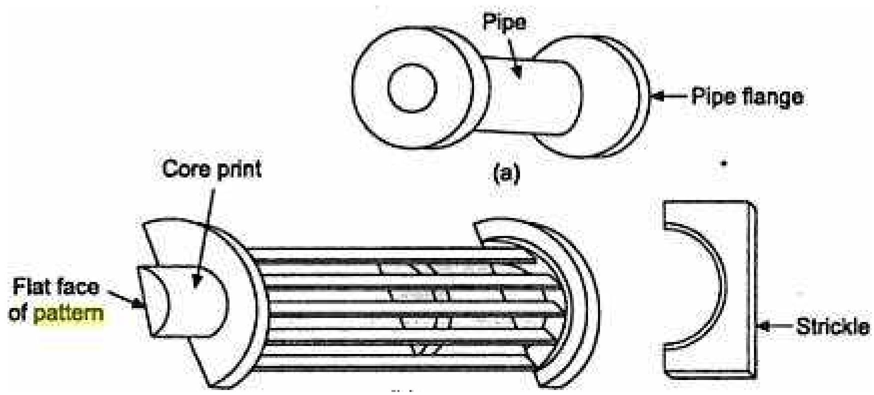
Segmental pattern: meant for circular ring shaped large sections. Instead of using a full pattern, part pattern is used. Once molding is done at one place, it is rotated to the adjacent region and molding is done.

Manufacturing Processes, By Kaushish

A complete handbook of sand casting, C.W. Ammen

Skeleton pattern:





Manufacturing Processes, By Kaushish

This consists of frame of wood representing the interior and exterior forms. Strickles (like strike off bars) are used to remove excess sand which is purposely rammed with extra thickness than required for desired mold surfaces

Loam molding: Loam consists of 50% clay as compared to ordinary molding sand. Mixed consistently to resemble mortar. Loam is applied on the surface of the brick framework. The molds are dried in ovens before put into use.

This was used for making casting bells for cathedrals or cannons for war in 13th century

Ingredients used in sand for making molds/cores

Refractory sand grains	Binder	Facing material	Cushion
Silica Zircon (has chilling properties) Olivine Magnesite Dolomite Sillimanite Carbon Coke	For bonding materials see next table *Note:* Clay required with practically all binders.	Sea coal Pitch (dry powder) Graphite Coke Silica flour	Wood flour Cereal hulls Cereal Cellulose Sea coal Coke Perlite (a siliceous lava, quick heating causes bubbles of steam, also has insulating properties)

J S Campbell, *Principles Of Manufacturing Materials And Processes*

Binders Used in Sand Casting for Molds, Cores

Clays:

Fire clay (kaolinite)

Southern bentonite (calcium montmorillonite)

Western bentonite (sodium montmorillonite)

Secondary mica clays (illite)

Oils:*

Vegetables (e.g. linseed oil)

Marine animal (e.g., whale oil)

Mineral (used for diluting oils given above)

Synthetic resins, thermosetting:*‡

Urea formaldehyde

Phenol Formaldehyde

Cereal binders made from corn:*

Gelatinized starch (made by wet milling, contains starch and gluten)

Gelatinized corn flour (made by dry-milling hominy)

Dextrin (made from starch, a water-soluble sugar)

Wood –product binders:*‡

Natural resin (e.g., rosin, thermoplastic)

Sulfite binders (contain lignin, produced in the paper pulp process)

Water-soluble gums, resins, and organic chemicals

Protein binders (containing nitrogen):*

Glue

Casien

Other binders:

Portland cement†

Pitch (a coal-tar product)*†

Molasses (usually applied in water as a spray)

Cements (e.g., rubber cement)†

Sodium silicate (water glass, CO_2 hardening binders)†

* Harden by baking.

† Harden at room temperature.

‡ Available as either a liquid or a dry powder.

Natural and Synthetic molding sand

Natural molding sand:

This is ready for use as it is dug from the ground. Good natural molding sand are obtained from Albany, New york etc.

The following average compositions are seen in natural molding sand:
65.5% silica grains, 21.7% clay content, 12.8% undesirable impurities.

Too much clay content and other impurities fill up the gaps between the sand grains. This will hinder the necessary passage of steam and other gases during pouring of the mold.

Synthetic molding sand

Synthetic molding sand is made by mixing together specially selected high quality clay free silica, with about 5% of clay. They are tailor made to give most desirable results.

Some of the advantages of synthetic molding sand are:

1. Refractory grain sizes are more uniform, 2. Higher refractoriness (= 3000^{o}F), 3. less bonding agent is required (about 1/3rd of the clay percentage found in natural molding sand), 4. More suitable for use with mechanical equipment

Advantages of natural molding sand: 1. moisture content range is wide, 2. molds can be repaired easily

Core making

• Generally Cores are used for making interior surfaces of hollow castings and now-a-days it is used for making exterior surfaces and for other purposes.

• Green sand cores contain ordinary molding sand and dry sand core contains hardened or baked sand.

• Core mix contains clay free silica sand. This is suitably mixed with binders, water and other ingredients to produce a core mix.

• Synthetic core binders have some unusual properties like shorter baking times and excellent collapsibilities which reduces the defect castings.

• Urea formaldehyde binders burn out faster and collapse at lower temperature as compared to phenol formaldehyde binders. Thus urea formaldehyde binders are suitable for use at lower temperature metals like Al, Mg, thin sections of brass, bronze.

• Phenol formaldehyde binders are employed for thick sections of CI, steel castings

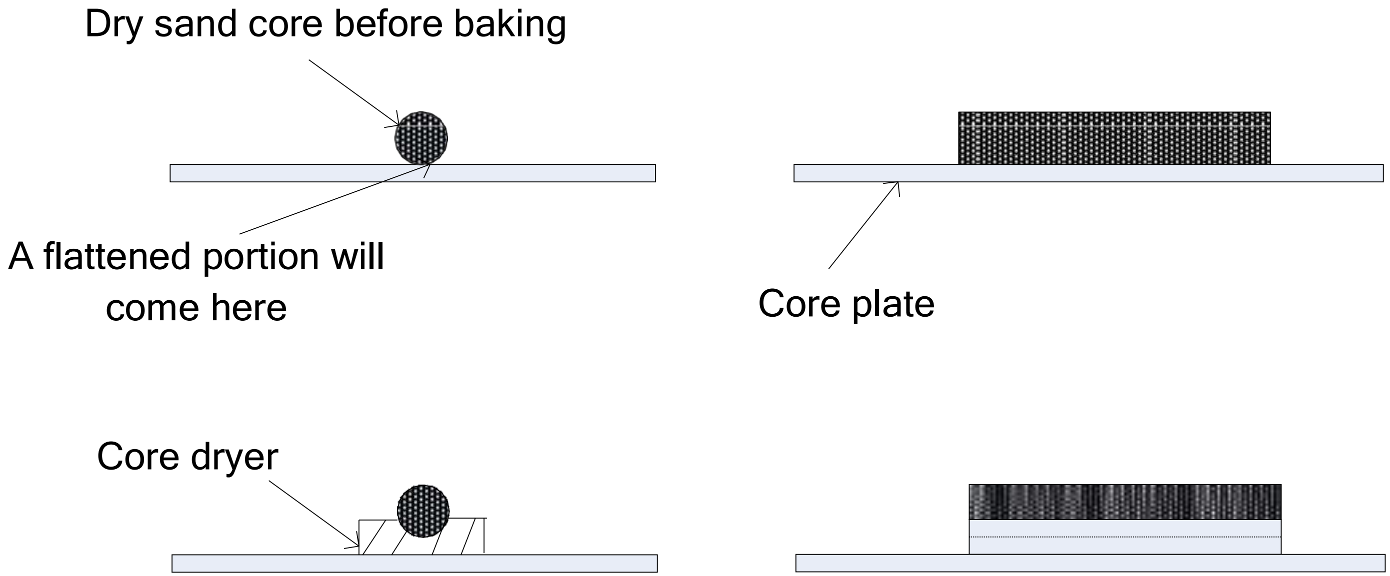
Core characteristics

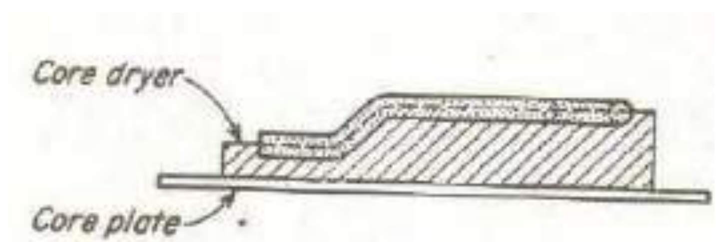
Good dry sand cores should have the following characteristics:

1. Good dry strength and hardness after baking
2. Sufficient green strength to retain the shape before baking
3. Refractoriness
4. Surface smoothness
5. Permeability
6. Lowest possible amount of gas created during the pouring of casting

Core dryers

- cores must be supported properly in the green state, before they are baked, hardened.
- Curved surfaces of the cores will be flattened if placed on the flat core plates
- Cores should be prevented from sagging and breaking
- Flat surfaces are required for supporting the cores. These are called ‘Core dryers’. They are designed to support the cores.





• Core dryers may be made as metal castings, with thin sections in order to absorb minimum heat.

• They are perforated for easy escape of gases.

• For large quantity production, many core dryers are required.

Loose pieces in core boxes

- Loose pieces are required for cores having backdraft on vertical sides. Such a loose piece will form an entire side of the core.
- The loose piece remains on the core, which will be removed later by horizontal movement.

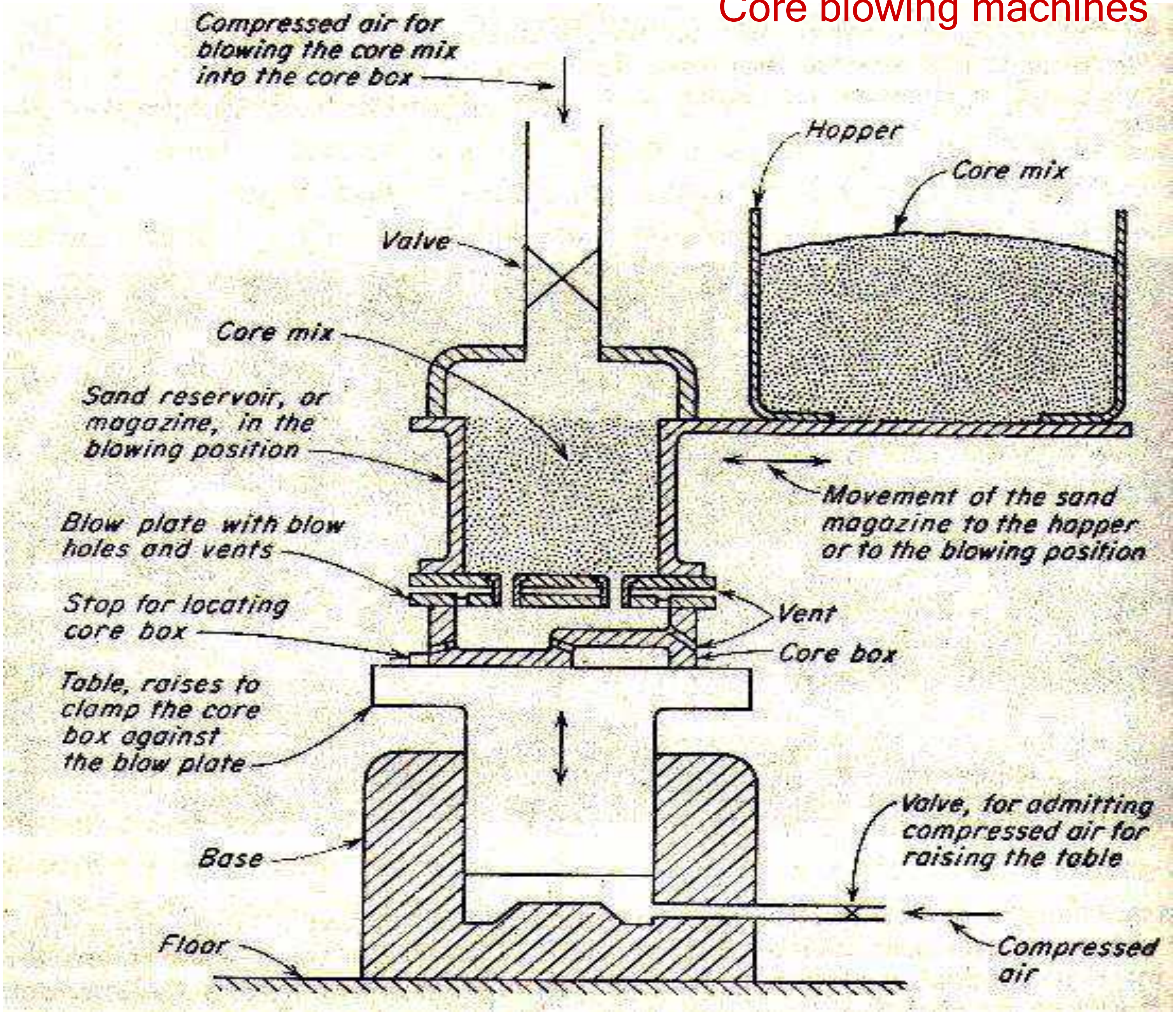
Core wires, rods, arbors

- Small core have sufficient strength after baking to withstand the molten metal upward force. For iron castings the lifting force is four times the weight of a core.
- Certain cores and slender cores which do not have strength are supported by embedding wires, rods, arbors into the core sections.
- Wires are meant for small cores, where as arbors are CI or steel based skeleton structures. Removing arbors is an issue here, sometimes arbors are made in parts, bolted together to facilitate easy removal. Hooks are provided in the arbors for easy removal. They sometimes project outside the core prints.

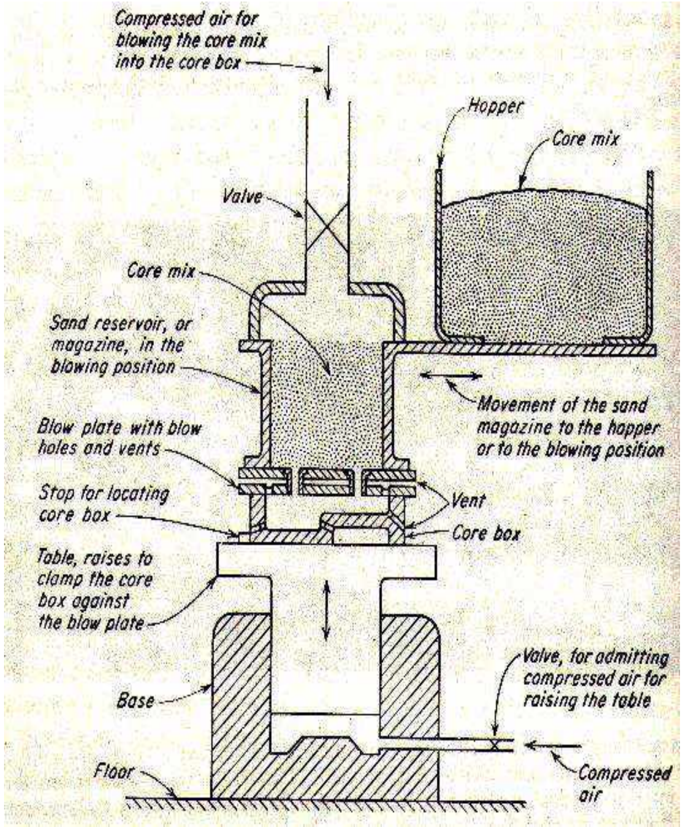
Core venting

- Proper core venting is required especially if the cores are surrounded largely by molten metal. The cores containing binders will produce gases, steam because of the heat generated due to molten metal.
- These gases should be vented out through core prints so that defects like 'blows' can be avoided.
- Large cores are sometimes made hollow.

Core blowing machines



Core blowing machines



• Core blowing machines are mainly suitable for large quantity parts manufacturing.

• The sand reservoir is first moved below the hopper, where it is filled with sand.

• The sand reservoir is then moved to the blowing position. The core box is placed on the table and pressed up with the blow plate.

• The core box is rapidly filled with sand using a blower at the top with the help of compressed air at high pressures.

• The air thus got trapped in the core box is vented out by suitable vents provided in the core box.

• It is generally understood that because of blowing operation, larger grains tend to move to the interior of the core and finer grains at the surface, creating a smoother surface.

J S Campbell, *Principles Of Manufacturing Materials And Processes*

Core box equipment for core blowing

• Core box should be complemented with core dryers for proper support, a blow plate to fasten to the reservoir

• The core box contains blowing holes and the number, locations, size of the blowing holes are important in proper filling of the core box. This prevents the presence of soft cores and soft spots.

• vent area to blowing hole area is 5:1

• Sometimes the sand grains may not be conveyed properly due to the presence of entrapped air channels.

• For continuous operation of the machine, many duplicate core boxes should be used. Conveyors are also used to handle the operations properly.

• The upper half of the core box is sometimes used as the blow plate that is fastened to the sand magazine.

• CORE SHOOTING can also be used to prevent some of the difficulties of core blowing.

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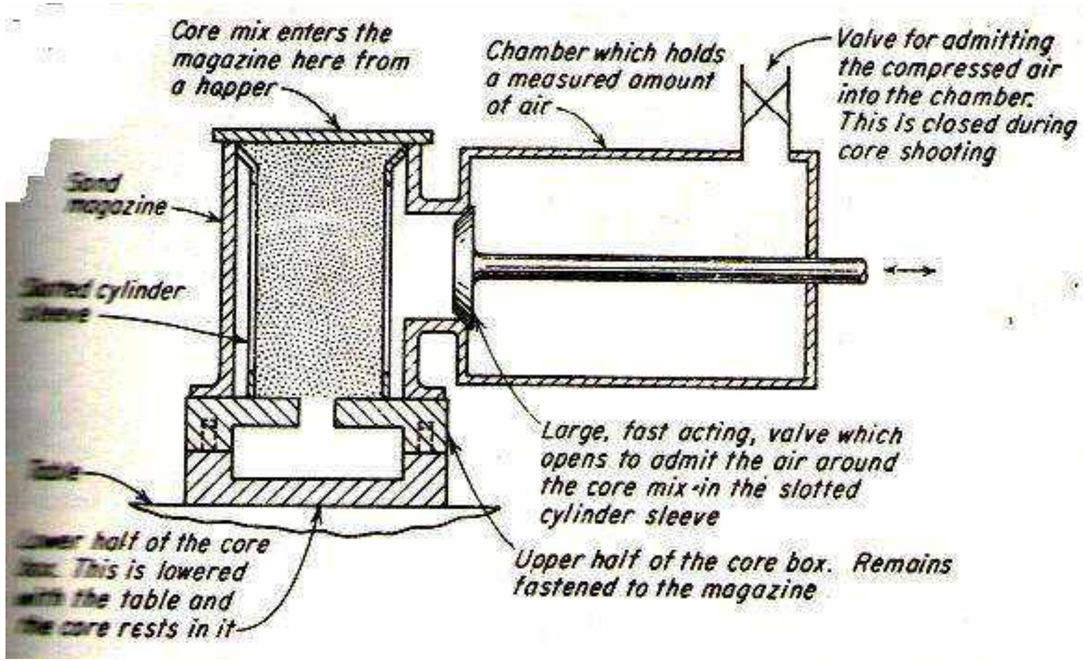

CORE SHOOTING MACHINE

• Compressed air is admitted into the chamber and the chamber is closed during core shooting

• large, fast acting valve is opened to admit the air around sand magazine

• this pressurizes the core mix and because of which sand gets filled in the core box

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Core baking

- After cores are made and placed on the core dryer, they are taken to ovens for baking
- Baking removes moisture and hardens core binders
- generally core sand is a poor conductor of heat and hence heat penetrates slowly into the interior sections of the cores
- In a core having thin and thick sections, the thin sections will be over baked, while thick sections will be optimally baked
- Over baking of cores will result in destroying the binders and hence core will be just a heap of sand
- Large core will be baked differently on the surface and in interiors, especially if the oven is too hot
- cores that are not baked fully will create an excess of gas and cause blows in castings

Core ovens

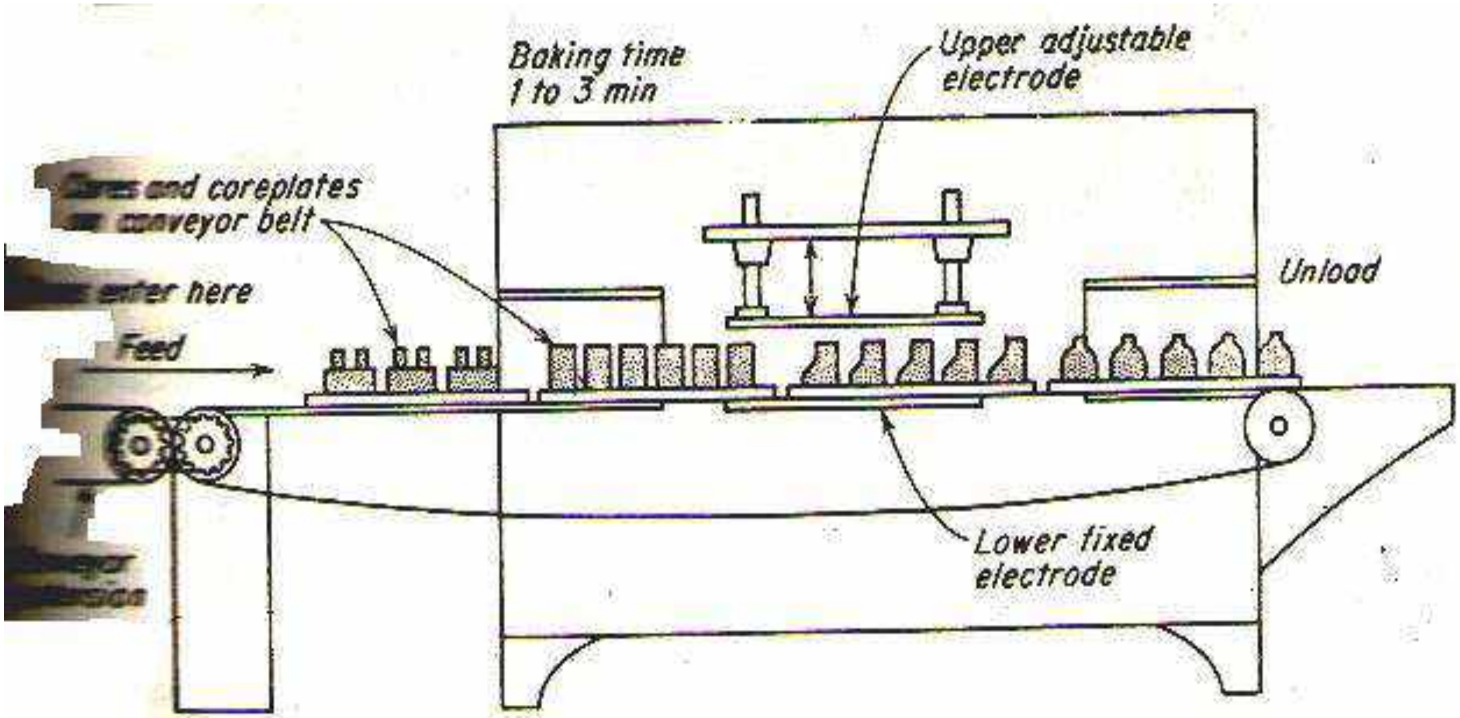
Continuous ovens:

- Are those through which the core moves slowly on the conveyor.
- Continuous loading and unloading is followed and hence the baking time is controlled by the rate of travel of the conveyor.
- Generally same sized cores are used in this.

Batch type ovens:

- No movement of cores occur
- Electricity, gas, oil are used for heating and temperature is maintained uniformly and closely controlled by suitable instruments.
- Temperature is of the order of 450^{o}F and this depends upon the binder.
- heating elements are properly spaced to have uniform/same temperature distribution throughout the container.
- replacing new air from outside is done through blowers so that moisture can be controlled.

Dielectric core baking



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- Rapid baking is possible by dielectric heating.
- Induction heating: used for heating materials which are conductors of electricity, like metals, and is done in continuously varying magnetic field.
- Dielectric heating is done for non-conductors of electricity. In this alternating electric field is established betn two parallel plates which act as an electric condenser.

- The material to be heated is placed in between these parallel electrodes
- With a high frequency electric current (15 million times/sec) in ON condition, heat is generated into the molecules.
- IN this case, the interior of the cores are heated rapidly as outer surfaces.
- Thermosetting synthetic resin binders, which cure app. at 250°F and which do not require oxidation are well suited for dielectric heating.
- Small sized samples can be baked within 30 secs, while large sections need few minutes
- less chance of over baking or under baking

Core coatings

• A fine refractory coating or facing is generally applied on the core surface by spraying or by dipping the core into a tank containing facing liquid

• this is done to have a smoother cast surface by preventing the penetration of molten metal into spaces between sand grains.

• Facing materials: finely ground graphite, silica, zircon flour

• after coating, the layer is dried, usually by torches, burners

Green sand cores

• Yield considerable cost savings.

• Handling them and keeping them in mold is tricky.

• Method 1: A green sand core can be rammed up on the dry sand core base.

• Method 2: Ram the green sand core around an arbor, by which it can be lifted.

Sand testing

Criteria used for sand testing:

Moisture content, green and dry sand permeabilities, compression, tension, transverse and shear strengths, deformation during compression tests, green and dry hardness, clay content, grain-size distribution, combustible content, pressure, volume of gases evolved, flowability, sintering point, resistance to spalling etc.

Moulding sand preparation and moisture content determination:

The moisture content controls practically all other properties of the sand. It is a varying property since water content constantly evaporates during mold preparation.

Purpose: adding sufficient water to bring the moisture content to within desired limits, uniform distribution of water, adequate coating of colloidal clay to each sand grain.

Moisture content determination:

• The simplest method is to dry a sample thoroughly at a few degrees above 212°F and to consider its loss in weight as moisture.

• Drying can be done in a thermostatically controlled oven or in a instrument designed for this purpose

• There is one MOISTURE TELLER which blows air through a 50 gm sample of sand that is placed in a plate.

Testing rammed sand:

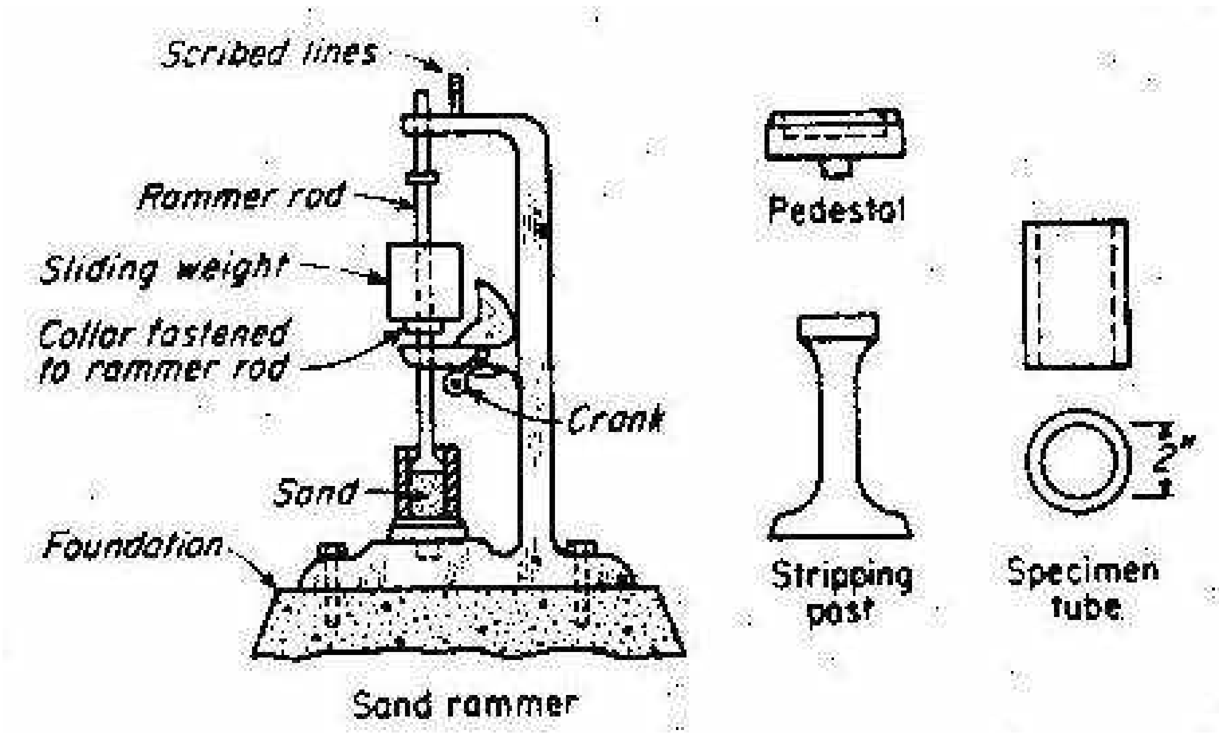
• Green permeability, green compression and few other properties are tested when the sand is in rammed condition.

• The rammed densities should be within some range which is actually encountered in the sand molds

• A predetermined weight of sand is placed into the hardened steel tube, which is closed at the bottom by a pedestal

• actually the tube filled with sand and the pedestal are weighed

• the entire set up is placed into the sand rammer and the rammer is dropped few times depending on particular standards, like three times etc.



J S Campbell, *Principles Of Manufacturing Materials And Processes*

- the weight used will be a standard one. Depending on the ramming times, a standard density is obtained.
- once the ramming is completed, the height of the rammed sand is evaluated and this should be equal to 2 inches in length. If it is equal to this height, required density is expected to be in the rammed sand.
- If the sand height is outside the range, the entire procedure will be repeated.

Green compression strength

The sand specimen is compressed between two plates connected to the ram of the universal testing machine.

The load at which the sand sample breaks will give the compression strength.

The same tests can be performed at high temperatures in furnaces to find the compression strength at elevated temperatures.

Deformation and green hardness

During compression tests, the deformation of the sample can be recorded. The toughness can be obtained from its ultimate strength times its corresponding deformation.

Green hardness is the hardness of the rammed sand that is measured by hardness tester like Brinell hardness tester. A ½ inch diameter, spring loaded ball indenter is forced into the rammed sand surface. The resistance to penetration will give the hardness of the sand surface.

Heating the metal

Furnaces are used to heat (and melt) the metal to a molten temperature sufficient for casting. The total heat energy required is the sum of

(1) the heat to raise the temperature to the melting point,

(2) the heat of fusion to convert it from solid to liquid, and

(3) the heat to raise the molten metal to the desired temperature for pouring

This is expressed as: $$H = \rho V \left\{ C_S (T_m - T_a) + H_f + C_l (T_p - T_m) \right\}$$

(1) **(2)** **(3)**

H: total heat required to increase the temperature of the metal to the pouring temp (in J)
ρ: density (in g/cm^3)
V: Volume of metal used for heating (in cm^3)
C_s: Specific heat for the solid (in J/gC)
T_m : Melting temperature of the metal (in C)
T_a: Ambient temperature (or starting) (in C)
H_f : Heat of fusion (in J/g)
C_l: specific heat of the liquid metal (in J/gC)
Tp: Temperature of the pouring liquid (in C)

Assumptions valid for the above eqn. are,

1. Specific heat and other thermal properties of a solid metal are constant and not dependent on temperature, but not really true especially if the metal undergoes a phase change during heating.

2. Sometimes specific heat of metal in solid and liquid states are assumed same, but not really true

3. Single melting point which is not valid for alloys as there is a temperature range between solidus and liquidus temperature.
   Thus, the heat of fusion cannot be applied so simply as indicated above.

4. There are no heat losses to the environment during heating, but not really true

A disk 40 cm in diameter and 5 cm thick is to be casted of pure aluminum in an open mold operation. The melting temperature of aluminum = 660°C and the pouring temperature will be 800°C. Assume that the amount of aluminum heated will be 5% more than needed to fill the mold cavity. Compute the amount of heat that must be added to the metal to heat it to the pouring temperature, starting from a room temperature of 25°C. The heat of fusion of aluminum = 389.3 J/g. density = 2.7 g/cm^3 and specific heat C = 0.88 J/g-°C. Assume the specific heat has the same value for solid and molten aluminum.

Ans: Heat required = 19,082,756 J

$$H = \rho V \left\{ C_S (T_m - T_a) + H_f + C_l (T_p - T_m) \right\}$$

M.P. Groover, Fundamental of modern manufacturing Materials, Processes and systems, 4ed

A sufficient amount of pure copper is to be heated for casting a large plate in an open mold. The plate has dimensions: L = 20 in, W = 10 in, and D = 3 in. Compute the amount of heat that must be added to the metal to heat it to a temperature of 2150 F for pouring. Assume that the amount of metal heated will be 10% more than needed to fill the mold cavity. Properties of the metal are:
density = 0.324 lbm/in^3, melting point = 1981 F, specific heat of the metal = 0.093 Btu/lbm-F in the solid state and 0.090 Btu/lbm-F in the liquid state; and heat of fusion = 80 Btu/lbm.

Ans: Heat required = 58265 btu

$$H = \rho V \left\{ C_S (T_m - T_a) + H_f + C_l (T_p - T_m) \right\}$$

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Melting of metals

Gases in metals:

The gases in metal is important in deciding the defect free castings. In metal castings, gases may be mechanically trapped, generated due to variation in their solubility at different temperatures and phases, generated because of chemical reaction.

Gases generally present are: hydrogen, nitrogen

Hydrogen: Based on the solubility of hydrogen, metals are divided as

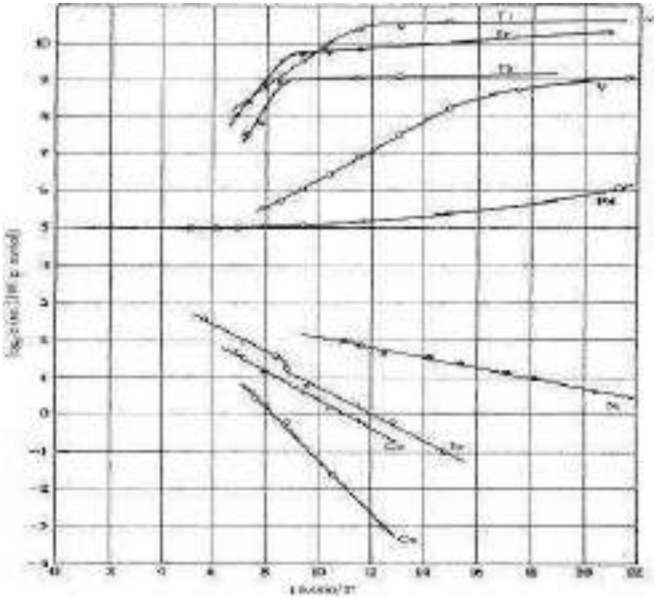
Endothermic (metals like Al, Mg, Cu, Fe, Ni), Exothermic (like Ti, Zr)

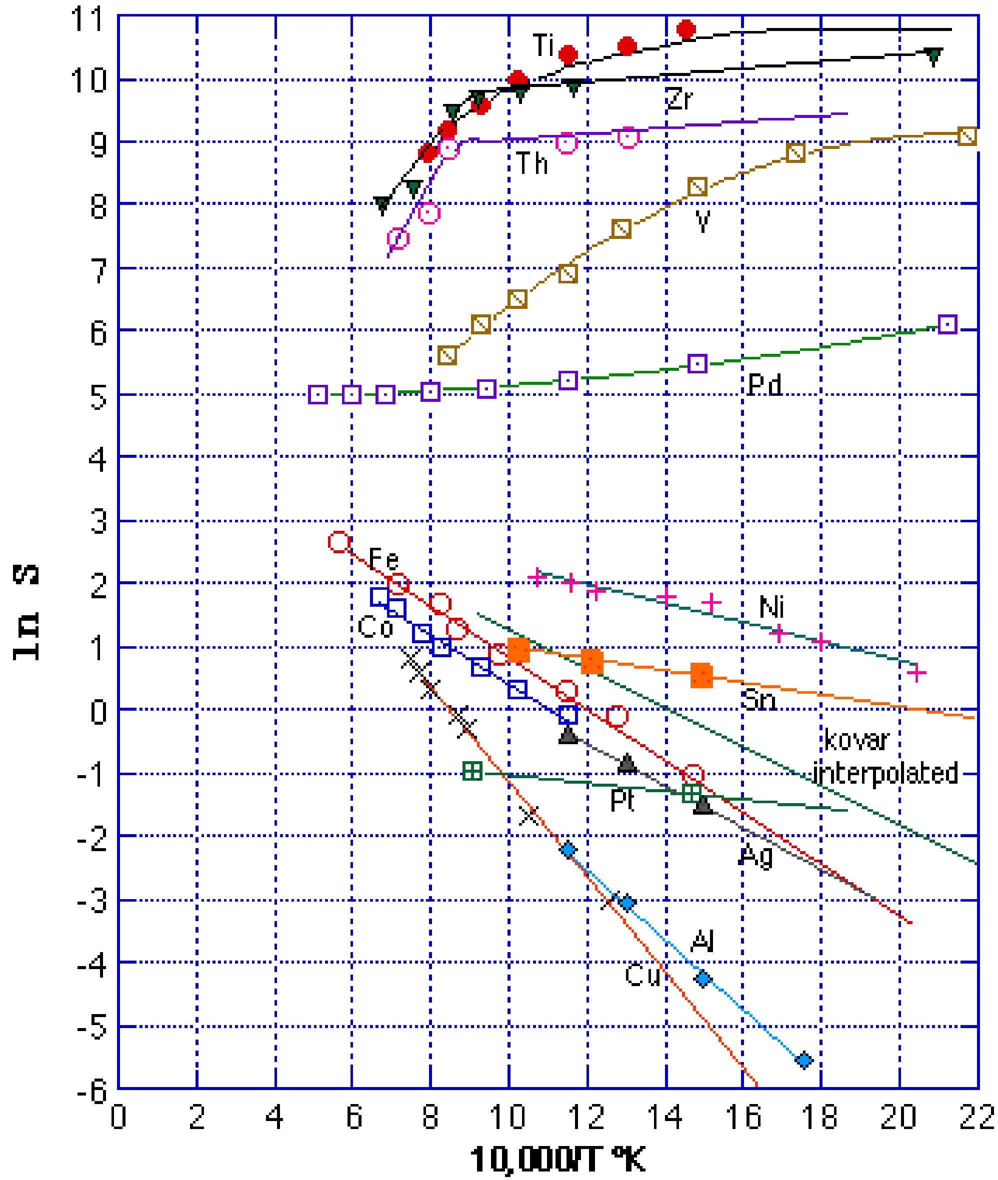
The solubility of hydrogen in various metals are shown in figure. Here solubility S is the volume of H_2 gas absorbed by 100 g. of metal. The solubility of hydrogen in solid and liquid phases (pressure = 1 atm) at solidus temperature is given in table.

$$S = C \exp\left[- E_s / (k\theta) \right]$$

E_S : heat of solution of one mol of hydrogen; sign determines endothermic or exothermic

Metal	Liquid solubility (cc/kg)	Solid solubility (cc/kg)
Fe	**270**	**70**
Mg	260	180
Cu	55	20
Al	7	0.4





Both are Similar graphs

A Theoretical Formula for the Solubility of Hydrogen in Metals, R. H. Fowler and C. J. Smithells, Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, V160, 1937, p. 37

Sievert's law states that the amt. of hydrogen (and nitrogen) dissolved in a metal varies in proportion with square root of partial pressure of hydrogen in the atmosphere over the melt.

$$\%\text{hydrogen present} = K\sqrt{p_{H_2}}$$

A Ghosh and A K Mallik, *Manufacturing Science*

$$N_{eq}(wt\%) = K_{eq}\sqrt{P_{N_2}} = \sqrt{P_{N_2}}.\exp\left(-\frac{\Delta G_1^0}{RT}\right)$$

Std. free energy for nitrogen in liquid iron

Partial pressure of N_2 in atmosphere over the melt

Gas constant

Temperature (K)

Sources of hydrogen in a melt are furnace dampness, air, oil and grease.

Most of the hydrogen removal techniques are based on the above equation - this is by reducing the partial pressure of hydrogen by bubbling dry insoluble gases through the molten melt.

Hydrogen removal:
For non-ferrous metals, chlorine, nitrogen, helium or argon is used.
For ferrous metals and Ni based alloys, nitrogen cannot be used. They form nitrides that affects the grain size. In this case, carbon monoxide is used.

Nitrogen removal: carbon monoxide can be used. A marked decrease in solubility of nitrogen in ferrous metal leads to porosity in casting. **Vacuum melting is used nowadays for preventing the solution of gases in metals.**

Pouring, Gating design

A good gating design should ensure proper distribution of molten metal without excessive temperature loss, turbulence, gas entrapping and slags.

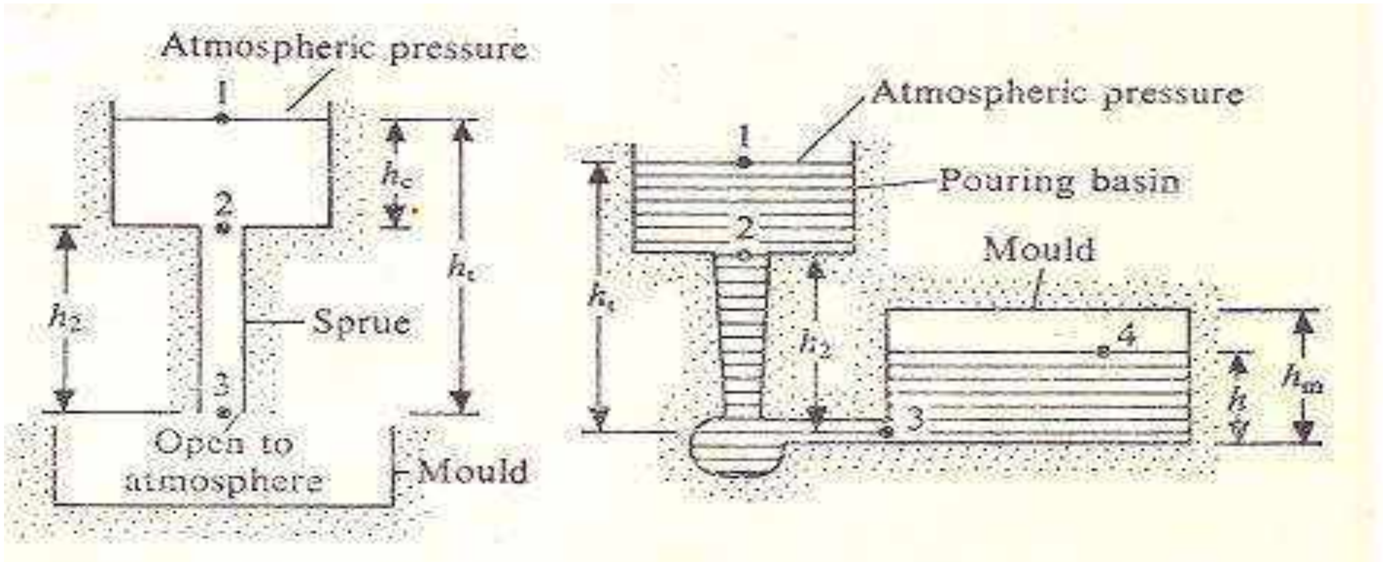
If the molten metal is poured very slowly, since time taken to fill the mould cavity will become longer, solidification will start even before the mould is completely filled. This can be restricted by using super heated metal, but in this case solubility will be a problem.

If the molten metal is poured very faster, it can erode the mould cavity.

So gating design is important and it depends on the metal and molten metal composition. For example, aluminium can get oxidized easily.

Gating design is classified mainly into two (modified: three) types:

Vertical gating, bottom gating, horizontal gating



Simple vertical gating Bottom gating

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Vertical gating: the liquid metal is poured vertically, directly to fill the mould with atmospheric pressure at the base end.

Bottom gating: molten metal is poured from top, but filled from bottom to top. This minimizes oxidation and splashing while pouring.

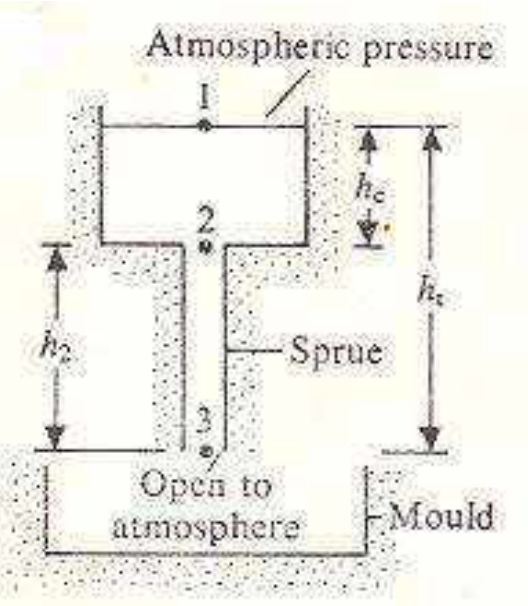
Horizontal gating is a modification of bottom gating, in which some horizontal portions are added for good distribution of molten metal and to avoid turbulence

Analysis of pouring and filling up mould

(a) Vertical gating

For analysis we use energy balance equation like Bernoulli's equation

$$h_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} + F_1 = h_3 + \frac{p_3}{\rho g} + \frac{v_3^2}{2g} + F_3$$



Simple vertical gating

Assuming $p_1 = p_3$ and level at 1 is maintained constant, so $v_1 = 0$; frictional losses are neglected.

The energy balance between point 1 and 3 gives,

$$gh_t = v_3^2 / 2 \qquad\qquad v_3 = \sqrt{2gh_t}$$

Here v_3 can be referred as velocity at the sprue base or say gate, v_g

Continuity equation: Volumetric flow rate, $Q = A_1 v_1 = A_3 v_3$

Above two equations say that sprue should be tapered.

As the metal flows into the sprue opening, it increases in velocity and hence the cross-sectional area of the channel must be reduced

Otherwise, as the velocity of the flowing molten metal increases toward the base of the sprue, air can be aspirated into the liquid and taken into the mould cavity.

To prevent this condition, the sprue is designed with a taper, so that the volume flow rate, $Q = Av$ remains the same at the top and bottom of the sprue.

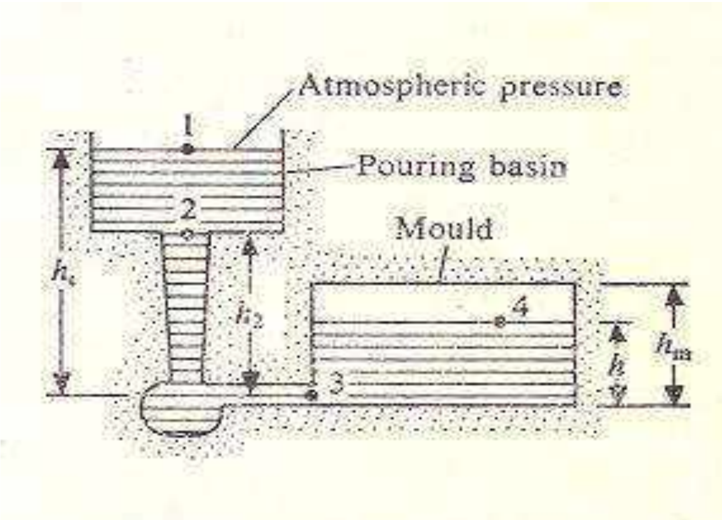
The mould filling time is given by, $\boxed{t_f = \frac{V}{Q} = \frac{V}{A_g v_3}}$

A_g = cross-sectional area of gate; V = volume of mould

Note: This is the minimum time required to fill the mould cavity. Since the analysis ignores friction losses and possible constriction of flow in the gating system; the mould filling time will be longer than what is given by the above equation.

(b) Bottom gating

$$h_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} + F_1 = h_3 + \frac{p_3}{\rho g} + \frac{v_3^2}{2g} + F_3$$



(b) Bottom gating

Apply Bernoulli's eqn. between points 1 and 3 and between 3 and 4 is equivalent to modifying V_3 equation in the previous gating.

$$v_g = v_3 = \sqrt{2g(h_t - h)}$$

Effective head

Between 3 and 4:

Assume:

- V_4 is very small
- All KE at 3 is lost after the liquid metal enters the mould

Assuming in the mould the height moves up by '*dh*' in a time '*dt*'; A_m and A_g are mould area and gate area, then

$$A_m dh = A_g v_g dt$$

$$\frac{1}{\sqrt{2g}} \frac{dh}{\sqrt{h_t - h}} = \frac{A_g}{A_m} dt$$

Combining above two eqns., we get

$$\frac{1}{\sqrt{2g}} \int_0^{h_m} \frac{dh}{\sqrt{h_t - h}} = \frac{A_g}{A_m} \int_0^{t_f} dt \Rightarrow$$

$$\boxed{t_f = \frac{A_m}{A_g} \frac{1}{\sqrt{2g}} 2\left(\sqrt{h_t} - \sqrt{h_t - h_m}\right)}$$

(Check integration)

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Find the filling time for both the mould types. Area of C.S. of gate = 5 cm^2

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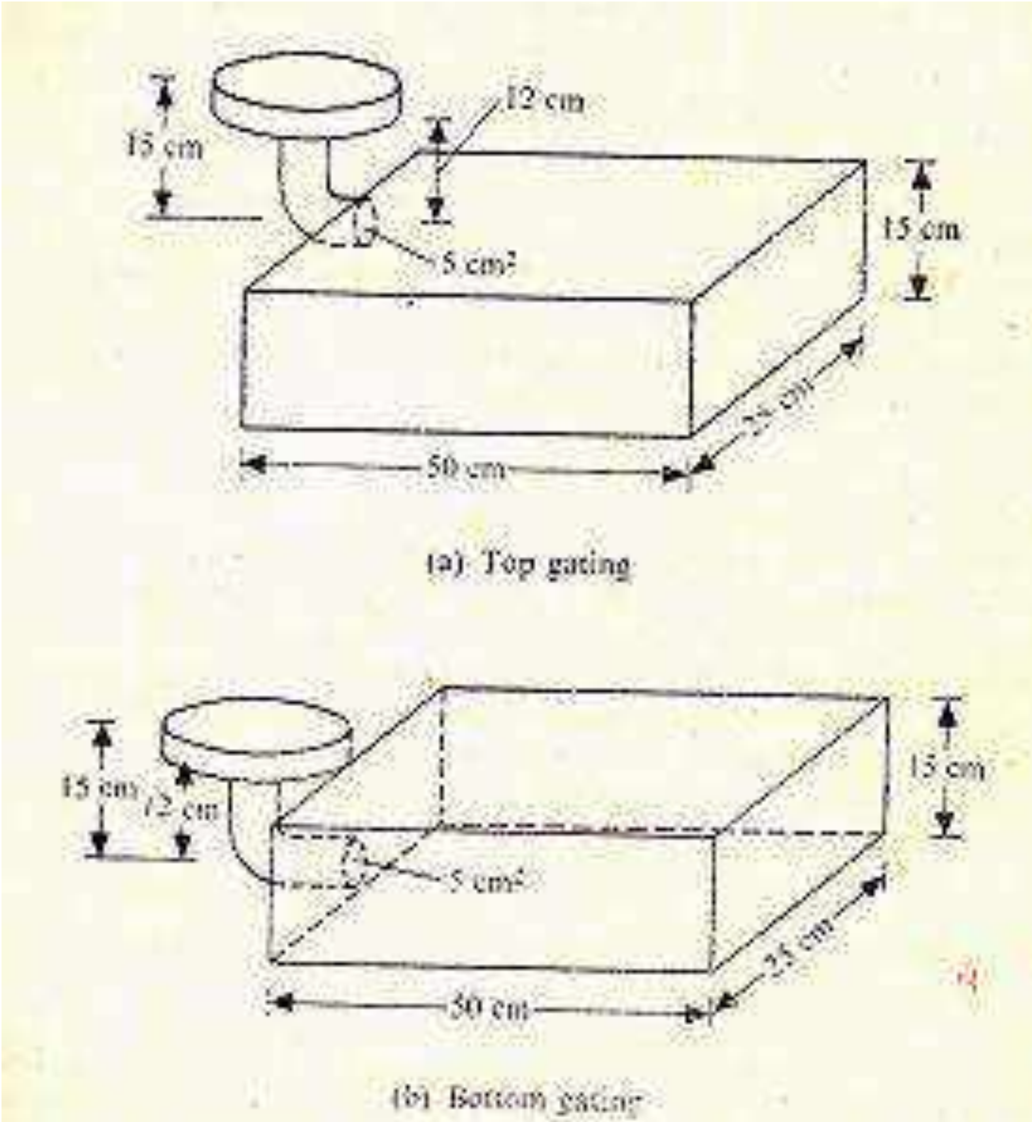

(a) Top gating

(b) Bottom gating

Answer:

t_f = 21.86 sec; 43.71 sec.

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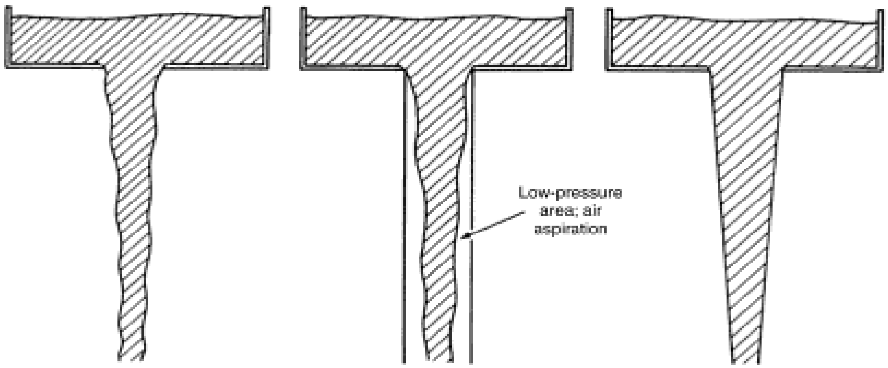
Aspiration effect

Aspiration effect: entering of gases from baking of organic compounds present in the mould into the molten metal stream. This will produce porous castings. **Pressure anywhere in the liquid stream should not become negative.**



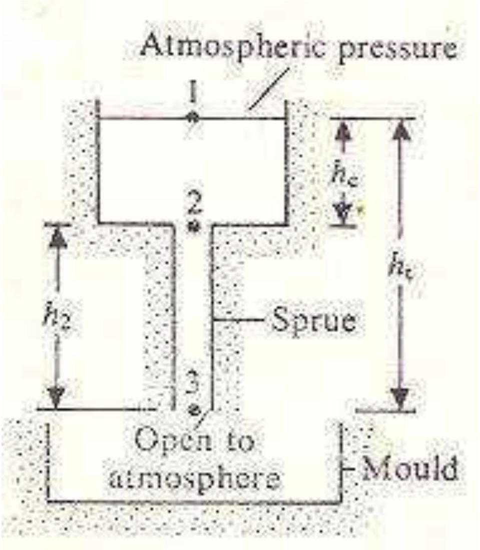
Free falling liquid

Metal flow with aspiration effect

A tapered sprue without aspiration effect

Case 1: straight Vs tapered sprue

Pressure anywhere in the liquid stream should not become negative.

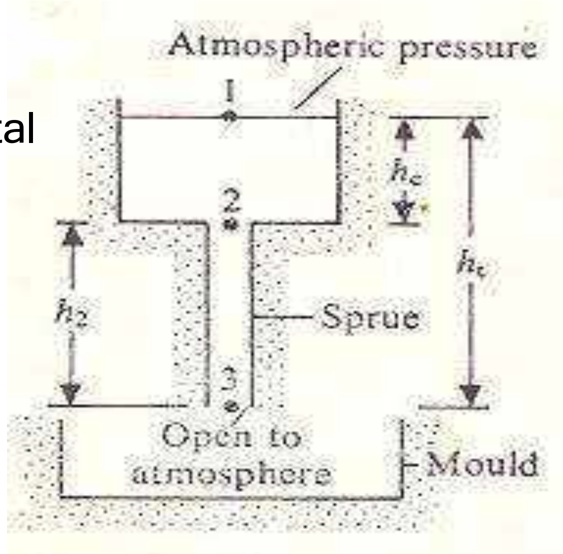


(a) Simple vertical gating

Points 2 & 3

$$gh_2 + \frac{p_2}{\rho_m} + \frac{v_2^2}{2} = \frac{p_3}{\rho_m} + \frac{v_3^2}{2}$$

ρ_m = density of molten metal



(a) Simple vertical gating

Let in the limiting case, $p_2 = p_3$, then from above equation

$$\frac{v_3^2}{2} = gh_2 + \frac{v_2^2}{2}$$

We know that, $v_2 = \frac{A_3}{A_2} v_3 = R v_3$

Combining above two eqns., $\frac{v_3^2}{2g} = h_2 + \frac{R^2 v_3^2}{2g}$ $\boxed{R^2 = 1 - \frac{2gh_2}{v_3^2}}$

We know that between points 1 and 3, $gh_t = v_3^2 / 2$

Put this in R^2 eqn, we get, $R^2 = 1 - \frac{h_2}{h_t} = \frac{h_c}{h_t}$ $\boxed{R = \frac{A_3}{A_2} = \sqrt{\frac{h_c}{h_t}}}$

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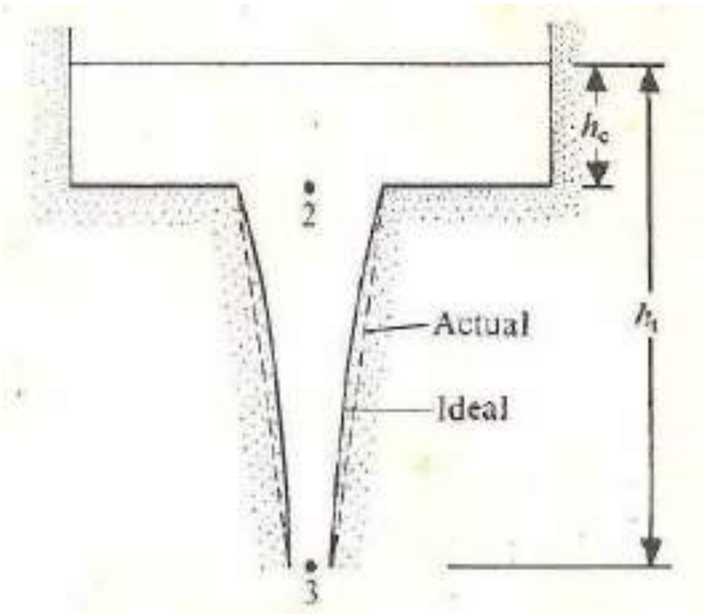
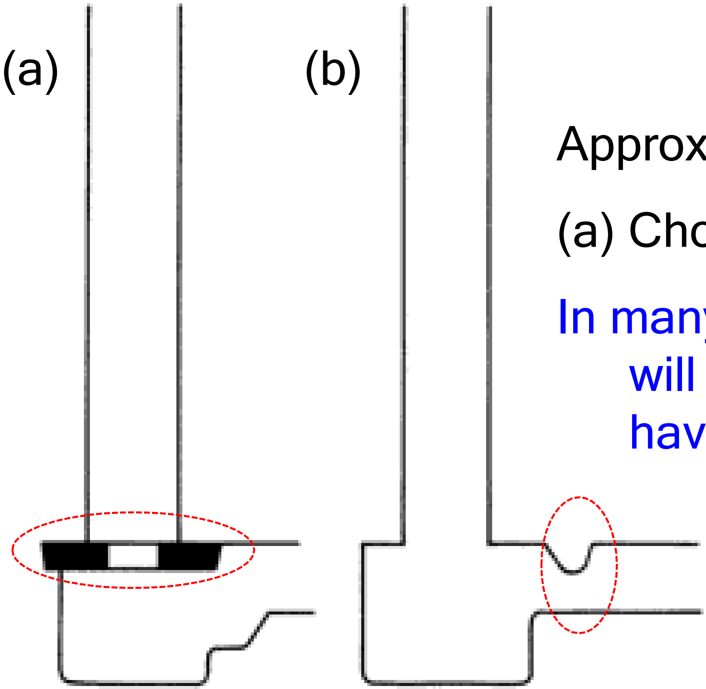
Ideal and actual profiles of sprue



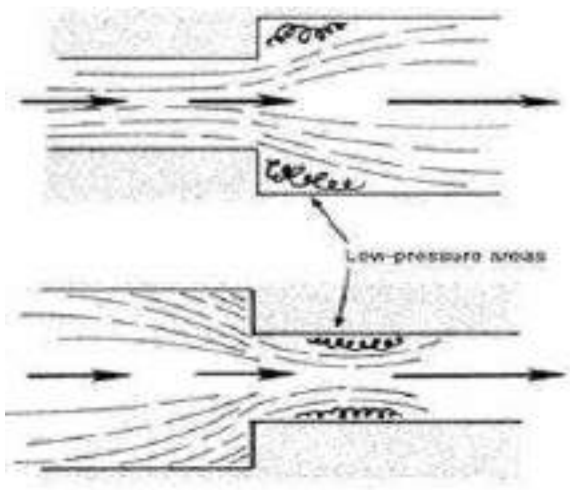


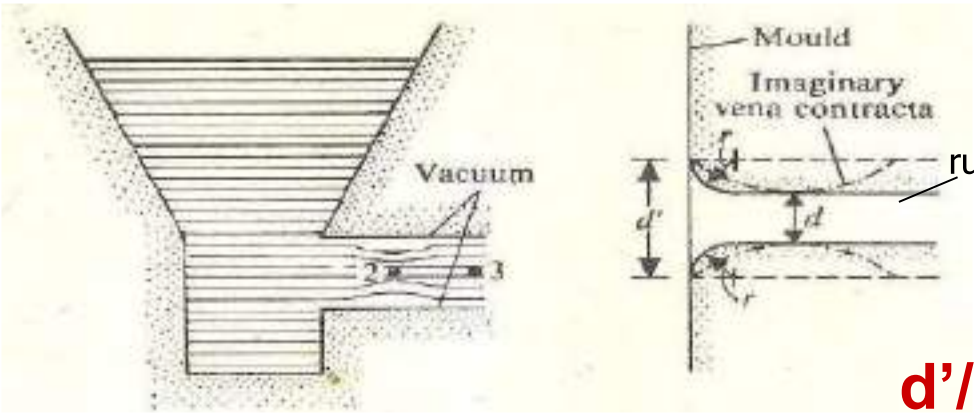
Approximating tapered spure using choke mechanism

(a) Choke core, (b) Runner choke

In many high production casting systems, tapered sprue will not be provided. Instead it is compensated by having chokes at the end of sprue or runner.

Case 2: sudden change in flow direction





runner

d'/d = 1.3

A sharp change in flow direction is avoided by designing the mould to fit vena contracta.

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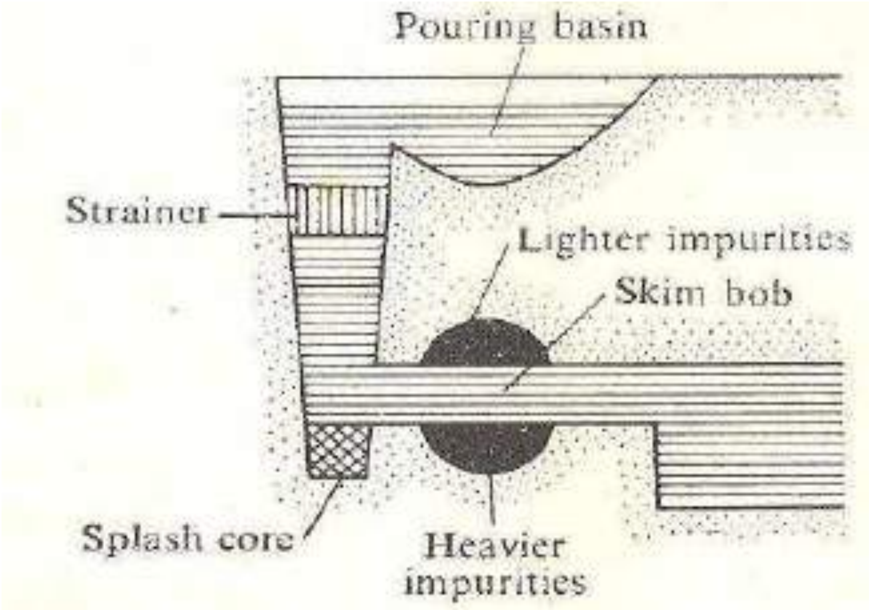
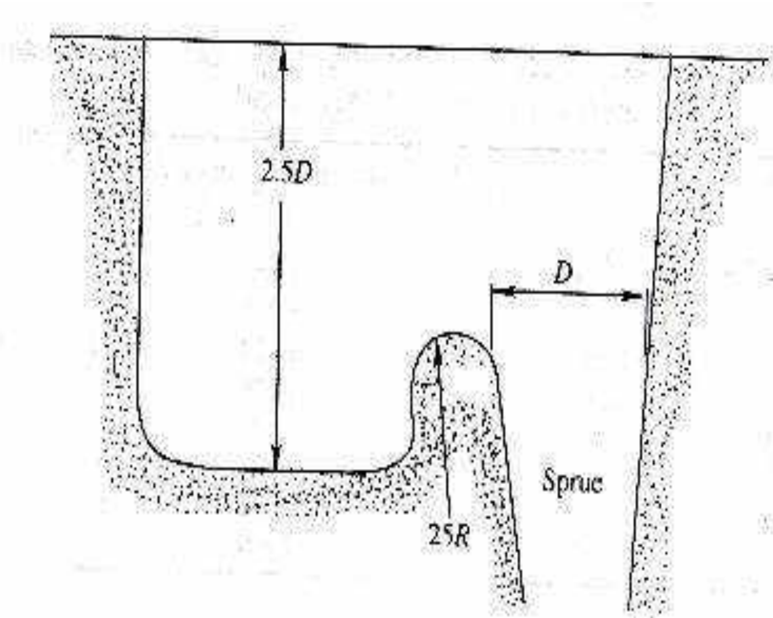
Preventing impurities and turbulence in casting

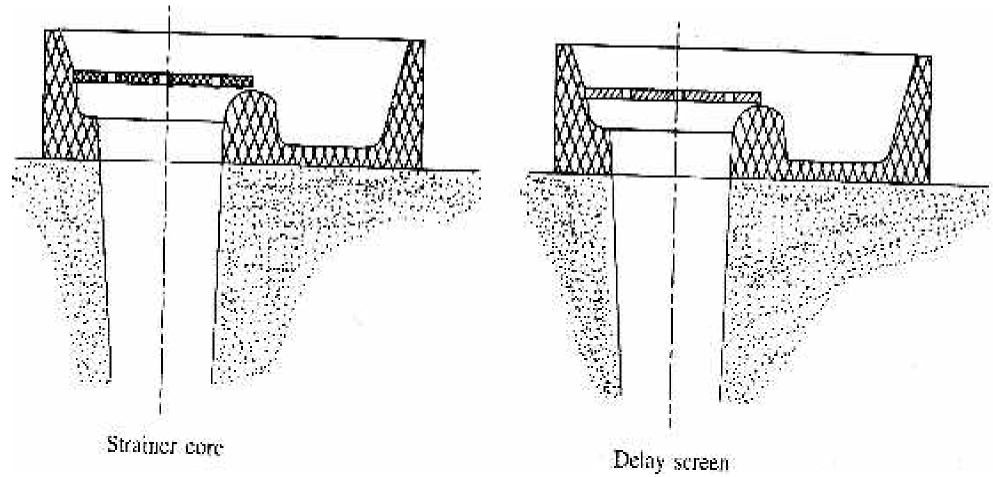


The items provided in the gating system to avoid impurities and turbulence are:

Pouring basin:

This reduces the eroding force of the liquid metal poured from furnace. This also maintains a constant pouring head. Experience shows that pouring basin depth of 2.5 times the sprue entrance diameter is enough for smooth metal flow. Radius of 25R (mm) is good for smooth entrance of sprue.





P Rao, *Manufacturing Technology: Foundry, Forming And Welding*

Delay screen/Strainer core:
A delay screen is a small piece of perforated screen placed on top of the sprue. This screen actually melts because of the heat from the metal and this delays the entrance of metal into the sprue, maintaining the pouring basin head. This also removes dross in the molten metal.
Strainer core is a ceramic coated screen with many small holes and used for same purpose.

Splash core: provided at the end of the sprue length which reduces the eroding force of the liquid metal

Skim bob: this traps lighter and heavier impurities in the horizontal flow

Gating ratios

Gating ratio: sprue area : runner area : gate area

Non-pressurized:

has choke at the bottom of the sprue base, has total runner area and gate areas higher than the sprue area. No pressure is present in the system and hence no turbulence. But chances of air aspiration is possible. Suitable for Al and Mg alloys.

In this, Gating ratio = 1 : 4 : 4

Pressurized:

Here gate area is smallest, thus maintaining the back pressure throughout the gating system. This backpressure generates turbulence and thereby minimizes the air aspiration even when straight sprue is used.

Not good for light alloys, but good for ferrous castings.

In this, Gating ratio = 1 : 2 : 1

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Gating ratios used in practice

Aluminium	1 : 2 : 1
	1 : 1.2 : 2
	1 : 2 : 4
	1 : 3 : 3
	1 : 4 : 4
	1 : 6 : 6
Aluminium bronze	1 : 2.88 : 4.8
Brass	1 : 1 : 1
	1 : 1 : 3
	1.6 : 1.3 : 1
Copper	2 : 8 : 1
	3 : 9 : 1
Ductile iron	1.15 : 1.1 : 1
	1.25 : 1.13 : 1
	1.33 : 2.67 : 1
Grey cast iron	1 : 1.3 : 1.1
	1 : 4 : 4
	1.4 : 1.2 : 1
	2 : 1.5 : 1
	2 : 1.8 : 1
	2 : 3 : 1
	4 : 3 : 1
Magnesium	1 : 2 : 2
	1 : 4 : 4
Malleable iron	1 : 2 : 9.5
	1.5 : 1 : 2.5
	2 : 1 : 4.9
Steels	1 : 1 : 7
	1 : 2 : 1
	1 : 2 : 1.5
	1 : 2 : 2
	1 : 3 : 3
	1.6 : 1.3 : 1

P Rao, *Manufacturing Technology: Foundry, Forming And Welding*

The flow rate of liquid metal into the downsprue of a mold = 1 liter/sec. The cross-sectional area at the top of the sprue = 800 mm^2 and its length = 175 mm. What area should be used at the base of the sprue to avoid aspiration of the molten metal?

Ans: A = 540 mm^2

- convert Q in lit/sec to mm^3/sec
- Find $v = \sqrt{2gh}$
- Base area, A = Q/v

Molten metal can be poured into the pouring cup of a sand mold at a steady rate of 1000 cm^3/s. The molten metal overflows the pouring cup and flows into the downsprue. The cross-section of the sprue is round, with a diameter at the top = 3.4 cm. If the sprue is 25 cm long, determine the proper diameter at its base so as to maintain the same volume flow rate.

Ans: D = 2.4 cm

- Find velocity at base, $v = \sqrt{2gh}$
- find area at base, A = Q/v
- Find D = √4A/π

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed

During pouring into a sand mold, the molten metal can be poured into the downsprue at a constant flow rate during the time it takes to fill the mold. At the end of pouring the sprue is filled and there is negligible metal in the pouring cup.

The downsprue is 6.0 in long. Its cross-sectional area at the top = 0.8 in^2 and at the base = 0.6 in^2.

The cross-sectional area of the runner leading from the sprue also = 0.6 in^2, and it is 8.0 in long before leading into the mold cavity, whose volume = 65 in^3.

The volume of the riser located along the runner near the mold cavity = 25 in^3. It takes a total of 3.0 sec to fill the entire mold (including cavity, riser, runner, and sprue). This is more than the theoretical time required, indicating a loss of velocity due to friction in the sprue and runner.

Find: (a) the theoretical velocity and flow rate at the base of the downsprue; (b) the total volume of the mold; (c) the actual velocity and flow rate at the base of the sprue; and (d) the loss of head in the gating system due to friction.

Ans: (a) 68.1 in/sec, 40.8 in^3/sec; (b) 99 in^3; (c) 33 in^3/sec, 55 in/sec; (d) 2.086 in

Effect of friction and velocity distribution

The velocity of the liquid metal in the sprue and gate are assumed constant. This depends on the nature of flow and shape of the channel.
Moreover no frictional losses are considered. In real cases, friction losses are always present, specifically when there is sudden contraction and expansion in cross-sections.

The non-uniform velocity distribution is accounted for by modifying the KE term in the energy balance equation by replacing $(v)^2$ by $\frac{\bar{v}^2}{\beta}$ where β is a constant and $\bar{v}$ is the average velocity.

For circular conduit, β is equal to 0.5 for laminar flow and 1 for turbulent flow.

The energy loss due to friction in a circular channel (per unit mass) is given by, $E_{f1} = \frac{4 f l \bar{v}^2}{2d}$

Here *l* and *d* are length and diameter of channel. The value of *f* (friction factor) depends on the nature of flow and channel smoothness. This E_{f1} should be added to energy at point 2 (say there are two points 1 and 2 discussed earlier).

For smooth channel: $f = 16/R_e$ where R_e < 2000 for laminar flow

$$\frac{1}{\sqrt{f}} = 4\log_{10}(R_e\sqrt{f}) - 0.4$$ for turbulent flow (R_e > 2000)

$$f = 0.079(R_e)^{-0.25}$$ for the range 2100 < Re < 10^5 (simplified from above eqn.)

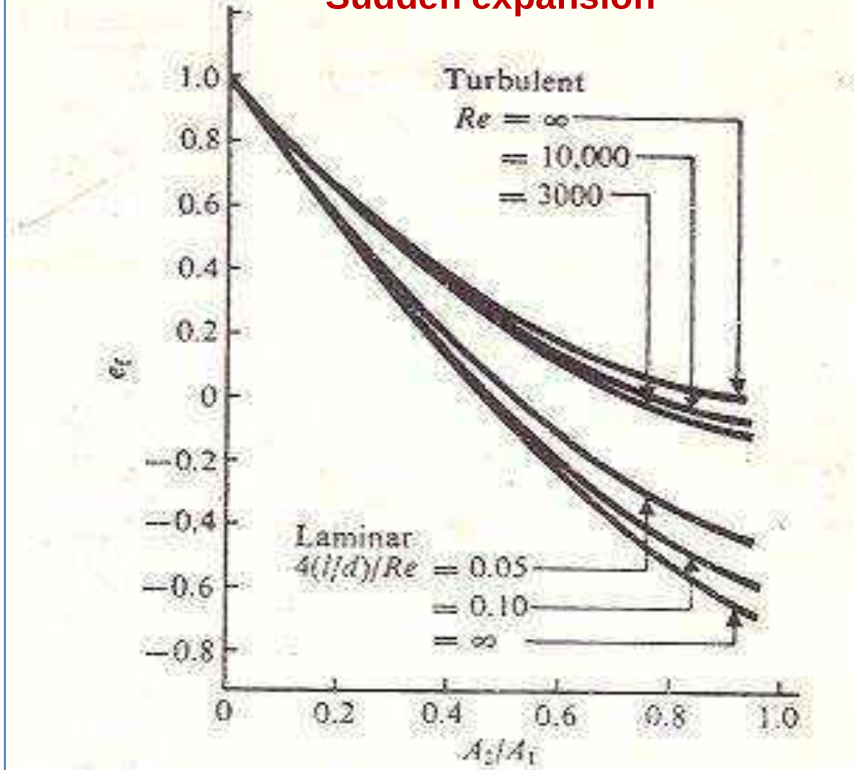
Frictional losses also occur due to sudden change in flow direction like in 90° bends. In such cases, proper (*l/d*) ratio should be considered in E_{f1} equation.

The energy loss due to sudden contraction and enlargement of flow area (per unit mass),

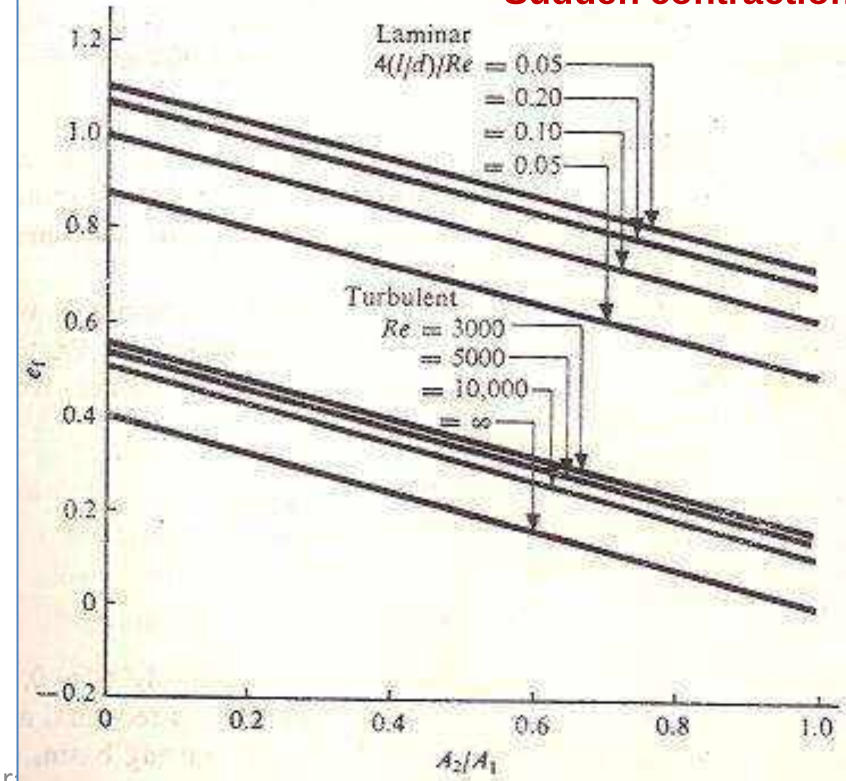
$$E_{f2} = \frac{\bar{v}^2}{2} e_f$$

. Here $\bar{v}$ is the average velocity of the fluid in smaller CS region and e_f is the friction loss factor and it depends on the ratio of flow area and R_e. In this e_f depends on sudden expansion or sudden contraction as shown in figure.

Sudden expansion



Sudden contraction



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$$h_1 + \frac{p_1}{\rho g} + \frac{v_1^{\,2}}{2g} + F_1 = h_3 + \frac{p_3}{\rho g} + \frac{v_3^{\,2}}{2g} + F_3$$

The energy balance eqn. between points 1 and 3, after accounting for sudden contraction loss at 2 is given by,

$$\frac{p_1}{\rho_m} + 0 + gh_t = \frac{p_3}{\rho_m} + \frac{\bar{v}_3^{\,2}}{2\beta} + Ef_1 + Ef_2$$

By having $P_1 = P_3$, and using equations $E_{f1} = \frac{4 fl\bar{v}^2}{2d}$ and $E_{f2} = \frac{\bar{v}^2}{2} e_f$, *we get*

$$\boxed{v_3 = C_D \sqrt{2gh_t}}$$

where $C_D = (\frac{1}{\beta} + e_f + 4f\frac{l}{d})^{-1/2}$

C_D = discharge coefficient

If the sprue has got a bend or fitting,

$$C_D = \{\frac{1}{\beta} + e_f + 4f[\frac{l}{d} + (\frac{L}{D})_{eq}]\}^{-1/2}$$

Here *l* and *d* are length and diameter of channel (like sprue), $(L/D)_{eq}$ is for the bend.

Cooling and Solidification

Solidification of pure metals

- Change of molten metal to solid state

- Solidification of pure metals and alloys are different

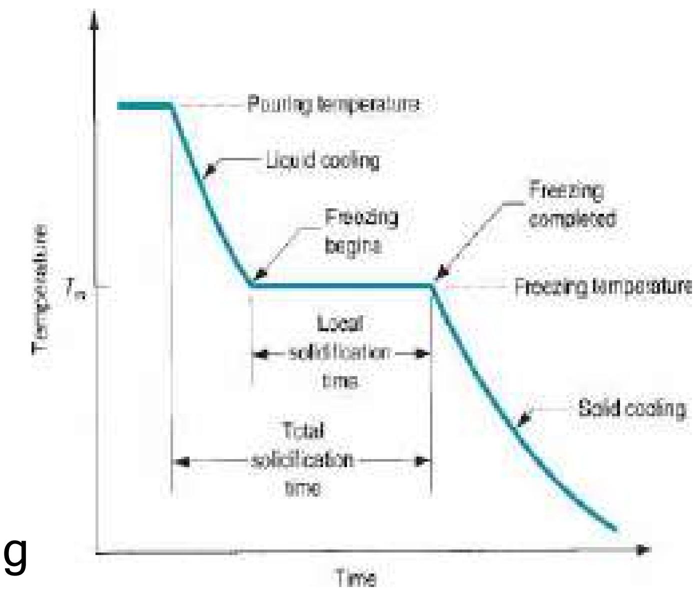
- The cooling curve of pure metals is shown in figure. Here solidification occurs at constant temperature equal to its freezing point.

-The solidification occurs at prescribed time duration.

- Local solidification time: time between freezing start and freezing completion. In this time, the molten metal heat of fusion is delivered into mould.

- Total solidification time: time between pouring and final solidification

- First liquid cooling occurs till freezing starts. Then solidification occurs for a time duration, till freezing completes. Even after solidification is over, solid cooling occurs at a particular rate as shown in the figure.



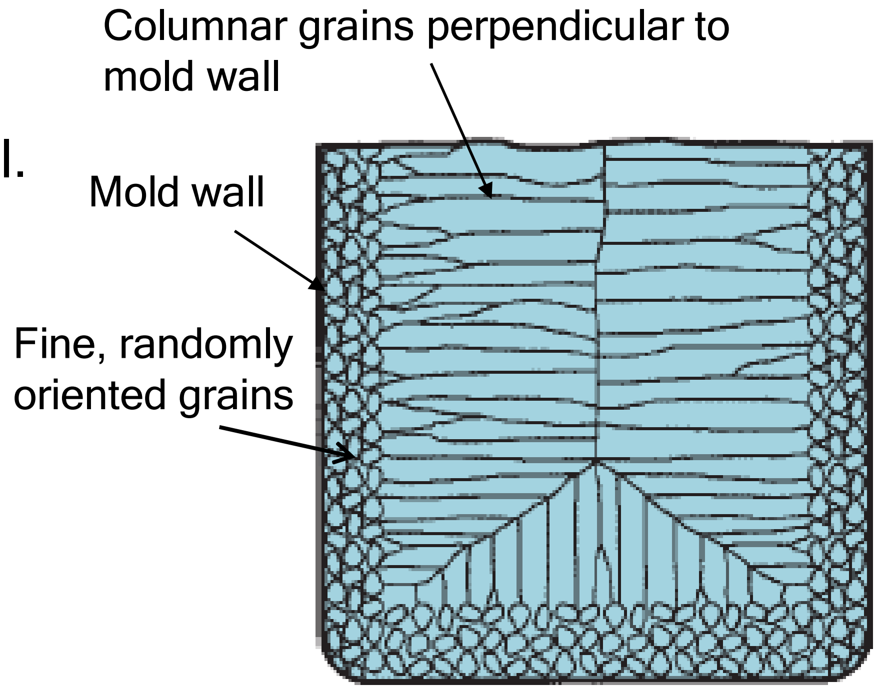
M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed

The grain structure in pure metals depends on the heat transfer into the mold and thermal properties of the metal.

The mold wall acts as a chiller and hence solidification starts first in the molten metal closer to the mold wall.

A thin skin of solid metal is first formed near the mold wall. The solidification continues inwards towards the mold center.

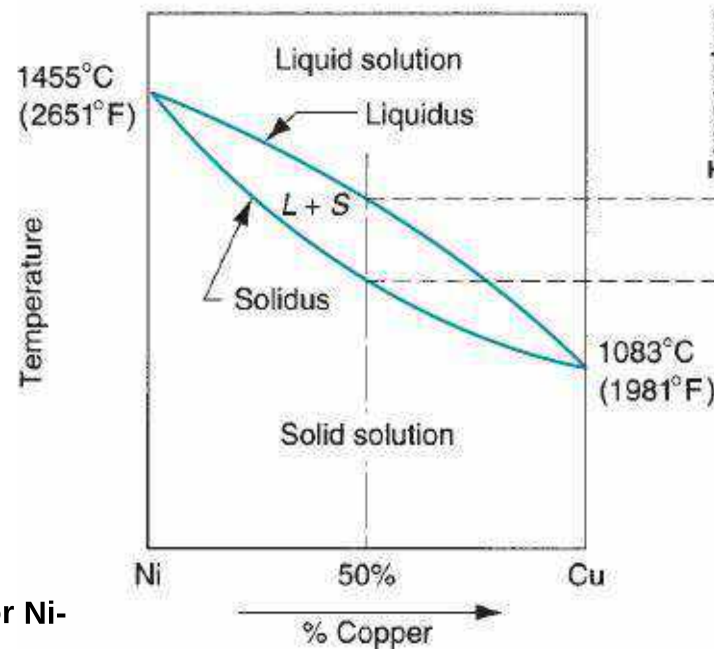
The initial skin formed near the mold wall has gone through fast removal of heat and hence fine, equiaxed and randomly oriented grains are formed.



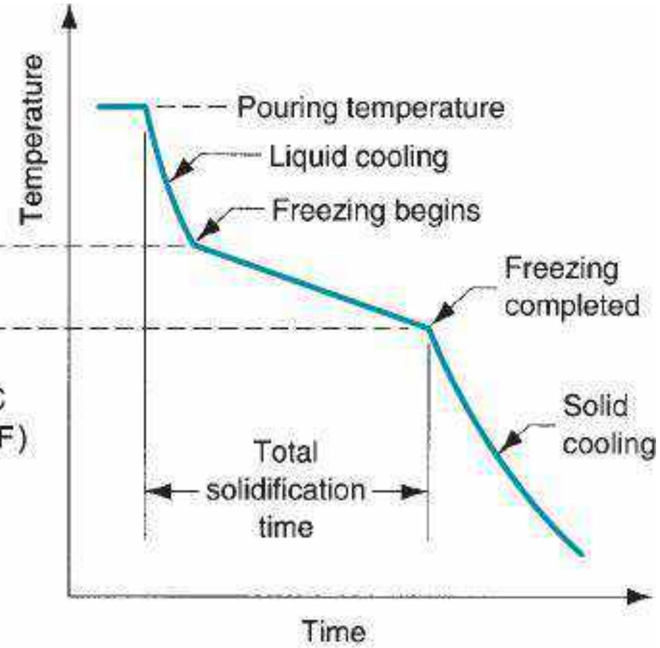
Grain structure in casting of pure metals

When the solidification continues inwardly, heat is removed through the mold wall and thin solid skin. Here the grains grow as needles with preferred orientation. As these needles enlarge, side branches develop, and as these branches grow, further branches form at right angles to the first branches. **This type of grain growth is referred to as dendritic growth.** It occurs at the freezing of pure metals and in alloys.

Solidification of alloys



Phase diagram for Ni-Cu alloy system



Cooling curve for 50%Ni-50% Cu during casting

- **Important:** Mushy zone formation, segregation of elements

- In alloys, solidification will not occur at a particular temperature. It happens at a temperature range. This range depends on the alloy composition.

- Referring above figure, solidification occurs between liquidus line and solidus line. Freezing starts at liquidus temperature and ends at solidus temperature. A skin layer is formed at the mold end and the dendrites grow in a similar fashion normal to the mold wall.

- However, because of the temperature difference between the liquidus and solidus line, the nature of the dendritic growth is such that an advancing zone is formed in which both liquid and solid metal exist together. The solid portions are the dendrite structures that have formed sufficiently to hold small regions of liquid metal in the matrix. This solid-liquid region has a soft consistency and hence called the **mushy zone**. Depending on the conditions of solidification, the mushy zone can be a narrow zone, or it can exist throughout the casting.

- Slowly the liquid islands solidify as the temperature of the casting goes down to the solidus.

- **Another complexity is the segregation of elements.** As solidification continues and the dendrites grow, an imbalance in composition between the solidified metal and the remaining molten metal will develop. This composition imbalance will finally result in the segregation of the elements.

- Segregation of elements can be microscopic and macroscopic. At microscopic level, chemical composition varies with each grain. This is due to out of balancing of composition between the first solidified region and the last solidified region. Thus, the variation in chemical composition within single grains of the casting is generated.

- At macroscopic level, the chemical composition varies throughout the entire casting. Since the regions of the casting that freeze first (say near the mold walls) are richer in one component than the other, the remaining molten metal has got reduction in that component by the time freezing occurs at the mold center. This creates difference in composition at different cross sections of the casting. This is called **ingot segregation.**

Eutectic alloys:

In these alloys, solidification occurs at a constant temperature rather than over a temperature range. For these alloys, the solidus and liquidus are at the same temperature.

Example:

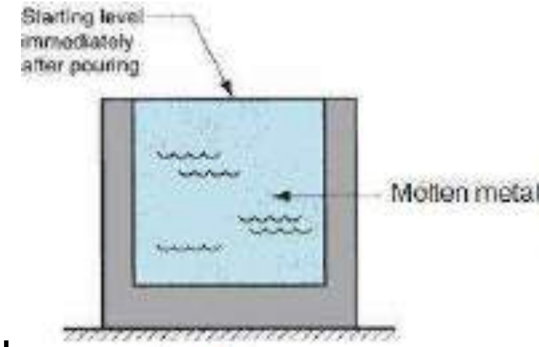
(i) 61.9% tin and 38.1% lead has a melting point of 183°C. This composition is the eutectic composition of the Pb-Sn alloy system. The temperature 183°C is its eutectic temperature.

(ii) Aluminum-silicon (11.6% Si) and cast iron (4.3% C)

Solidification shrinkage

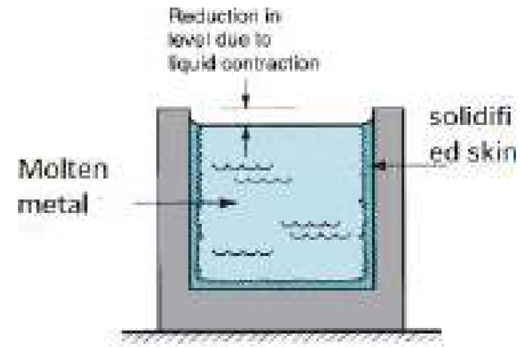
Major three stages in shrinkage:
(i) Contraction of liquid before solidification during cooling
(ii) Contraction during liquid to solid phase change
(iii) Contraction of solid metal during cooling to RT

Stage 1: The level of poured molten metal is shown in a mold container.



stage 1

Stage 2: Solidification front has started at the mold wall. The level of liquid metal has reduced at the open surface due to liquid contraction. The amount of liquid contraction is app. 0.5%.

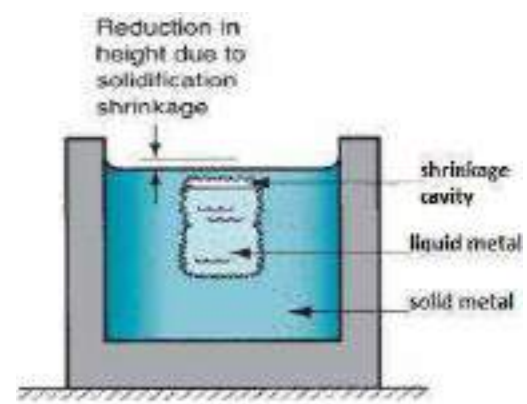


stage 2

Stage 3: Two effects are seen in this stage.

First effect - contraction causes further reduction in the height of the casting.

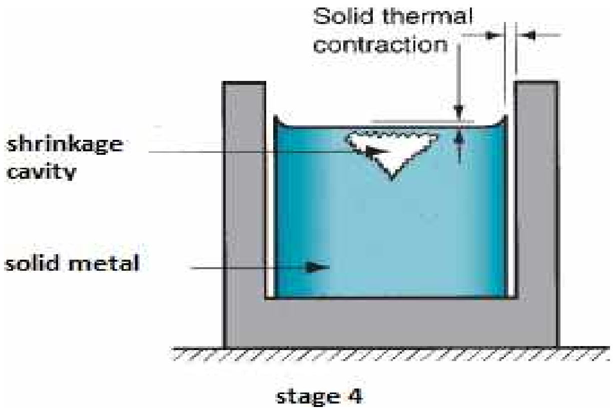
Second effect – top centre portion is the last to get freezed. The amount of liquid metal present to feed the top centre portion of the casting becomes restricted. Absence of metal in this region creates a void in the casting. This will be converted into **'shrinkage cavity'.**



stage 3

Stage 4:

Once solidified, both height and diameter contracts resulting in **shrinkage cavity** at the top centre. **This will be seen as a 'Pipe', in case casting is done in a tube like container which does not have mold wall at the bottom.**



Solidification shrinkage occurs almost in all metals because the solid phase has a higher density than the liquid phase.

The phase transformation that occurs during solidification causes a reduction in the volume per unit weight of metal. But cast iron containing high carbon content is an exception, whose solidification during the final stages is complicated by graphitization, which results in expansion. This will tend to oppose the decrease in cast volume associated with the phase change.

Compensation for shrinkage cavity : by providing riser, by following shrink rule to have shrinkage allowances

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Directional solidification

There are few methods by which damages due to shrinkage can be minimized. They are directional solidification methods.

Method 1: Providing risers:

It is desirable for the regions of the casting far away from the liquid metal supply to freeze first and for solidification to progress from these remote regions toward the location of riser. In this way, molten metal will continually be available from the risers to prevent shrinkage voids during freezing.

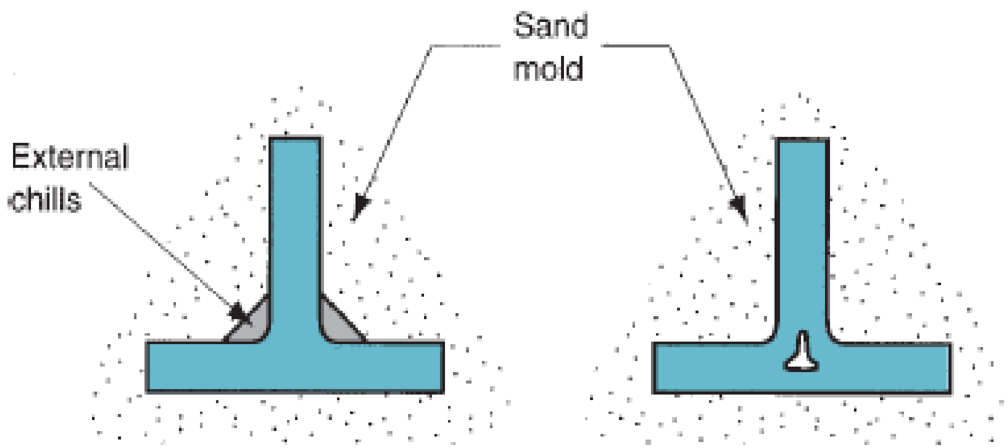
For example, the regions of the cast with lower V/A ratios should be placed far away from the riser location. Solidification will start from these locations and it will progress towards the riser location where bulkier sections of the cast are present. Hence the bulkier sections will continually received molten metal from the risers till freezing.

Method 2: Providing chills:

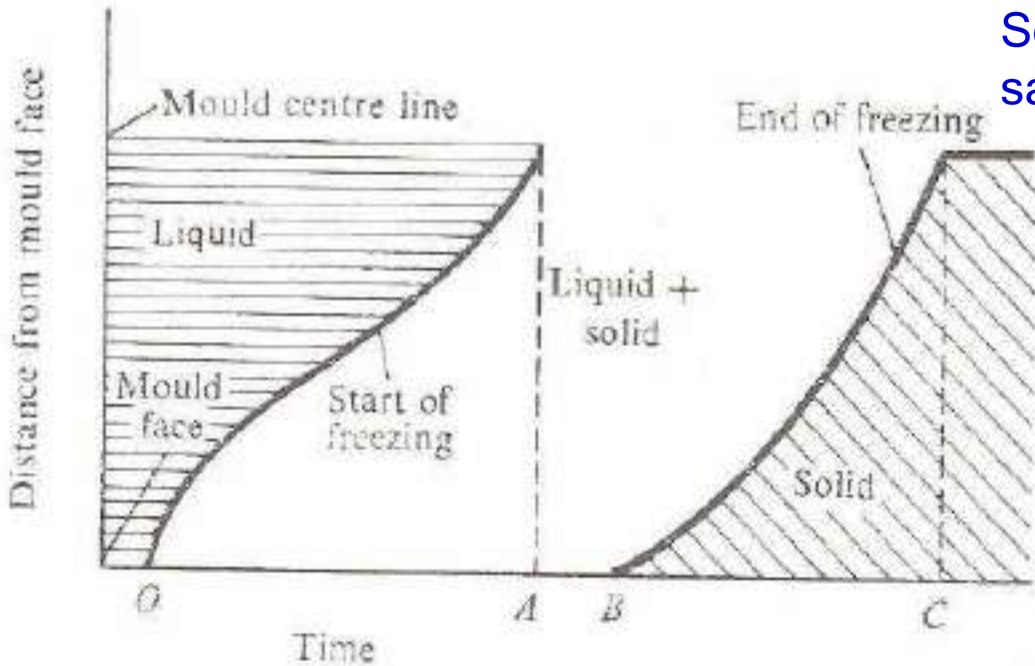
Chills can be provided at appropriate locations in order to have rapid solidification at those points. Internal and external chills can be provided.

Internal chills: small metal parts are placed inside the mould cavity before pouring so that the molten metal will solidify first around these parts. The internal chill should have a chemical composition similar to the metal being poured, so that it can be made out of same cast metal.

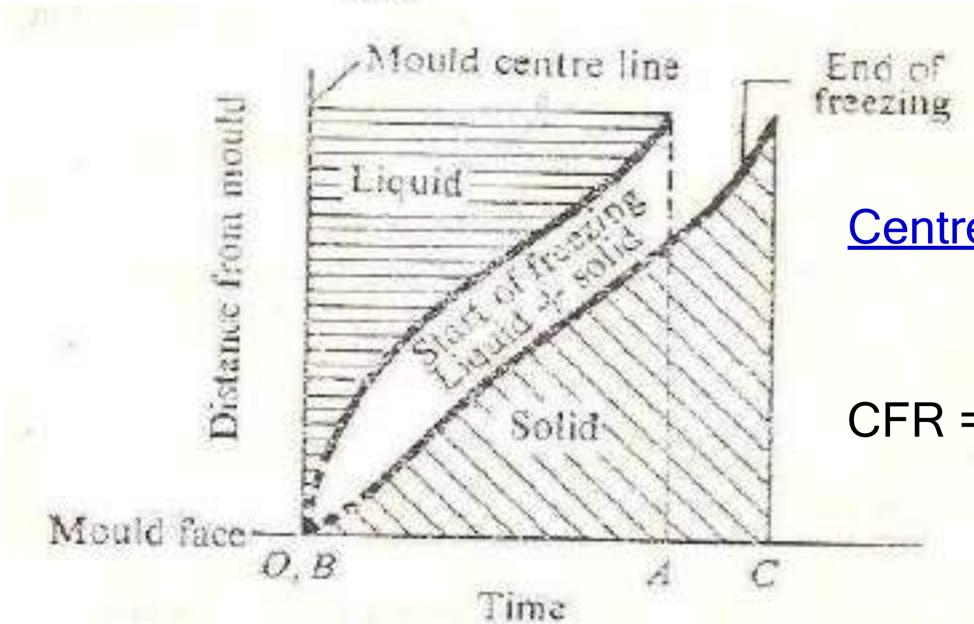
External chills: They are metal inserts kept in mould walls that can extract heat from the molten metal more rapidly than the surrounding sand in order to promote localized solidification. They are mainly used in sections of the casting that are difficult to supply with molten metal.



With external chill Without external chill



Solidification diagram for ordinary sand mould



Solidification diagram for chilled mould

Centre-line feeding resistance (CFR)

$$CFR = \frac{\text{time interval between start and end of freezing at centre line (AC)}}{\text{total solidification time of casting (OC)}}$$

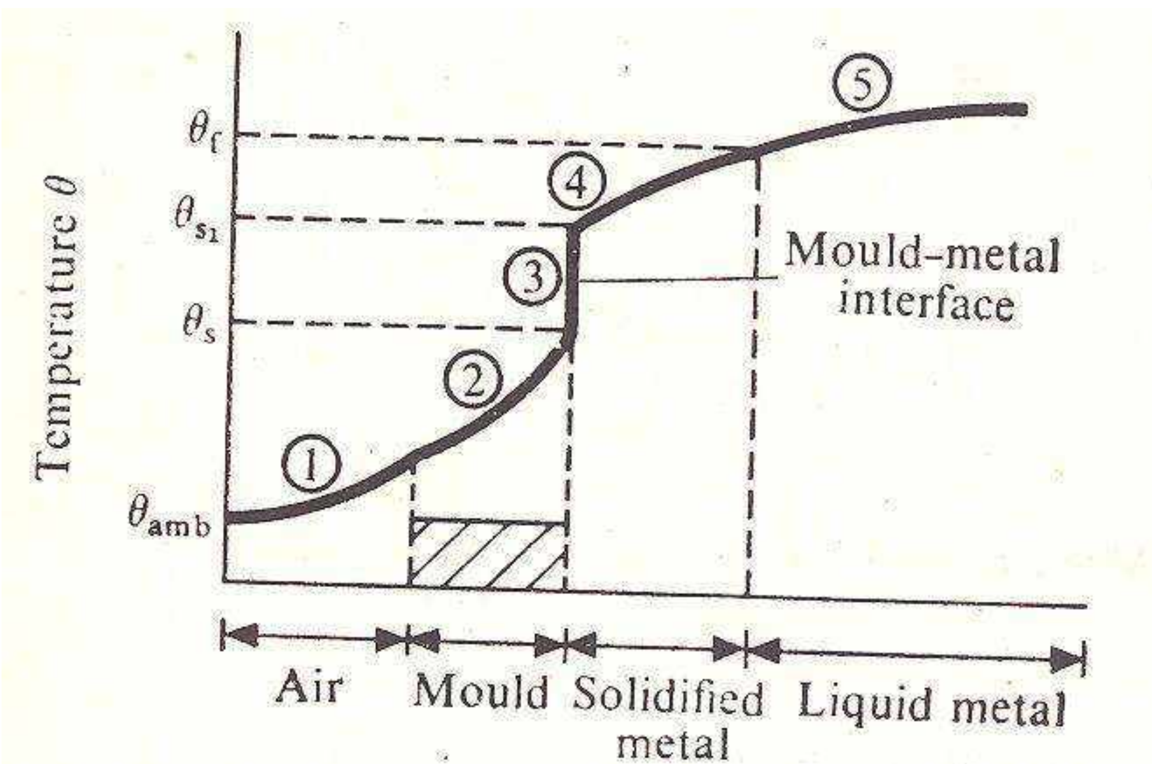
CFR > 70% : FEEDING IS CONSIDERED TO BE DIFFICULT

Rate of solidification

IN order to place the riser properly and it does not solidify before the casting, we should know about the (i) time taken by the casting to solidify, and (ii) distance to which solidification is completed from the mold surface.

We know that the heat rejected by the molten metal is dissipated through the mould wall. The heat thus released passes through FIVE different layers.

The temperature distribution in these layers is shown in figure.



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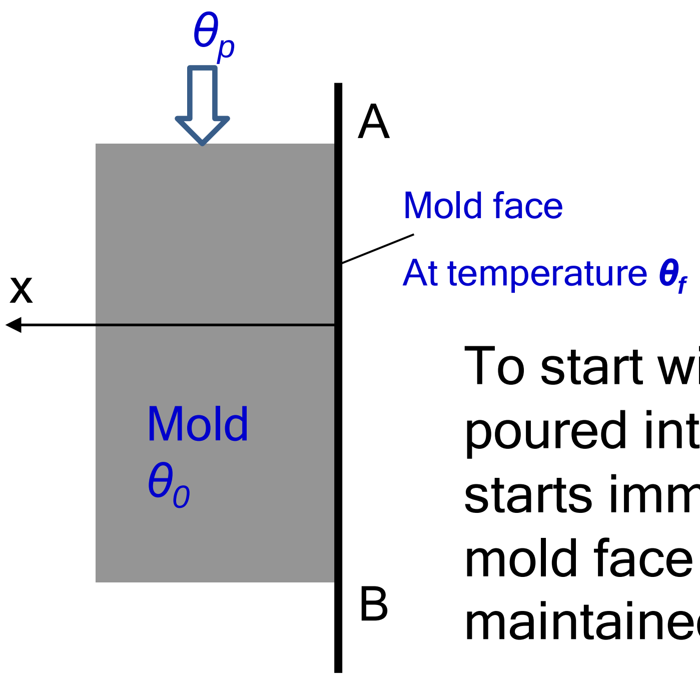
Solidification of casting in an insulating mold

During solidification of large casting like in sand casting, the entire thermal resistance is offered by the mold. **Hence we will consider region 2 only (from previous fig.).**



Consider the mold face AB as shown in figure. The large mold is at temperature θ_0 initially. Assume that the mold is extended up to infinity in x-direction.

To start with (at t = 0), the liquid metal at θp temperature is poured into the mold. Let us assume that solidification starts immediately near the mold surface and hence the mold face temperature be θ_f at $t = 0$. This temperature is maintained till freezing is completed.

The rate of heat flow through the mold face at any instant 't' is given by,

$$\dot{Q} = \frac{kA(\theta_f - \theta_0)}{\sqrt{\pi \alpha t}}$$

Here α is the thermal diffusivity of the mold material, $\alpha = k/(\rho c)$ where k = conductivity, ρ = density, c = specific heat of mold material.

Remember $\dot{Q} = -kA \frac{\partial \theta_x}{\partial x}$

Thus, the total heat quantity flow across the mold face up to a certain time 't_0' is given by,

$$Q_{t0} = \int_0^{t_0} Q\,dt = \frac{2kA(\theta_f - \theta_0)}{\sqrt{\pi\alpha}}\sqrt{t_0}$$

t_0=>t_s; Q_{t0}=> Q_{ts}

If the molten metal has a latent heat 'L', a specific heat c_m, and density ρ_m, the heat liquid metal rejects to solidify is,

$$Q_R = \rho_m V[L + c_m(\theta_p - \theta_f)]$$

The solidification time, say t_s, is given by assuming the total heat crossing the mold face and the heat rejected are equal, i.e.,

$Q_{ts} = Q_R$

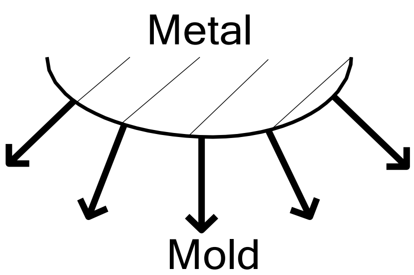
Chvorinov's rule

After simplification,

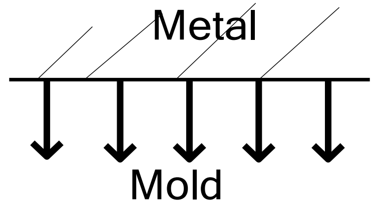
$$\boxed{t_s = \gamma\left(\frac{V}{A}\right)^2 \quad where\ \gamma = \left(\frac{\rho_m\sqrt{\pi\alpha}\,[L + c_m(\theta_p - \theta_f)]}{2k(\theta_f - \theta_0)}\right)^2}$$

Remember that we have used a plane contour (AB), but practically any shaped contour can be used.

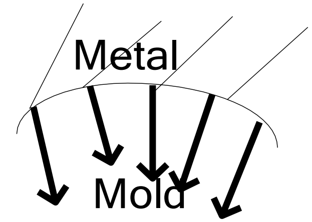
The different metal-mold interfaces possible are:



Convex surface



Plane surface



Concave surface

In order to consider the effect of metal-mold interfaces, we introduce two parameters like,

$$\beta = \frac{V/A}{\sqrt{\alpha t_s}};\lambda = \frac{\theta_f - \theta_0}{\rho_m L'}\rho c$$

Here ρ_m is for molten metal and ρ, c for sand; $L' = L + c_m(\theta_p - \theta_f)$

For infinite plane, $\beta = \lambda \frac{2}{\sqrt{\pi}}$

For a sphere, $\beta = \lambda\left(\frac{2}{\sqrt{\pi}} + \frac{1}{3\beta}\right)$

For infinite long cylinder, $\beta = \lambda\left(\frac{2}{\sqrt{\pi}} + \frac{1}{4\beta}\right)$

A Ghosh and A K Mallik, *Manufacturing Science*

Find the solidification time of the two iron castings when both are poured (with no superheats) into the sand molds at initial temperature 28°C.

(i) A slab shaped casting of 10 cm thickness, (ii) a sphere of 10 cm in dia.

Iron: freezing temp: 1540°C; L= 272 kJ/kg; density = 7850 kg/m^3

Sand: c = 1.17 kJ/kg-K; k = 0.865 W/mk; density = 1600 kg/m^3

Ans: (i) 0.675 hr, (ii) 0.055 hr

Riser design

The riser can be designed as per Chvorinov's rule mentioned earlier. The following example will illustrate the same.

A cylindrical riser must be designed for a sand-casting mold. The casting itself is a steel rectangular plate with dimensions 7.5 cm x12.5 cm x 2.0 cm. Previous observations have indicated that the solidification time for this casting is 1.6 min. The cylinder for the riser will have a diameter-to-height ratio as 1.0. Determine the dimensions of the riser so that its solidification time is 2.0 min.

For casting:

V/A ratio = (7.5 x 12.5 x 2) / 2(7.5x12.5 + 12.5x2 + 7.5x2)

= 187.5 / 267.5 = 0.7

$$\gamma = \frac{t_s}{(\frac{V}{A})^2} = 1.6/(0.7)^2 = 3.26 \text{ min/cm}^2$$

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed

For riser: $D/H = 1$ and $t_s = 2$ min; $V = \pi D^2H/4$; $A = \pi DH + 2\pi D^2/4$

From $D/H = 1 \Rightarrow D = H$ then

$V = \pi D^3/4$; $A = \pi D^2 + 2\pi D^2/4 = 1.5\, \pi D^2$

So, $V/A = D/6$.

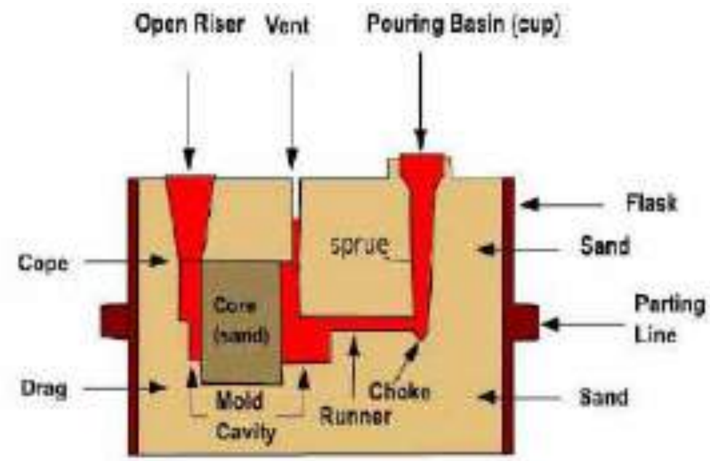
Now by Chvorinov's rule, $2.0 = 3.26\,(D/6)^2 \Rightarrow$

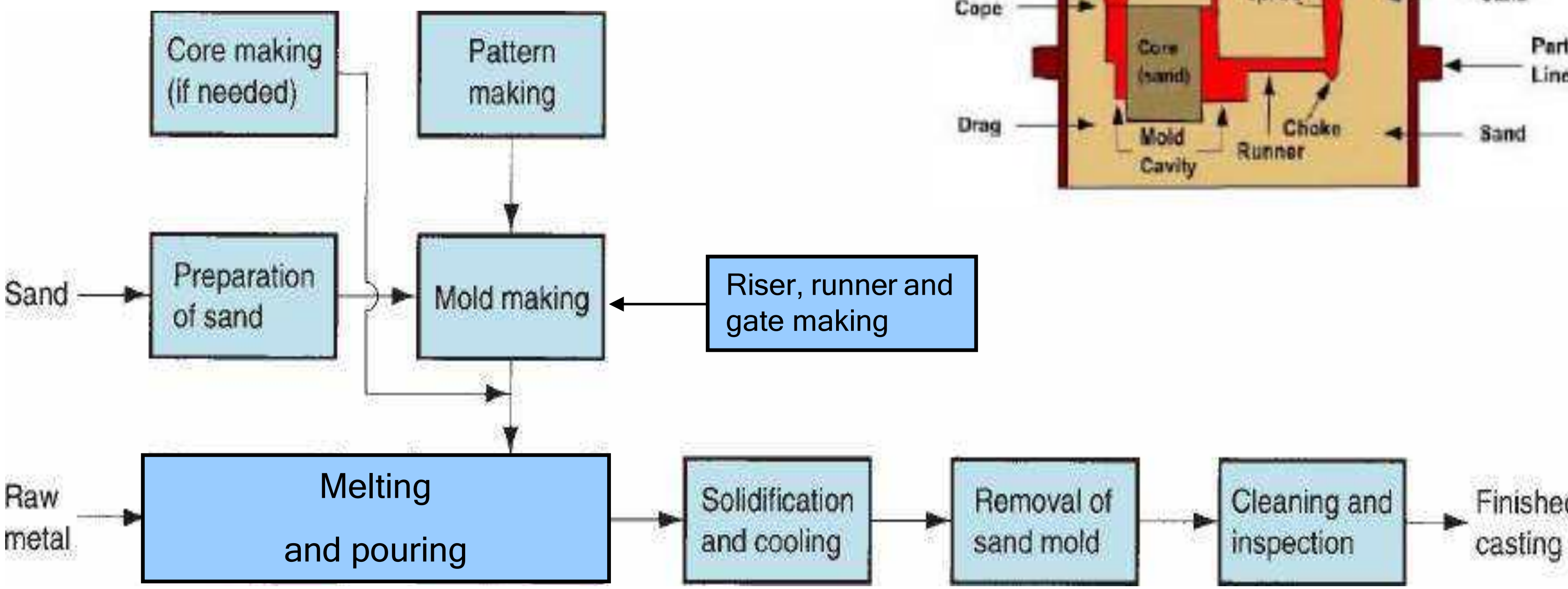
$D = 4.7$ cm and $H = 4.7$ cm (riser dimensions)

Note that the volume of the riser in this problem is $V = \pi/4\,(4.7)^2\,(4.7) = 81.5\ \text{cm}^3$, which is just 44% of the volume of the cast plate, though its solidification time is 25% longer.

Sand Casting

We have already seen sand casting processes. The steps involved in this process is shown here briefly.





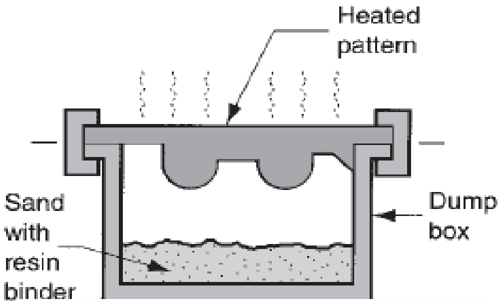
Other casting: Two types – (I) Expendable moulding, (II) Permanent moulding

Expendable moulding processes

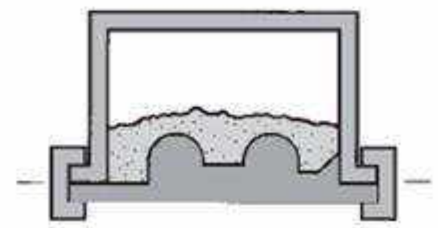
Shell moulding

The shell moulding is a casting process in which the mould is a thin shell of 9 mm thick. This is made of sand held together by thermosetting resin binder.

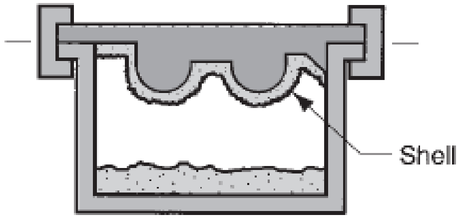
A metal pattern is heated and placed over a box containing sand mixed with thermosetting resin



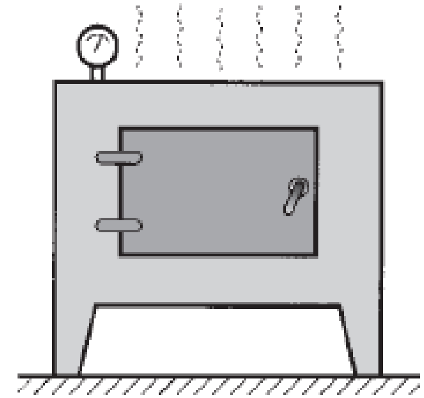
The dump box is inverted so that sand and resin mixture fall on the hot pattern, causing a layer of the mixture to partially cure on the pattern surface to form a hard shell



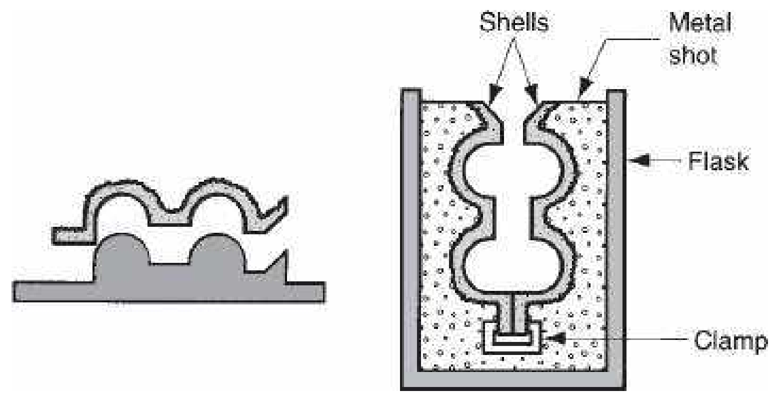
The box is positioned to the previous stage, so that loose, uncured particles drop away



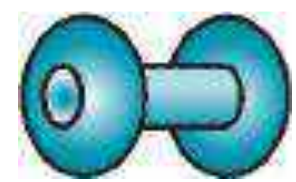
sand shell is heated in oven for several minutes to complete curing



The shell mold is removed from the pattern and two halves of the shell mold are assembled, supported by sand or metal shot in a box, and pouring is completed



The part made by this method is shown here



Advantages of shell moulding process

• The surface of the shell mould is smoother than conventional green sand mould. This permits easier flow of molten metal during pouring and better surface finish on the final casting.

• Surface finish of the order of 2.5 μm can be obtained. Good dimensional tolerances of the order of ± 0.25 mm can be reached in a small to medium sized parts.

• Machining operations are reduced because of good surface finish.

•can be mechanized for mass production and will be economical too.

Disadvantages

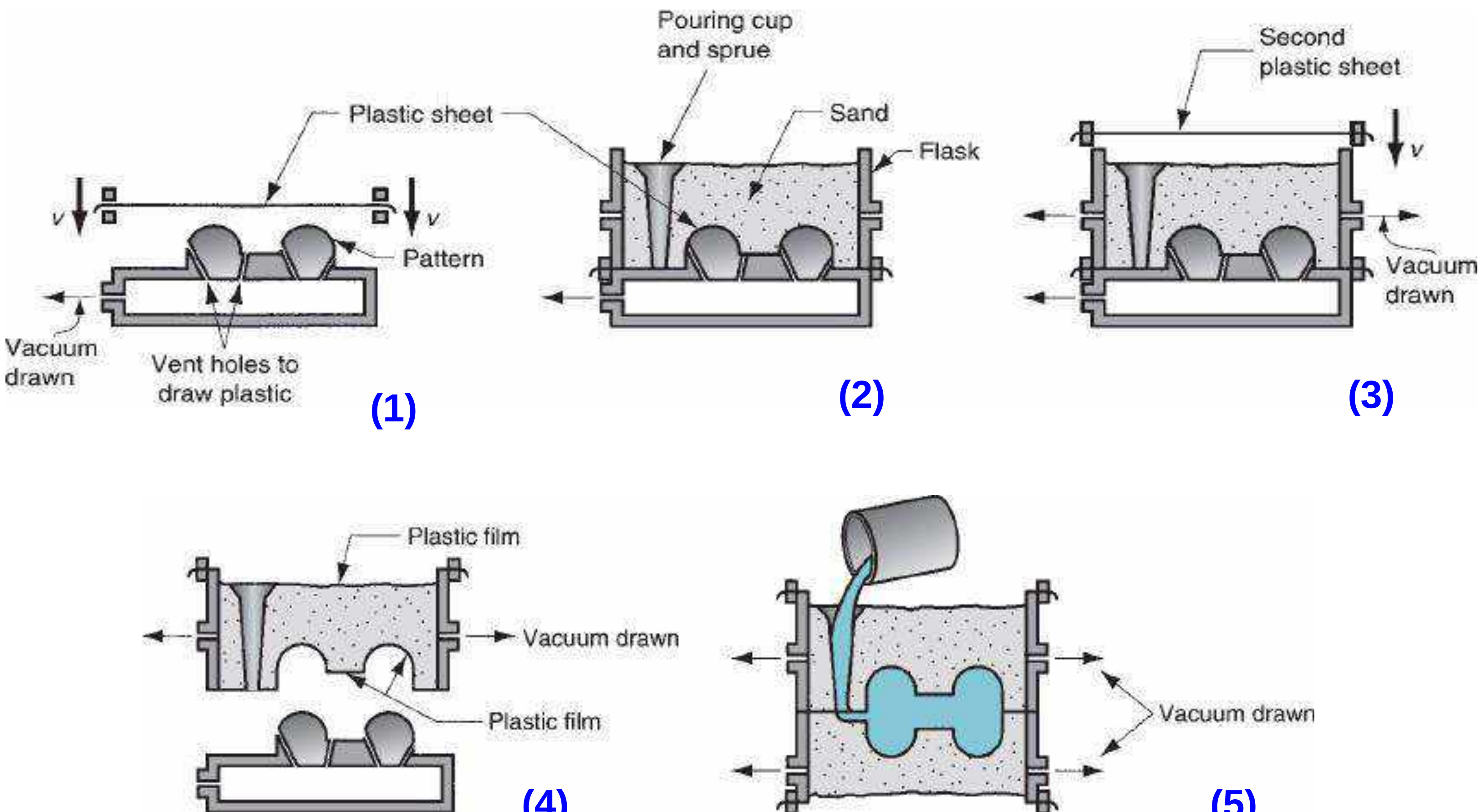
• expensive metal pattern is required, and hence not suitable for small quantities.

Examples of parts made using shell molding include gears, valve bodies, bushings, and camshafts.

Vacuum moulding

In this process, a sand mold is held together by vacuum pressure and not by a chemical binder.

The term vacuum in this process refers to the making of the mold, rather than the casting operation. Casting operation is same as any other process.



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Advantages:

• No binders are used and hence sand is readily recovered in vacuum molding

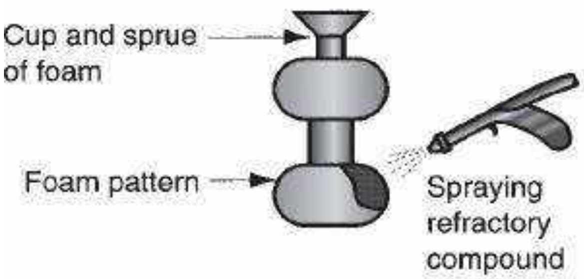
• Mechanical ramming is not required

• Since no water is mixed with the sand, moisture related defects are absent from the product

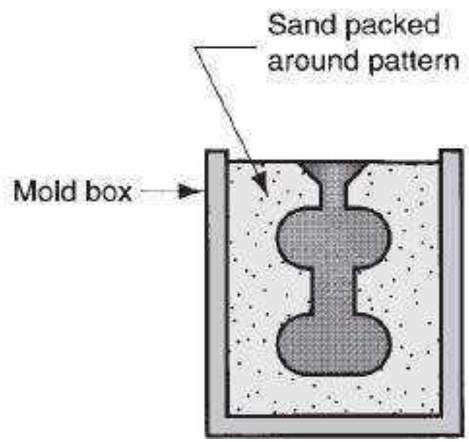
Disadvantages:

• relatively slow and not readily adaptable to mechanization

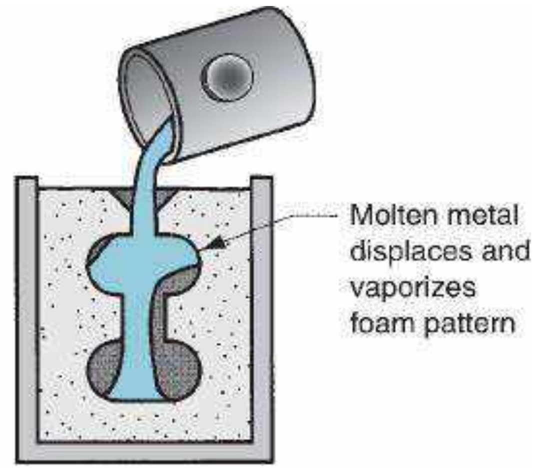
EXPANDED POLYSTYRENE PROCESS



Polystyrene pattern is coated with refractory compound



Pattern is placed in the mold box and packed with sand around it



molten metal is poured into the portion of the pattern

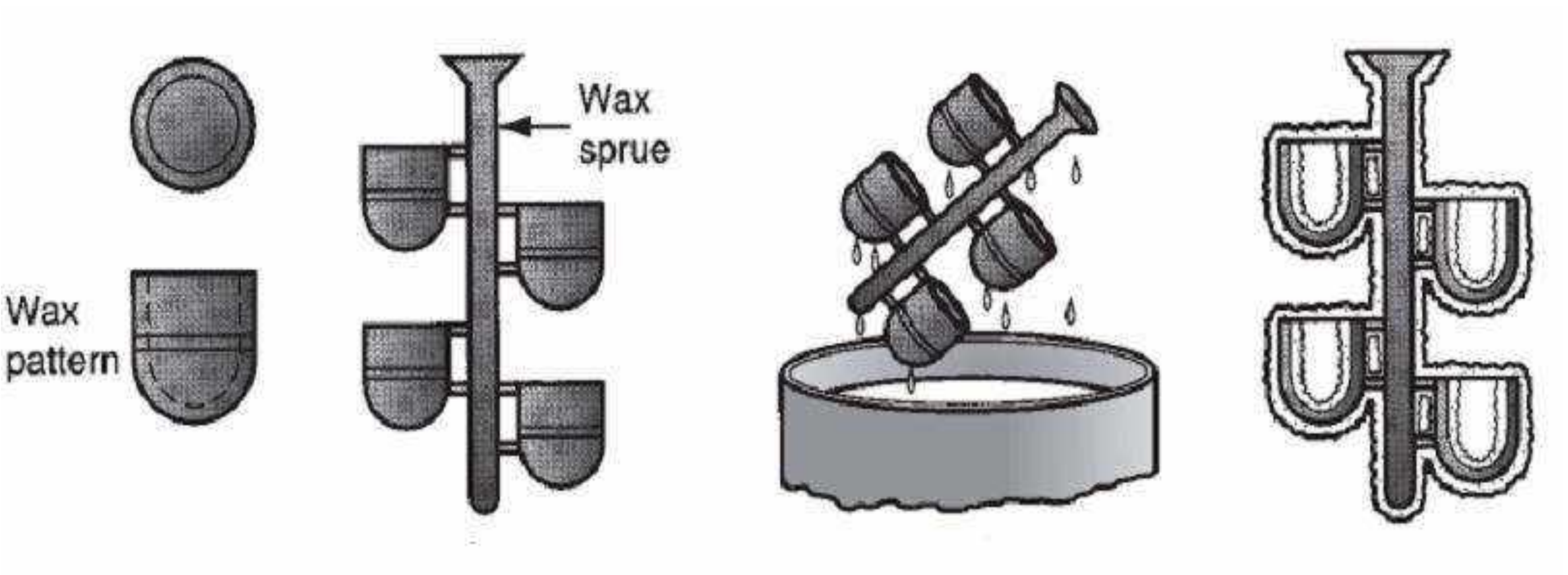
- In this process, a mold of sand packed around a polystyrene foam pattern is used. This pattern will vaporize when the molten metal is poured into the mold.
- The refractory compound will provide a smoother surface on the pattern and to improve its high temperature resistance.
- Molding sands usually include bonding agents.
- Also called as lost-foam process, lost pattern process, evaporative-foam process.
- The foam pattern includes risers, sprue, gating system, internal core.
- Parting lines and draft considerations are reduced.

Investment casting

In this casting process, a pattern made of wax is coated with a refractory material to make the mold surface, after which the wax is melted away while pouring the molten metal.

“Investment” means “to cover completely” which refers to the coating of the refractory material around the wax pattern.

This is a precision casting process. Using this we can make castings of high accuracy with intricate details.



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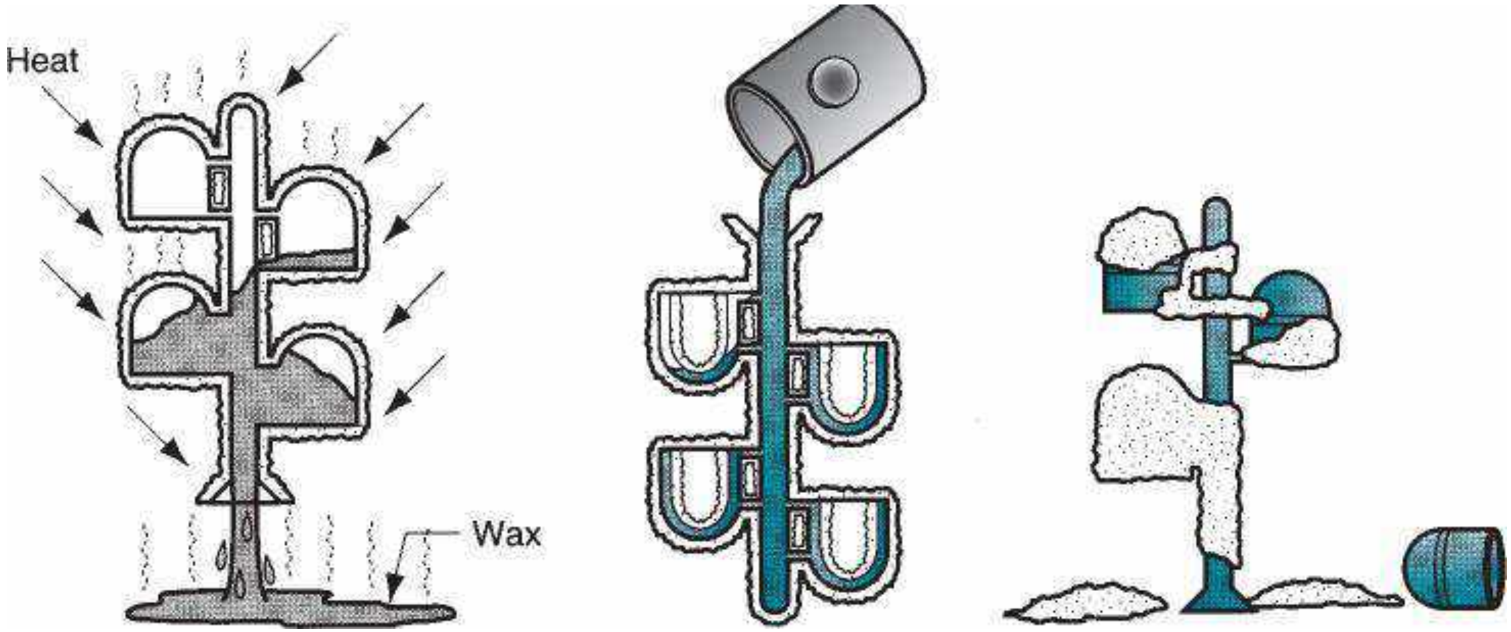


- Wax patterns are first made
- several patterns can be attached to a sprue to form a pattern tree, if required
- the pattern tree is coated with a thin layer of refractory material and later covered with thick coating to make the rigid full mold
- Heating of mold in inverted position to melt the wax and permit it to drip out of the cavity
- the mold is preheated to a high temperature so that contaminants are eliminated from the mold
- the molten metal is poured and it solidifies
- the mold is removed from the finished casting

Refractory coating:

• Slurry of very fine grained silica or other refractory, in powder form, mixed with plaster to bond the mold into shape. The small grain size of the refractory material delivers smooth surface and captures the intricate depths of the wax pattern.

• Mold is allowed to dry in air for about 8 hours to harden the binder.

Advantages:

(1) Complex and intricate parts can be cast
(2) tolerances of 0.075 mm are possible
(3) good surface finish is possible
(4) In general, additional machining is not required – near net shaped part

Applications:

- Steels, stainless steels, high temperature alloys can be cast
- Examples of parts: machine parts, blades, components for turbine engines, jewelry, dental fixtures

Plaster mold and ceramic mold casting

Plaster mold:

- similar to sand casting, except mold is made of POP and not sand
- To minimize contraction, curing time, reduce cracking, additives like talc and silica flour are mixed with the plaster.
- Curing time: 20 mts, baking time: several hours
- Permeability is low. This problem is solved by using a special mold composition and treatment known as the Antioch process. IN this operation, about 50% of sand is mixed with the plaster, heating the mold in an autoclave, and then drying is done. Good permeability is attained by this treatment.
- Used only for Al, Mg, Cu based alloys

Ceramic mold:

- mold is made of refractory ceramic materials which can withstand high temp. than plaster.
- Ceramic molding can be used to cast steels, CI, and other high temp. alloys.

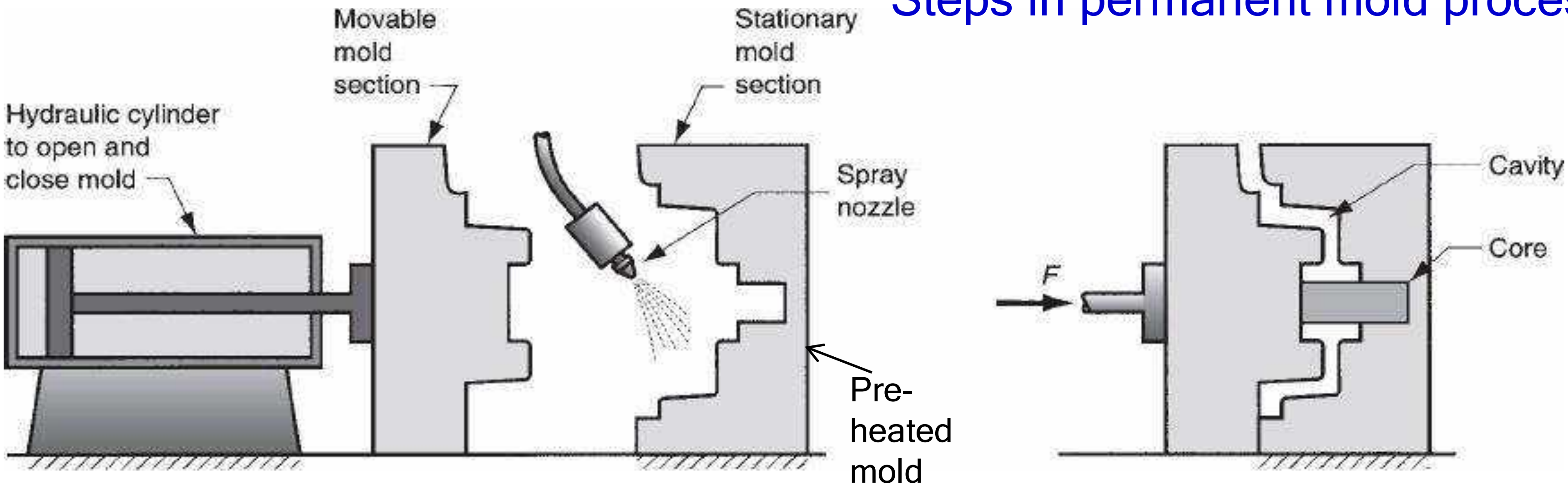
Permanent mold process

Disadvantage of expendable molding processes is that for every casting a new mold is required.

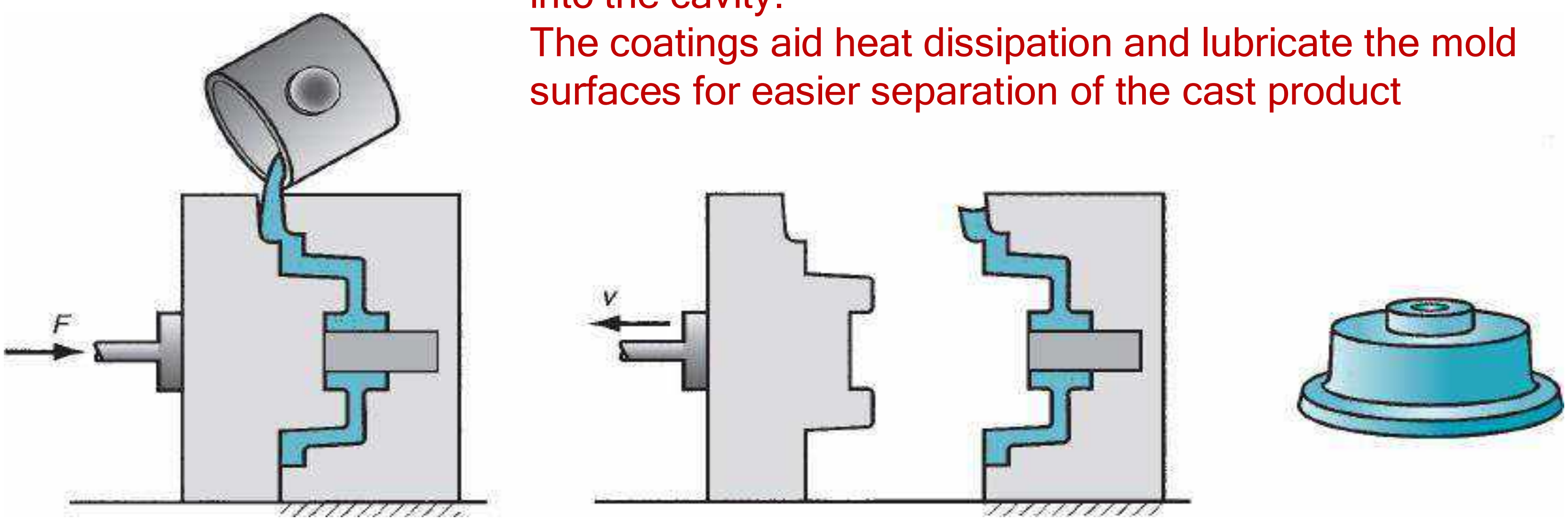
Permanent mold processes:

- using only metal mold for casting
- Molds are generally made of steel, CI
- materials that can be cast: Al, Mg, Cu based alloys, CI (affect the mold life, hence not used)
- cores are also made of metal, but if sand is used then called semi permanent-mold casting
- Advantages: good surface finish, dimension tolerance, rapid solidification causes fine grains to form giving stronger products
- limitations: restricted to simple part geometries, low melting point metals, mold cost is high. Best suitable for small, large number of parts

Steps in permanent mold process



Preheating facilitates metal flow through the gating system and into the cavity.
The coatings aid heat dissipation and lubricate the mold surfaces for easier separation of the cast product



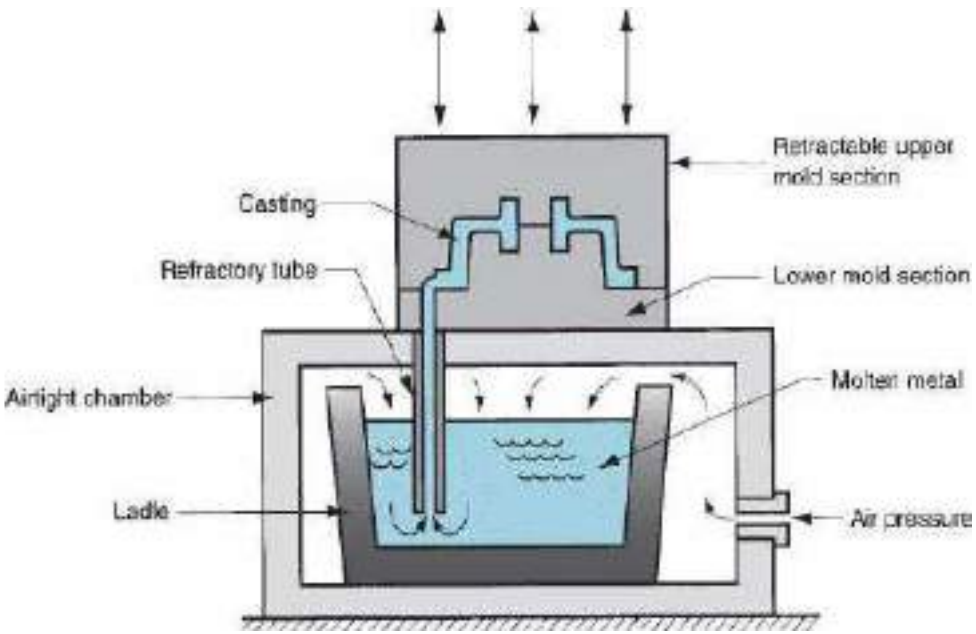
Variations of permanent mold casting

Low pressure casting:

• In the earlier casting process, metal flow in mold cavity is by gravity pull, but in low pressure casting, liquid metal is forced into the cavity under low pressure, app. 0.1 MPa, from beneath the surface so that metal flow is upward.

• advantage: molten metal is not exposed to air; gas porosity and oxidation defects are minimized

Vacuum permanent mold casting:
variation of low pressure casting, but in this vacuum is used to draw the molten metal into the mold cavity.



Low pressure casting

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed

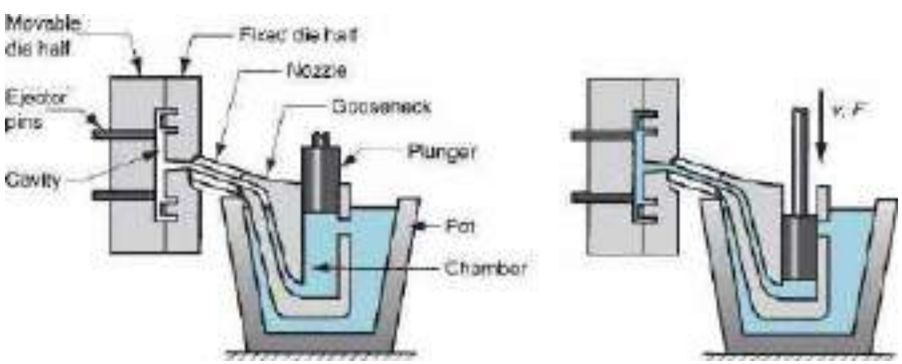
Die casting

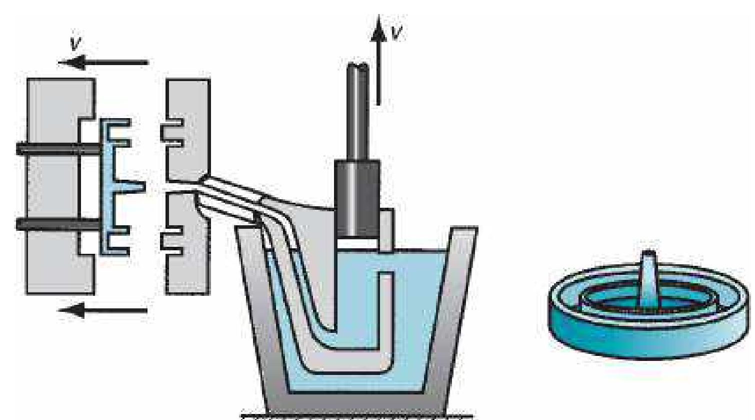
In this process, high pressure of app. 7 to 350 MPa is used to pressurize the molten metal into die cavity. The pressure is maintained during solidification.

Category: hot chamber machines, cold chamber machines

hot chamber machines:

- Molten metal is melted in a container attached to the machine, and a piston is used to pressurize metal under high pressure into the die. Typical injection pressures are between 7 and 35 MPa.
- Production rate of 500 parts/hour are common.
- Injection system is submerged into the molten metal and hence pose problem of chemical attack on the machine components. Suitable for zinc, tin, lead, Mg.



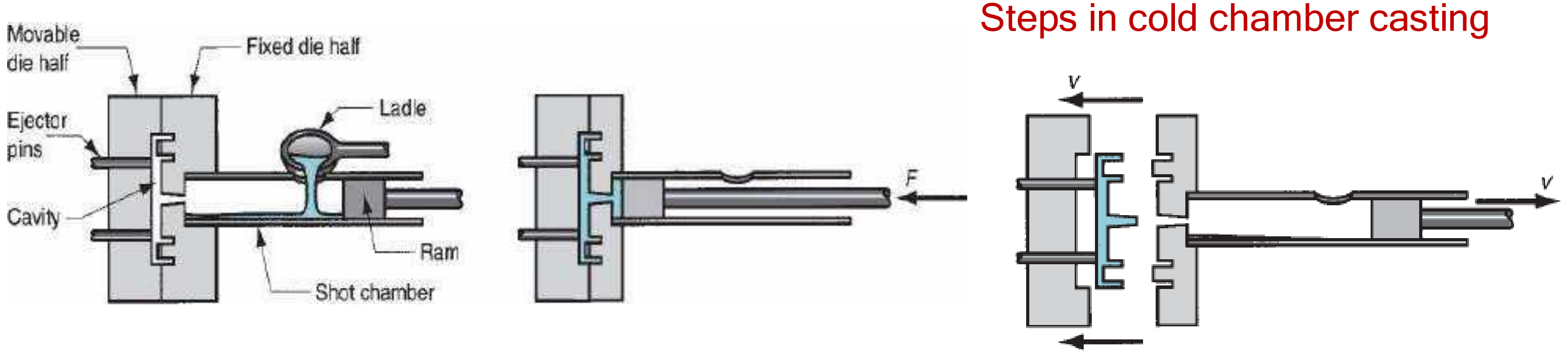


Steps in hot chamber casting

cold chamber machines:

- Molten metal is poured from an external unheated container into the mold cavity and piston is used to inject the molten metal into the die cavity.
- Injection pressure: 14 to 140 MPa.
- Though it is a high production operation, it is not as fast as hot chamber machines.

Steps in cold chamber casting



Die casting molds are made of tool steel, mold steel, maraging steels. Tungsten and molybdenum with good refractory qualities are also used for die cast steel, CI.

Advantages of die casting:

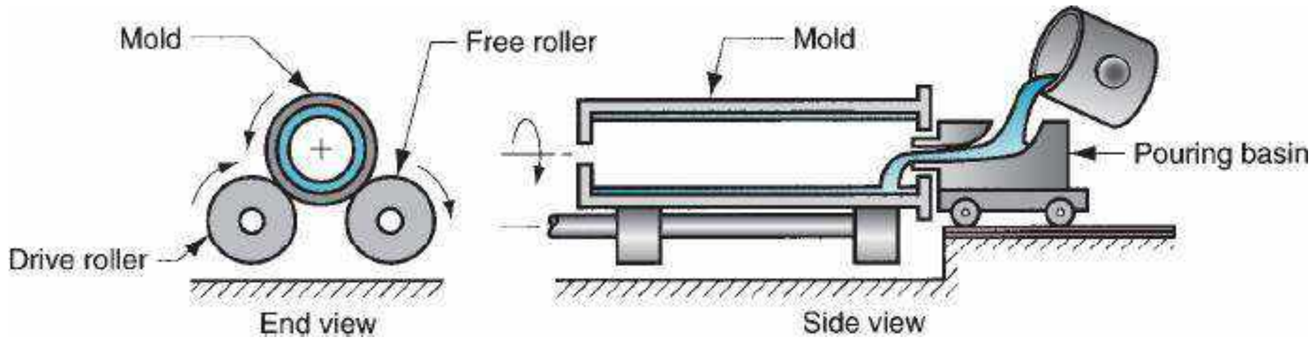
- high production rates and economical
- Close tolerances possible of the order of ±0.076 mm
- thin section with 0.5 mm can be made
- small grain size and good strength casting can be made because of rapid cooling

Centrifugal casting

- In this method, the mold is rotated at high speed so that the molten metal is distributed by the centrifugal force to the outer regions of the die cavity

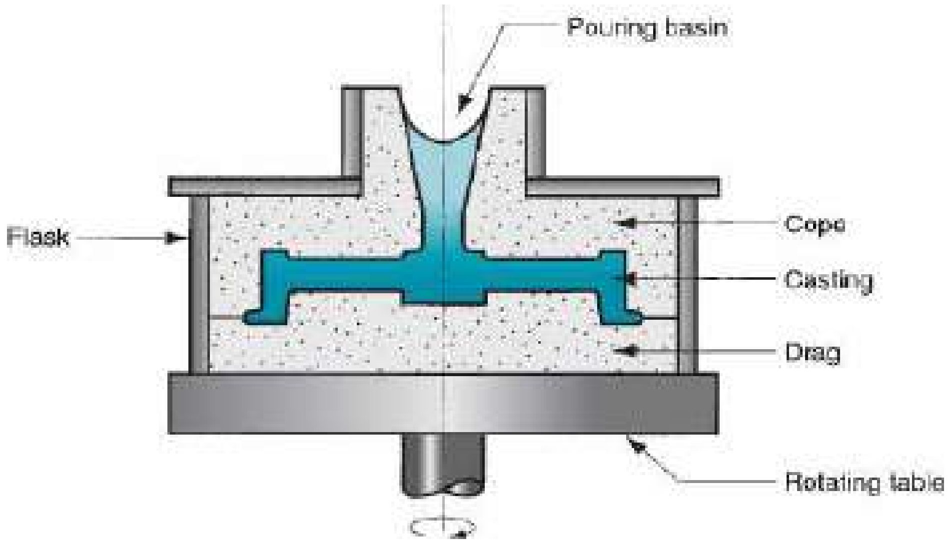
-includes : true centrifugal casting, semicentrifugal casting

True centrifugal casting:



- Molten metal is poured into a rotating mold to produce a tubular part (pipes, tubes, bushings, and rings)
- Molten metal is poured into a horizontal rotating mold at one end. The high-speed rotation results in centrifugal forces that cause the metal to take the shape of the mold cavity. The outside shape of the casting can be non-round, but inside shape of the casting is perfectly round, due to the radial symmetry w.r.t. forces

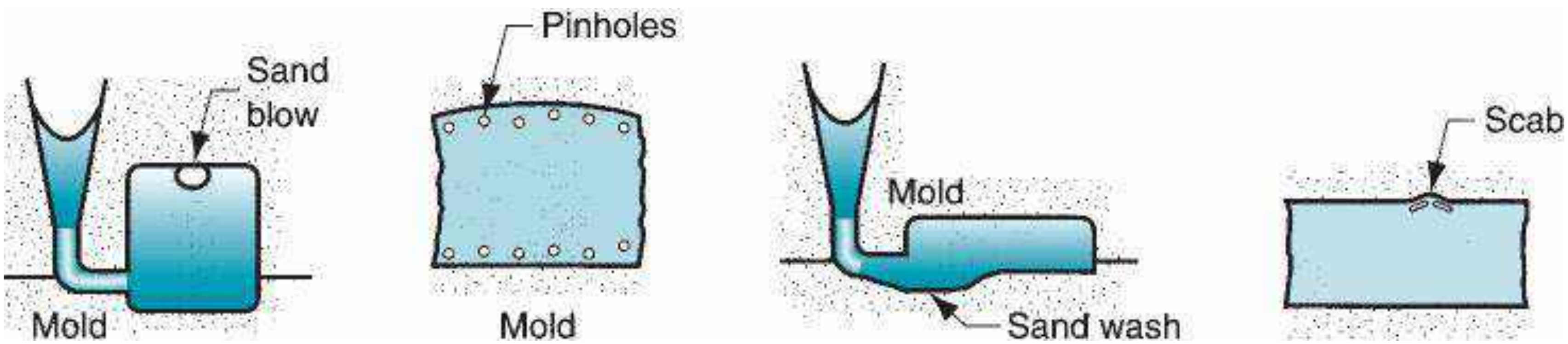
Semicentrifugal casting:



In this process, centrifugal force is used to produce non-tubular parts (solid), and not tubular parts. GF will be around 15 by controlling the rotation speed. Molds are provided with riser at the center.

Generally the density of metal will be more at the outer sections and not at the center of rotation. So parts in which the center region (less denser region) can be removed by machining (like wheels, pulleys) are usually produced with this method.

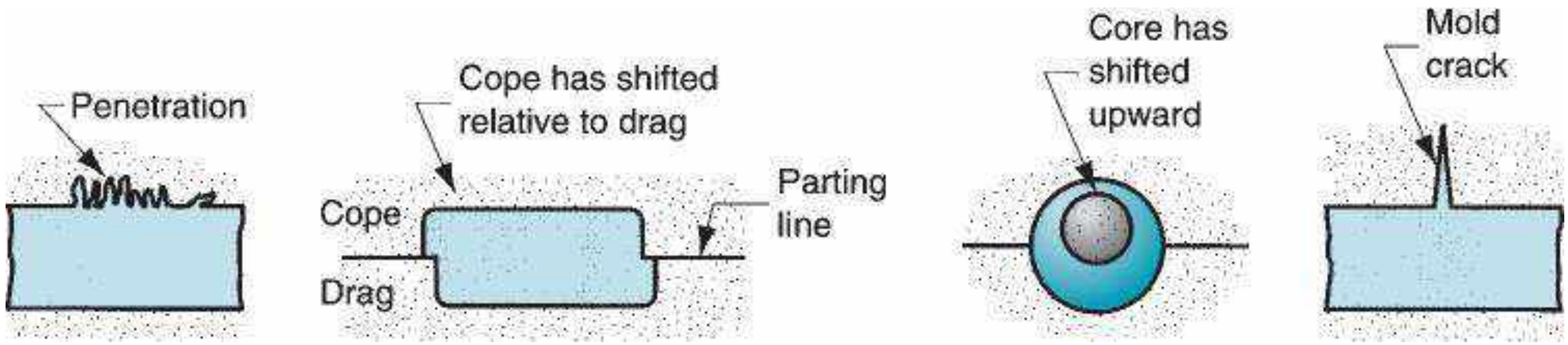
Defects in sand castings



Sand blow and Pinholes: defect consisting of a balloon-shaped gas cavity or gas cavities caused by release of mold gases during pouring. It is present just below the casting top surface. Low permeability, bad gas venting, and high moisture content of the sand mold are the usual causes.

Sand wash: surface dip that results from erosion of the sand mold during pouring. This contour is formed in the surface of the final cast part.

Scab: It is caused by portions of the mold surface flaking off during solidification and gets embedded in the casting surface.



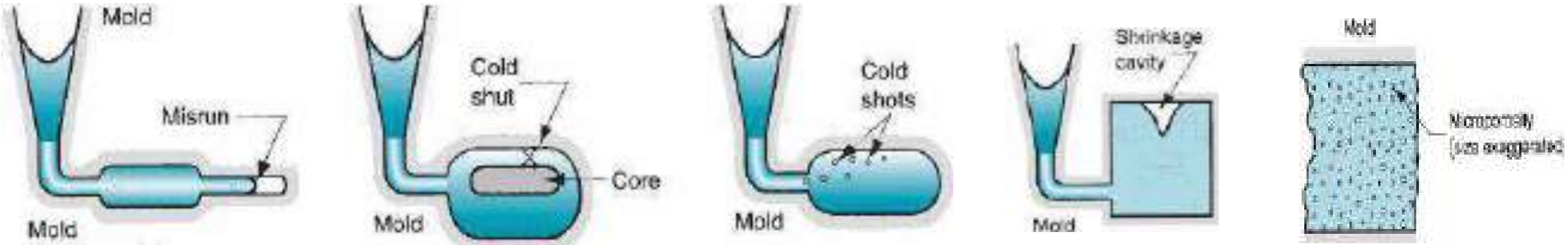
Penetration: surface defect that occurs when the liquid penetrates into the sand mold as the fluidity of liquid metal is high, After solidifying, the casting surface consists of a mixture of sand and metal. Harder ramming of sand mold minimize this defect.

Mold shift: defect caused by displacement of the mold cope in sideward direction relative to the drag. This results in a step in the cast product at the parting line.

Core shift: displacement of core vertically. Core shift and mold shift are caused by buoyancy of the molten metal.

Mold crack: ‘fin’ like defect in cast part that occurs when mold strength is very less, and a crack develops, through which liquid metal can seep.

Common defects in casting



Misruns: castings that solidify before completely filling the mold cavity. This occurs because of (1) low fluidity of the molten metal, (2) low pouring temperature, (3) slow pouring, (4) thinner cross-section of the mold cavity.

Cold Shuts: This defect occurs when two portions of the metal flow together but no fusion occurs between them due to premature freezing.

Cold shots: forming of solid globules of metal that are entrapped in the casting. Proper pouring procedures and gating system designs can prevent this defect.

Shrinkage cavity: cavity in the surface or an internal void in the casting, caused by solidification shrinkage that restricts the amount of molten metal present in the last region to freeze. It is sometimes called as ‘pipe’. Proper riser design can solve this problem.

Microporosity: network of small voids distributed throughout the casting caused by localized solidification shrinkage of the final molten metal.

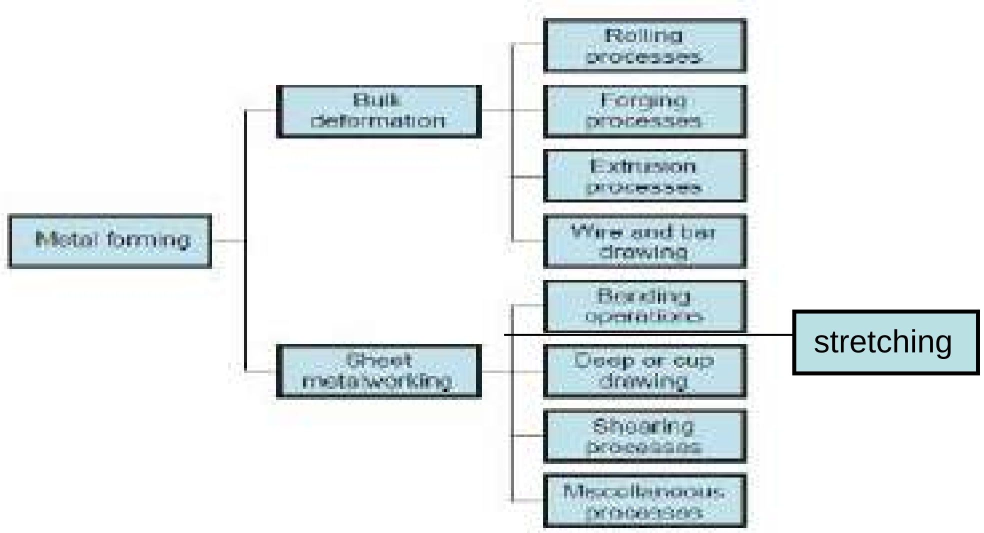
Module 2

Metal forming processes

Metal forming: Large set of manufacturing processes in which the material is deformed plastically to take the shape of the die geometry. The tools used for such deformation are called die, punch etc. depending on the type of process.

Plastic deformation: Stresses beyond yield strength of the workpiece material is required.

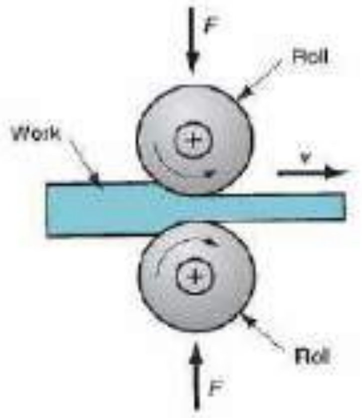
Categories: Bulk metal forming, Sheet metal forming



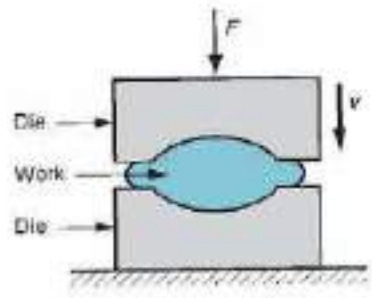
General classification of metal forming processes

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed

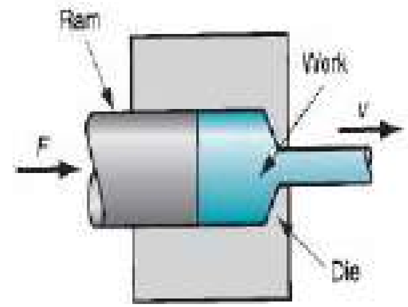
Classification of basic bulk forming processes



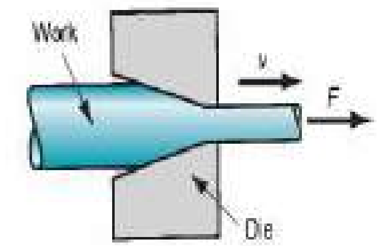
Rolling



Forging



Extrusion



Wire drawing

Bulk forming: It is a severe deformation process resulting in massive shape change. The surface area-to-volume of the work is relatively small. Mostly done in hot working conditions.

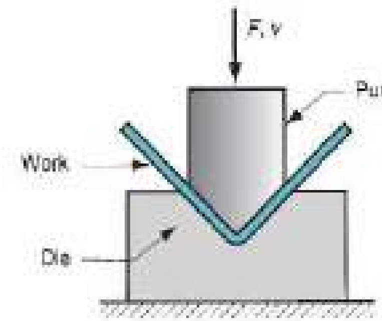
Rolling: In this process, the workpiece in the form of slab or plate is compressed between two rotating rolls in the thickness direction, so that the thickness is reduced. The rotating rolls draw the slab into the gap and compresses it. The final product is in the form of sheet.

Forging: The workpiece is compressed between two dies containing shaped contours. The die shapes are imparted into the final part.

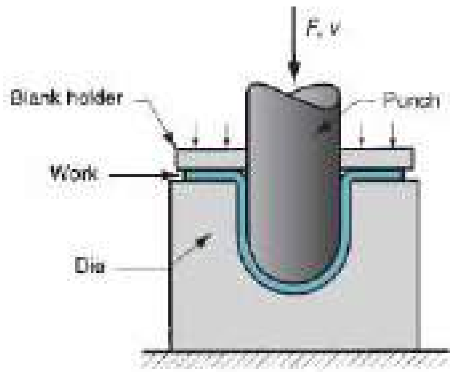
Extrusion: In this, the workpiece is compressed or pushed into the die opening to take the shape of the die hole as its cross section.

Wire or rod drawing: similar to extrusion, except that the workpiece is pulled through the die opening to take the cross-section.

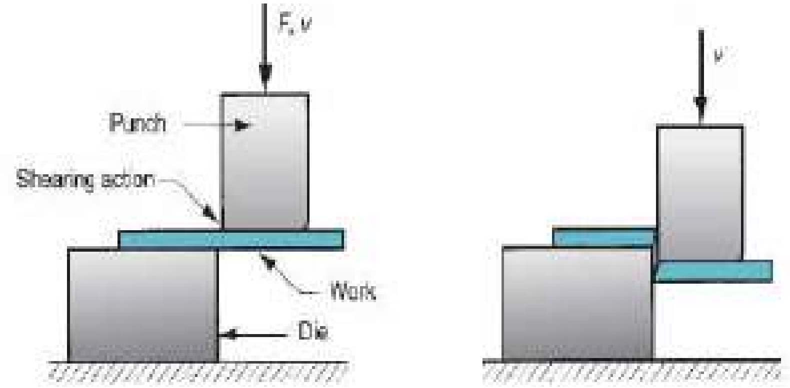
Classification of basic sheet forming processes



Bending



Deep drawing



shearing

Sheet forming: Sheet metal forming involves forming and cutting operations performed on metal sheets, strips, and coils. The surface area-to-volume ratio of the starting metal is relatively high. Tools include punch, die that are used to deform the sheets.

Bending: In this, the sheet material is strained by punch to give a bend shape (angle shape) usually in a straight axis.

Deep (or cup) drawing: In this operation, forming of a flat metal sheet into a hollow or concave shape like a cup, is performed by stretching the metal in some regions. A blank-holder is used to clamp the blank on the die, while the punch pushes into the sheet metal. The sheet is drawn into the die hole taking the shape of the cavity.

Shearing: This is nothing but cutting of sheets by shearing action.

Cold working, warm working, hot working

Cold working: Generally done at room temperature or slightly above RT.

Advantages compared to hot forming:
(1) closer tolerances can be achieved; (2) good surface finish; (3) because of strain hardening, higher strength and hardness is seen in part; (4) grain flow during deformation provides the opportunity for desirable directional properties; (5) since no heating of the work is involved, furnace, fuel, electricity costs are minimized, (6) Machining requirements are minimum resulting in possibility of near net shaped forming.
Disadvantages: (1) higher forces and power are required; (2) strain hardening of the work metal limit the amount of forming that can be done, (3) sometimes cold forming-annealing-cold forming cycle should be followed, (4) the work piece is not ductile enough to be cold worked.

Warm working: In this case, forming is performed at temperatures just above room temperature but below the recrystallization temperature. The working temperature is taken to be 0.3 T_m where T_m is the melting point of the workpiece.
Advantages: (1) enhanced plastic deformation properties, (2) lower forces required, (3) intricate work geometries possible, (4) annealing stages can be reduced.

Hot working: Involves deformation above recrystallization temperature, between $0.5T_m$ to $0.75T_m$.

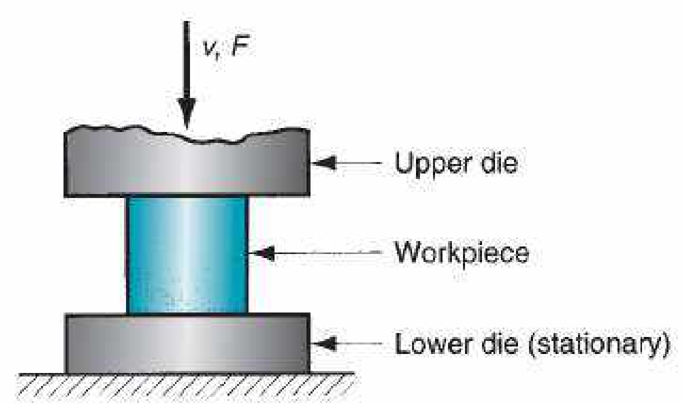
Advantages: (1) significant plastic deformation can be given to the sample, (2) significant change in workpiece shape, (3) lower forces are required, (4) materials with premature failure can be hot formed, (5) absence of strengthening due to work hardening.

Disadvantages: (1) shorter tool life, (2) poor surface finish, (3) lower dimensional accuracy, (4) sample surface oxidation

Forging

• It is a deformation process in which the work piece is compressed between two dies, using either impact load or hydraulic load (or gradual load) to deform it.
• It is used to make a variety of high-strength components for automotive, aerospace, and other applications. The components include engine crankshafts, connecting rods, gears, aircraft structural components, jet engine turbine parts etc.

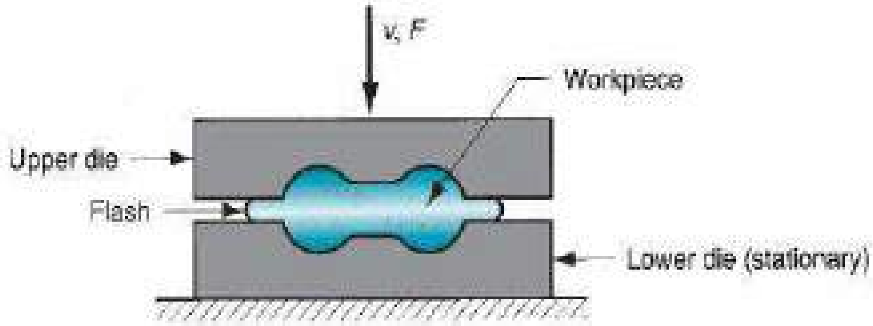
• Category based on temperature : cold, warm, hot forging
• Category based on presses:
impact load => forging hammer; gradual pressure => forging press
• Category based on type of forming:
Open die forging, impression die forging, flashless forging



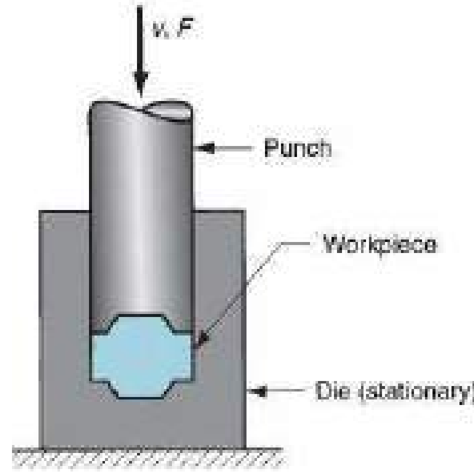
Open die forging

In open die forging, the work piece is compressed between two flat platens or dies, thus allowing the metal to flow without any restriction in the sideward direction relative to the die surfaces.

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed



impression die forging



flashless forging

In impression die forging, the die surfaces contain a shape that is given to the work piece during compression, thus restricting the metal flow significantly. There is some extra deformed material outside the die impression which is called as flash. This will be trimmed off later.

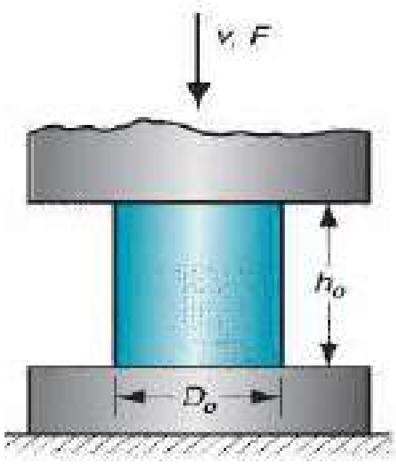
In flashless forging, the work piece is fully restricted within the die and no flash is produced. The amount of initial work piece used must be controlled accurately so that it matches the volume of the die cavity.

Open die forging

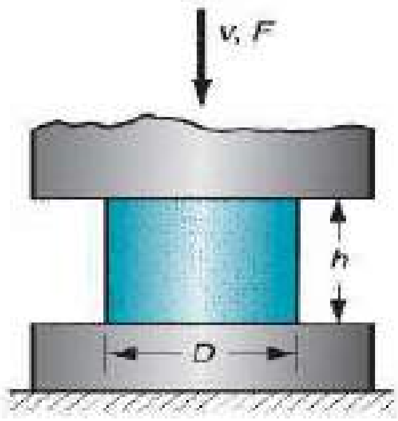
A simplest example of open die forging is compression of billet between two flat die halves which is like compression test. This also known as upsetting or upset forging. Basically height decreases and diameter increases.

Under ideal conditions, where there is no friction between the billet and die surfaces, homogeneous deformation occurs. In this, the diameter increases uniformly throughout its height.

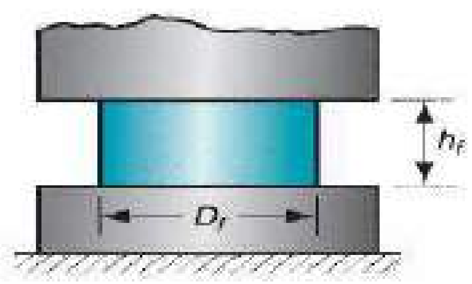
In ideal condition, $\varepsilon = \ln (h_o/h)$. h will be equal to h_f at the end of compression, ε will be maximum for the whole forming. Also $F = \sigma_f A$ is used to find the force required for forging, where σ_f is the flow stress corresponding to ε at that stage of forming.



Start of compression



Partial compression



Completed compression

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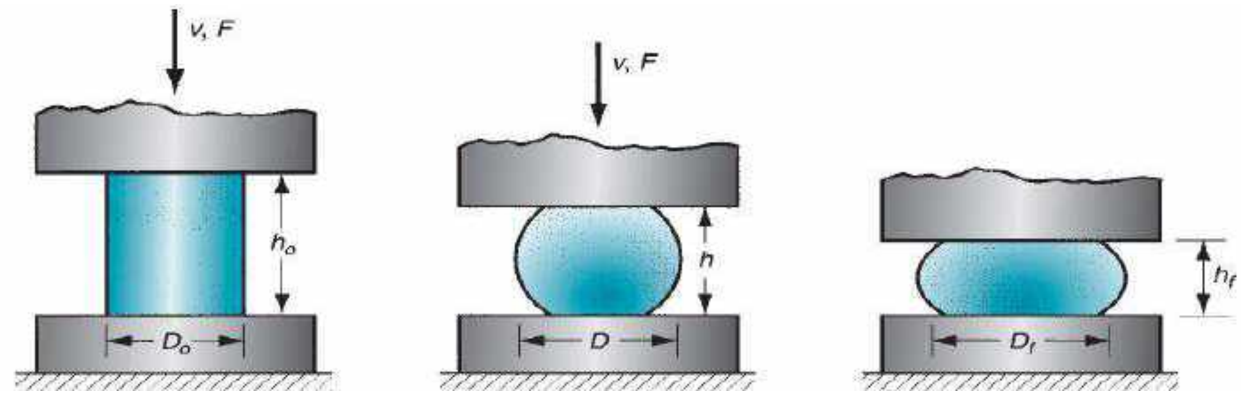
In actual forging operation, the deformation will not be homogeneous as bulging occurs because of the presence of friction at the die-billet interface. This friction opposes the movement of billet at the surface. This is called barreling effect.

The barreling effect will be significant as the diameter-to-height (*D/h*) ratio of the workpart increases, due to the greater contact area at the billet–die interface. Temperature will also affect the barreling phenomenon.



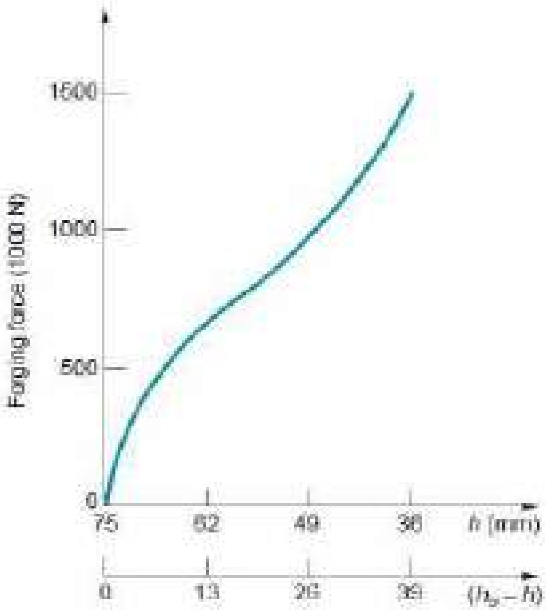
Start of compression **Partial compression** **Completed compression**

In actual forging, the accurate force evaluation is done by using, $F = K_f \sigma_f A$ by considering the effect of friction and *D/h* ratio. Here,

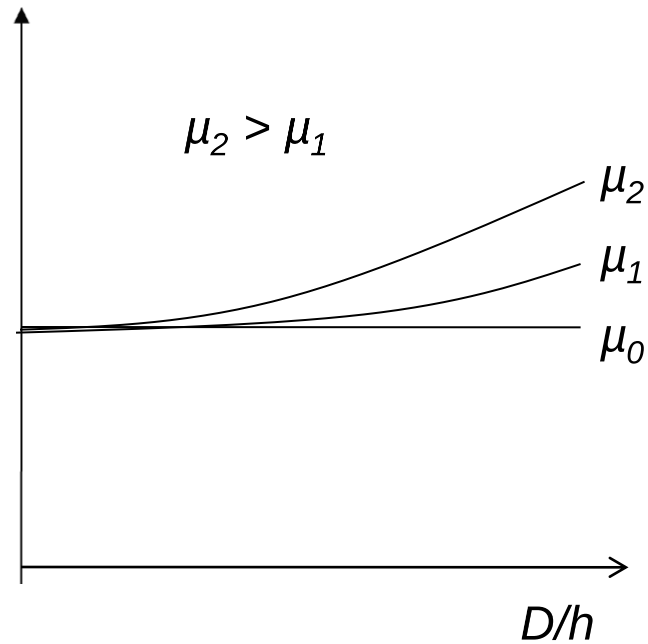
$$K_f = 1 + \frac{0.4 \mu D}{h}$$

Where K_f = forging shape factor, μ = coefficient of friction, D = work piece diameter, h = work piece height

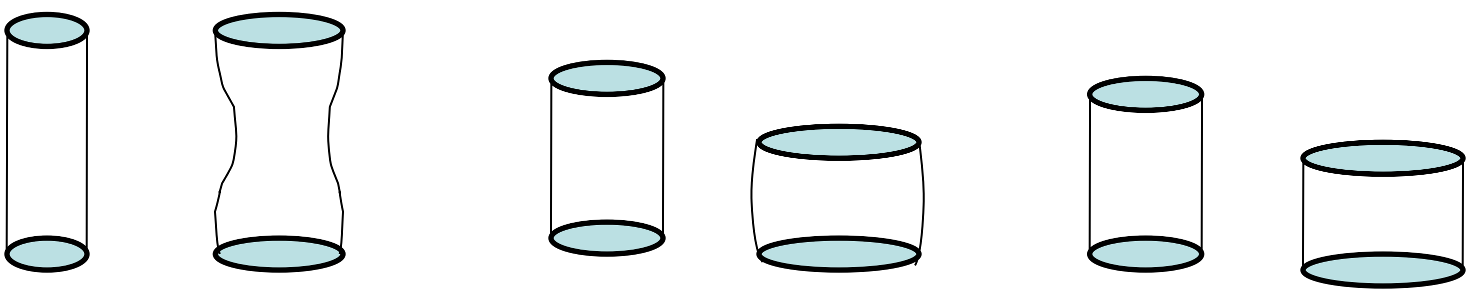
Typical load-stroke curve in open die forging



Effect of *D/h* ratio on load:



Effect of *h/D* ratio on barreling:



Long cylinder: *h/D* >2

Cylinder having *h/D* < 2 with friction

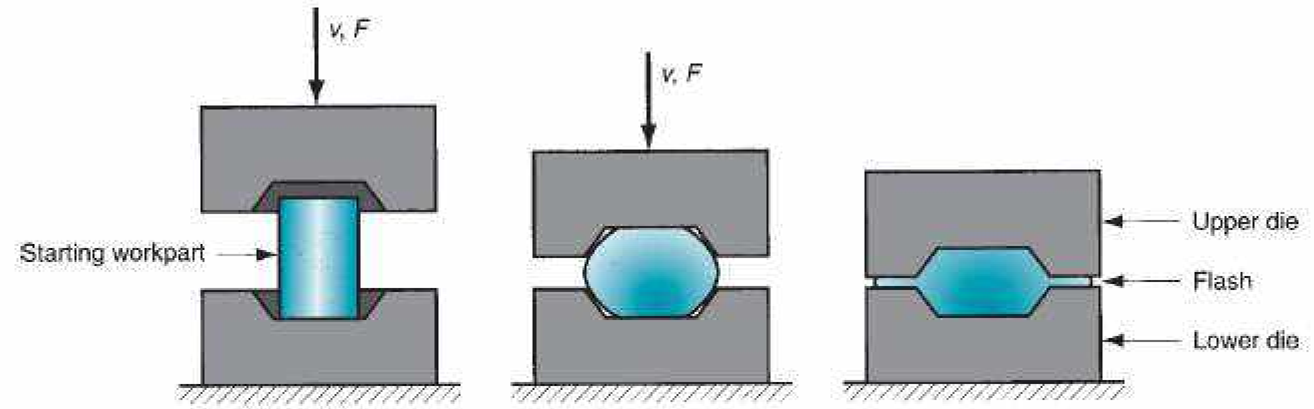
Frictionless compression

Closed die forging

Closed die forging called as impression die forging is performed in dies which has the impression that will be imparted to the work piece through forming.

In the intermediate stage, the initial billet deforms partially giving a bulged shape. During the die full closure, impression is fully filled with deformed billet and further moves out of the impression to form flash.

In multi stage operation, separate die cavities are required for shape change. In the initial stages, uniform distribution of properties and microstructure are seen. In the final stage, actual shape modification is observed. When drop forging is used, several blows of the hammer may be required for each step.



Starting stage | Intermediate stage | Final stage with flash formation

R. Ganesh Narayanan, IITG

M.P. Groover, *Fundamental of modern manufacturing Materials, Processes and systems*, 4ed

The formula used for open die forging earlier can be used for closed die forging, i.e.,

$F = K_f \sigma_f A$

Where F is maximum force in the operation; A is projected area of the part including flash, σ_f is flow stress of the material, K_f is forging shape factor.

Now selecting the proper value of flow stress is difficult because the strain varies throughout the work piece for complex shapes and hence the strength varies. Sometimes an average strength is used. K_f is used for taking care of different shapes of parts. Table shows the typical values of K_f used for force calculation. In hot working, appropriate flow stress at that temperature is used.

Part Shape	K_f	Part Shape	K_f
Impression-die forging:		Flashless forging:	
Simple shapes with flash	6.0	Coining (top and bottom surfaces)	6.0
Complex shapes with flash	8.0	Complex shapes	8.0
Very complex shapes with flash	10.0		

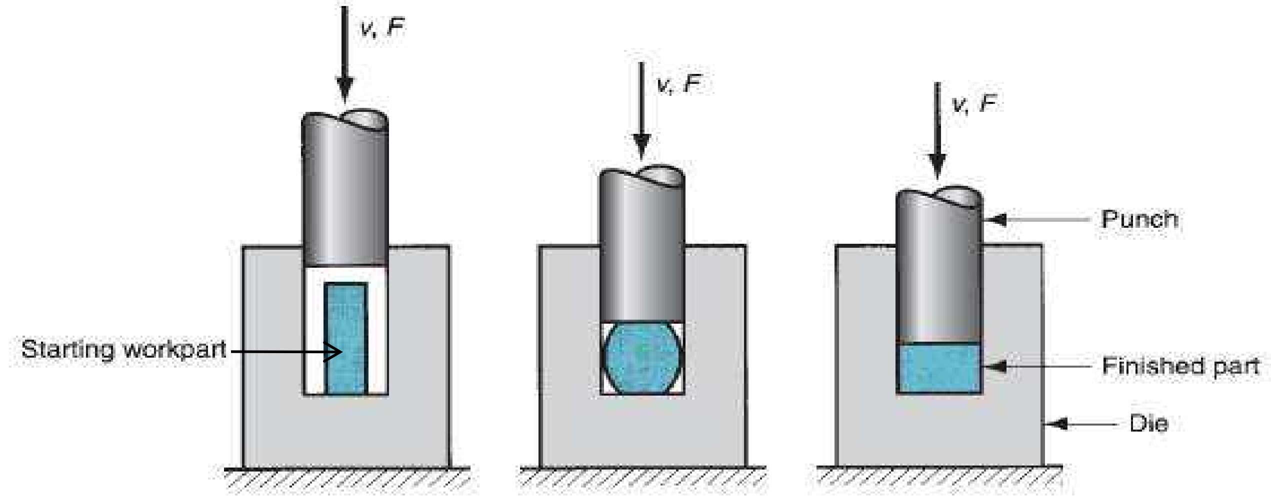
The above equation is applied to find the maximum force during the operation, since this is the load that will determine the required capacity of the press used in the forging operation.

Impression die forging is not capable of making close tolerance objects. Machining is generally required to achieve the accuracies needed. The basic geometry of the part is obtained from the forging process, with subsequent machining done on those portions of the part that require precision finishing like holes, threads etc.

In order to improve the efficiency of closed die forging, precision forging was developed that can produce forgings with thin sections, more complex geometries, closer tolerances, and elimination of machining allowances. In precision forging operations, sometimes machining is fully eliminated which is called near-net shape forging.

Flashless forging

The three stages of flashless forging is shown below:



In flashless forging, most important is that the work piece volume must equal the space in the die cavity within a very close tolerance.
If the starting billet size is too large, excessive pressures will cause damage to the die and press.
If the billet size is too small, the cavity will not be filled.

Because of the demands, this process is suitable to make simple and symmetrical part geometries, and to work materials such as Al, Mg and their alloys.

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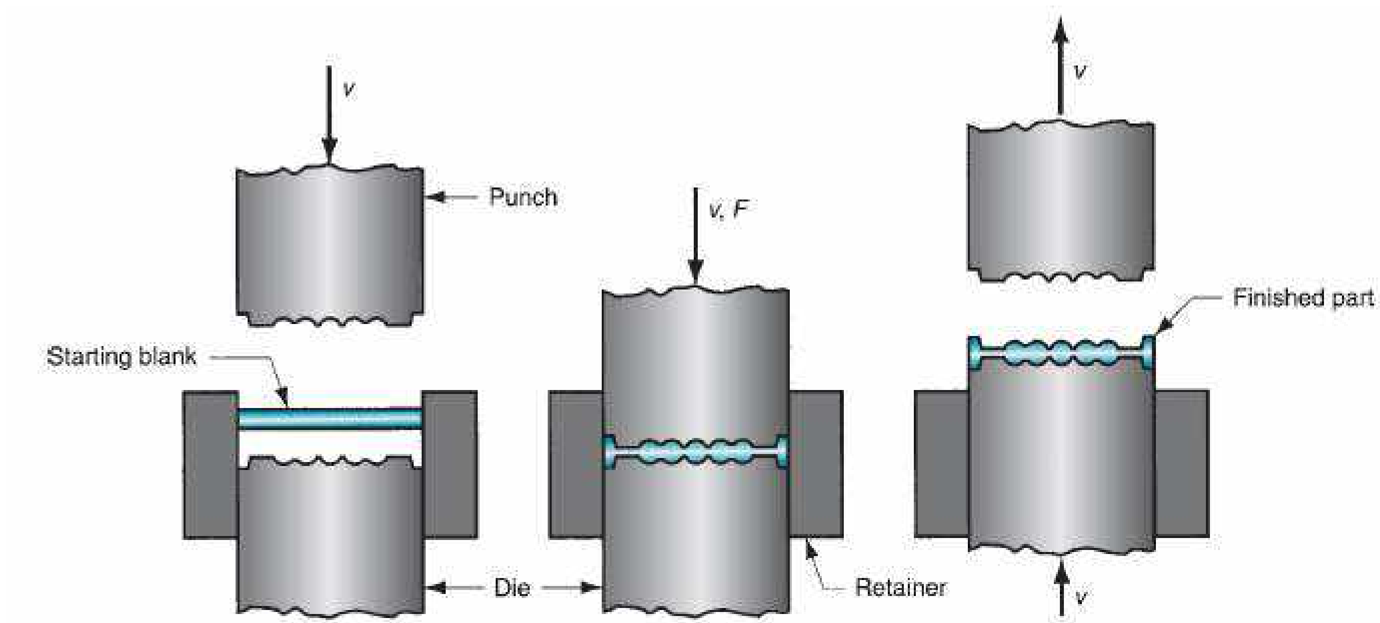
Coining is a simple application of closed die forging in which fine details in the die impression are impressed into the top or/and bottom surfaces of the work piece.

Though there is little flow of metal in coining, the pressures required to reproduce the surface details in the die cavity are at par with other impression forging operations.



Starting of cycle

Fully compressed

Ram pressure removed and ejection of part

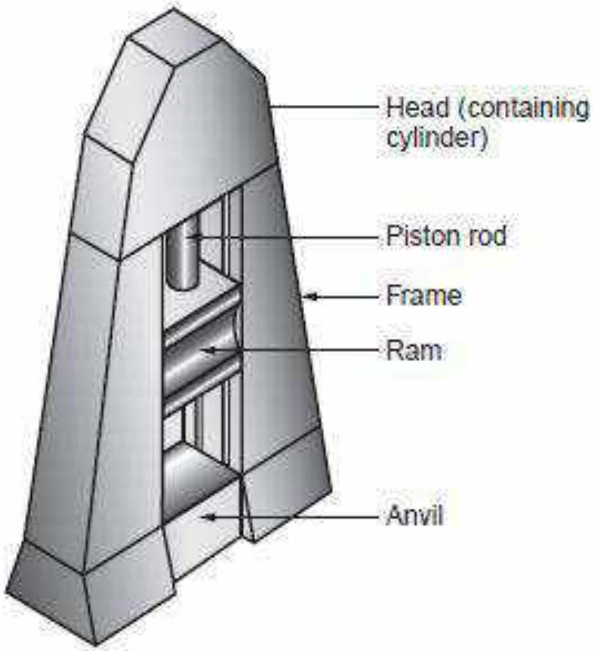
Making of coin

Forging hammers, presses and dies

Hammers:

Hammers operate by applying an impact loading on the work piece. This is also called as drop hammer, owing to the means of delivering impact energy.

When the upper die strikes the work piece, the impact energy applied causes the part to take the form of the die cavity. Sometimes, several blows of the hammer are required to achieve the desired change in shape.



Drop hammers

Drop hammers are classified as:
Gravity drop hammers, power drop hammers.

Gravity drop hammers - achieve their energy by the falling weight of a heavy ram. The force of the blow is dependent on the height of the drop and the weight of the ram.

Power drop hammers - accelerate the ram by pressurized air or steam.

Presses:

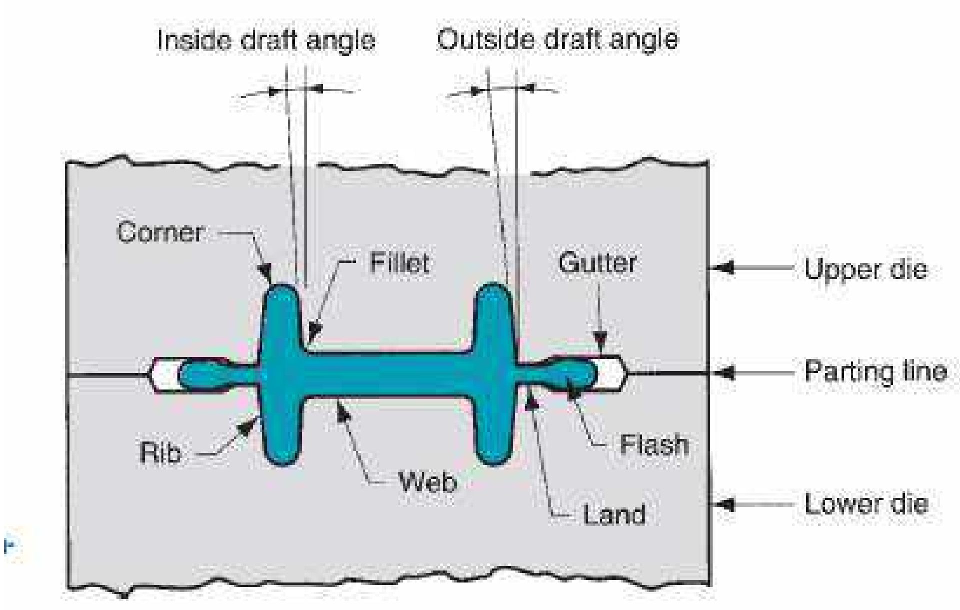
The force is given to the forging billet gradually, and not like impact force.

Mechanical presses: In these presses, the rotating motion of a drive motor is converted into the translation motion of the ram. They operate by means of eccentrics, cranks, or knuckle joints. Mechanical presses typically achieve very high forces at the bottom of the forging stroke.

Hydraulic presses : hydraulically driven piston is used to actuate the ram.

Screw presses : apply force by a screw mechanism that drives the vertical ram. Both screw drive and hydraulic drive operate at relatively low ram speeds.

Forging dies:



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Parting line: The parting line divides the upper die from the lower die. In other words, it is the plane where the two die halves meet. The selection of parting line affects grain flow in the part, required load, and flash formation.

Draft: It is the amount of taper given on the sides of the part required to remove it from the die.

Draft angles: It is meant for easy removal of part after operation is completed. 3° for Al and Mg parts; 5° to 7° for steel parts.

Webs and ribs: They are thin portions of the forging that is parallel and perpendicular to the parting line. More difficulty is witnessed in forming the part as they become thinner.

Fillet and corner radii: Small radii limits the metal flow and increase stresses on die surfaces during forging.

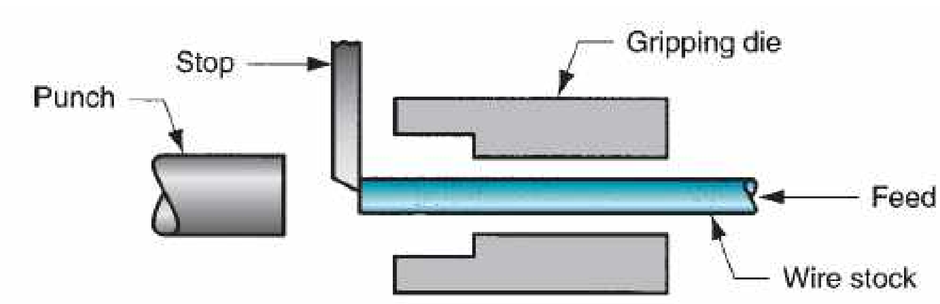
Flash: The pressure build up because of flash formation is controlled proper design of gutter and flash land.

Other forging operations

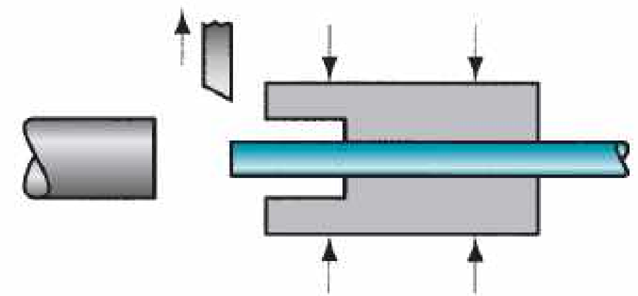
Upset forging:

It is a deformation operation in which a cylindrical work piece is increased in diameter with reduction in length. In industry practice, it is done as closed die forging.

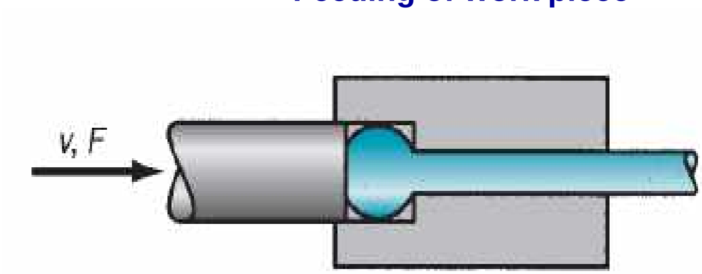
Upset forging is widely used in the fastener industries to form heads on nails, bolts, and similar products.



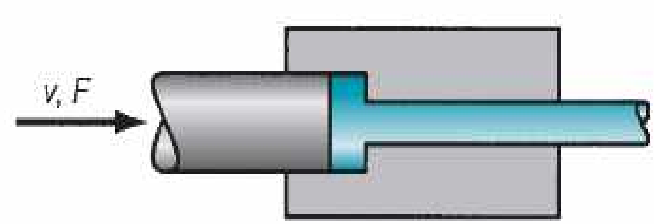
Feeding of work piece



Gripping of work piece and retracting of stop



Forward movement of punch and upsetting



Forging operation completes

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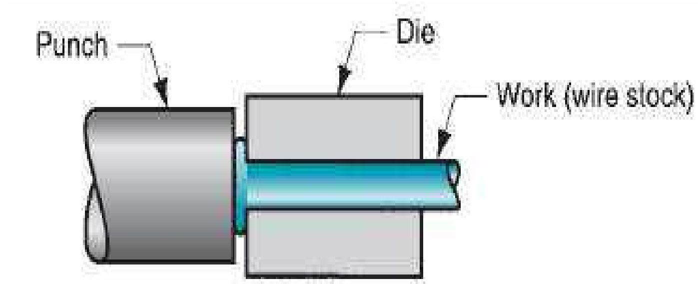
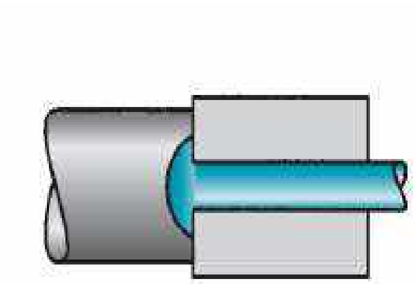
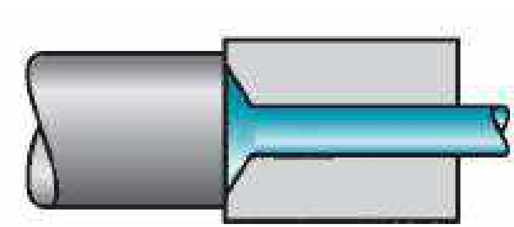
Heading:

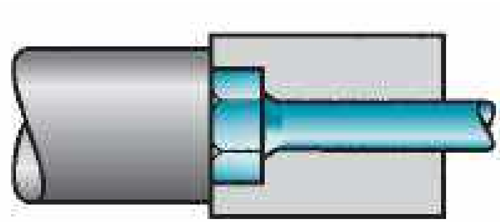
The following figure shows variety of heading operations with different die profiles.

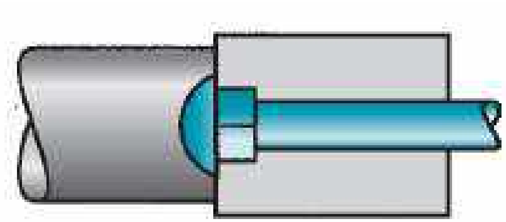




Heading a die using open die forging **Round head formed by punch only**







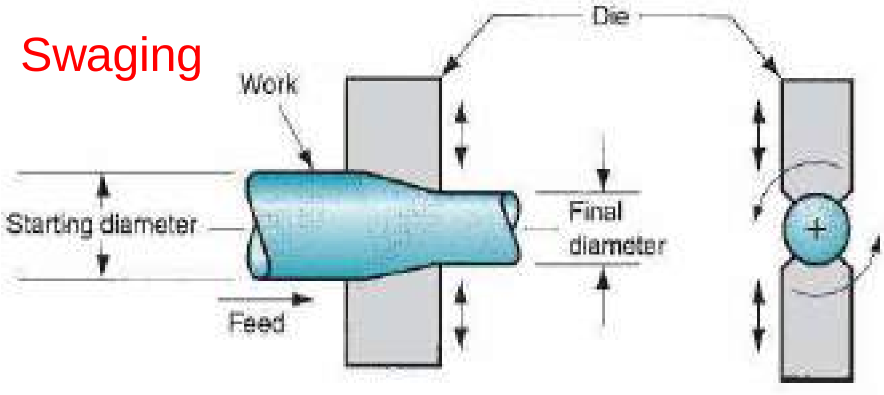
Head formed inside die only **Bolt head formed by both die and punch**

Long bar stock (work piece) is fed into the machines by horizontal slides, the end of the stock is upset forged, and the piece is cut to appropriate length to make the desired product. The maximum length that can be upset in a single blow is three times the diameter of the initial wire stock.

Swaging:

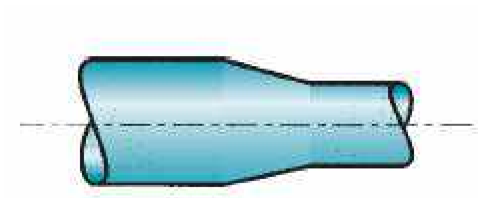
Swaging is used to reduce the diameter of a tube or a rod at the end of the work piece to create a tapered section. In general, this process is conducted by means of rotating dies that hammer a workpiece in radial direction inward to taper it as the piece is fed into the dies. A mandrel is required to control the shape and size of the internal diameter of tubular parts during swaging.

Swaging

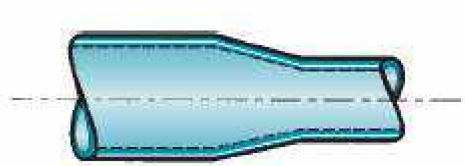


Radial forging:

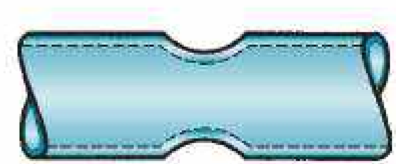
This operation is same as swaging, except that in radial forging, the dies do not rotate around the work piece, instead, the work is rotated as it feeds into the hammering dies.



Diameter reduction of solid work



Tube tapering



Swaging to form a groove on the tube

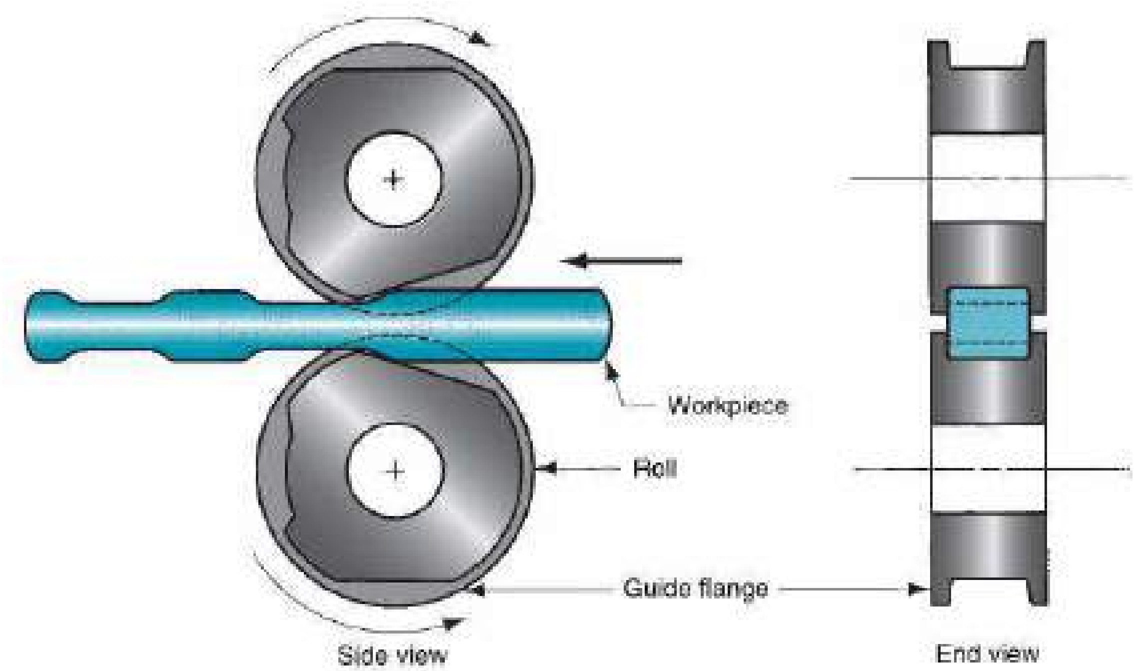
Swaging with different die profiles

Swaging the edge of a cylinder

Roll forging:

It is a forming process used to reduce the cross section of a cylindrical or rectangular rod by passing it through a set of opposing rolls that have matching grooves w.r.t. the desired shape of the final part. It combines both rolling and forging, but classified as forging operation.

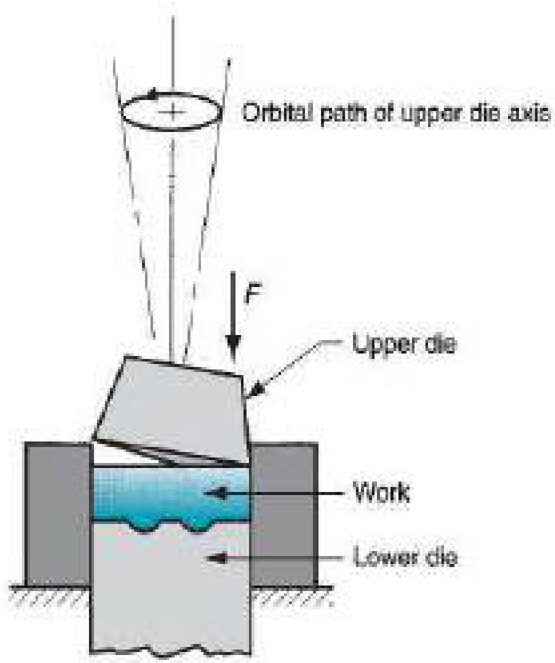
Depending on the amount of deformation, the rolls rotate partially. Roll-forged parts are generally stronger and possess desired grain structure compared to machining that might be used to produce the same part.

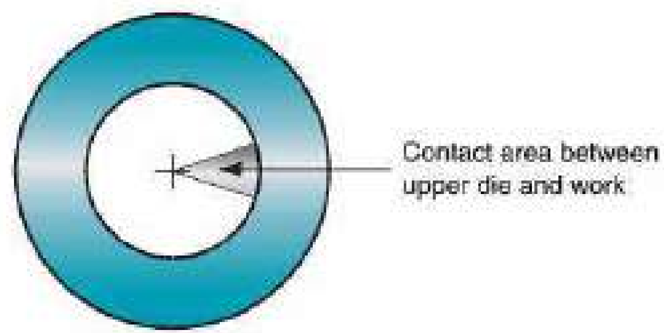


Orbital forging:

In this process, forming is imparted to the workpiece by means of a cone-shaped upper die that is simultaneously rolled and pressed into the work. The work is supported on a lower die.

Because of the inclined axis of cone, only a small area of the work surface is compressed at any stage of forming. As the upper die revolves, the area under compression also revolves. Because of partial deformation contact at any stage of forming, there is a substantial reduction in press load requirement.





Isothermal forging:

It is a hot-forging operation in which the work is maintained at some elevated temperature during forming. The forging dies are also maintained at the same elevated temperature. By avoiding chill of the work in contact with the cold die surfaces, the metal flows more readily and the force requirement is reduced.

The process is expensive than conventional forging and is usually meant for difficult-to-forge metals, like Ti, superalloys, and for complex part shapes. The process is done in vacuum or inert atmosphere to avoid rapid oxidation of the die material.

Extrusion

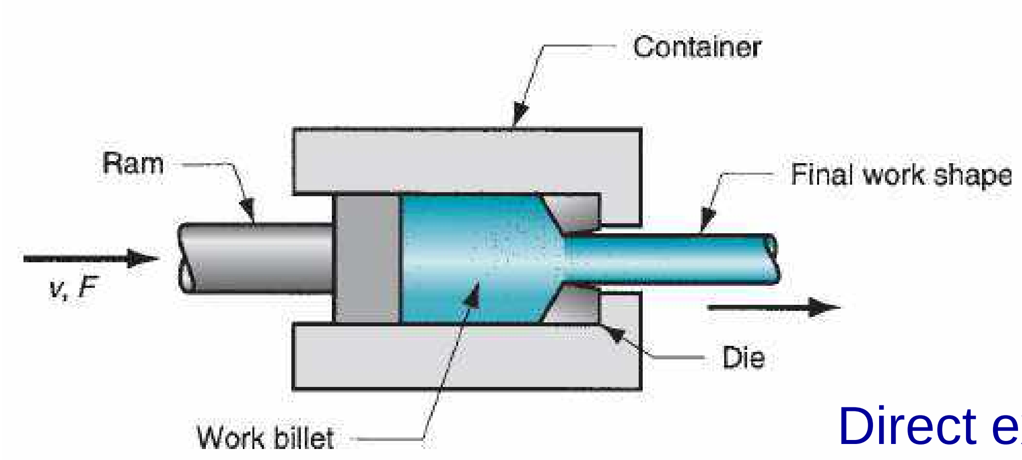
Extrusion is a bulk forming process in which the work metal is forced or compressed to flow through a die hole to produce a desired cross-sectional shape. Example: squeezing toothpaste from a toothpaste tube.

Advantages :
- Variety of shapes are possible, especially using hot extrusion
- Grain structure and strength properties are enhanced in cold and warm extrusion
- Close tolerances are possible, mainly in cold extrusion

Types of extrusion:
Direct or forward extrusion, Indirect or backward extrusion

Direct extrusion: - A metal billet is first loaded into a container having die holes. A ram compresses the material, forcing it to flow through the die holes.

- Some extra portion of the billet will be present at the end of the process that cannot be extruded and is called *butt*. It is separated from the product by cutting it just beyond the exit of the die.



Direct extrusion

- In direct extrusion, a significant amount of friction exists between the billet surface and the container walls, as the billet is forced to slide toward the die opening. Because of the presence of friction, a substantial increase in the ram force is required.
- In hot direct extrusion, the friction problem is increased by the presence of oxide layer on the surface of the billet. This oxide layer can cause defects in the extruded product.
- In order to address these problems, a dummy block is used between the ram and the work billet. The diameter of the dummy block is kept slightly smaller than the billet diameter, so that a thin layer of billet containing the oxide layer is left in the container, leaving the final product free of oxides.

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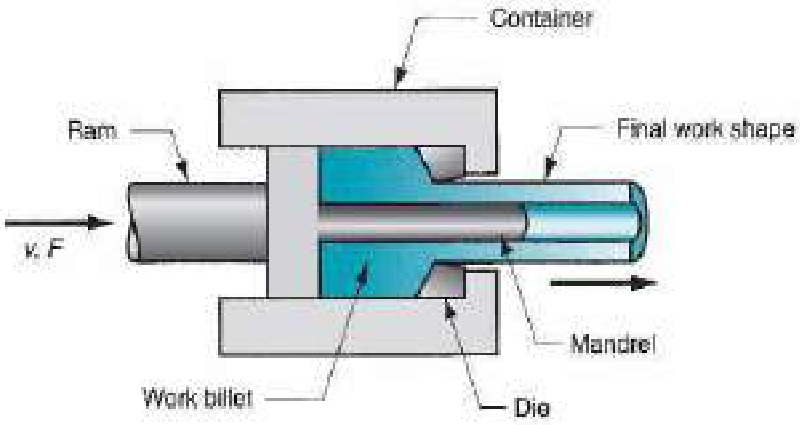
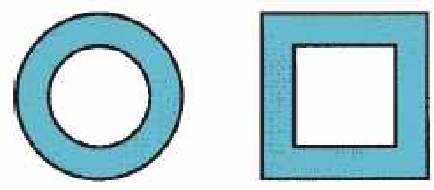




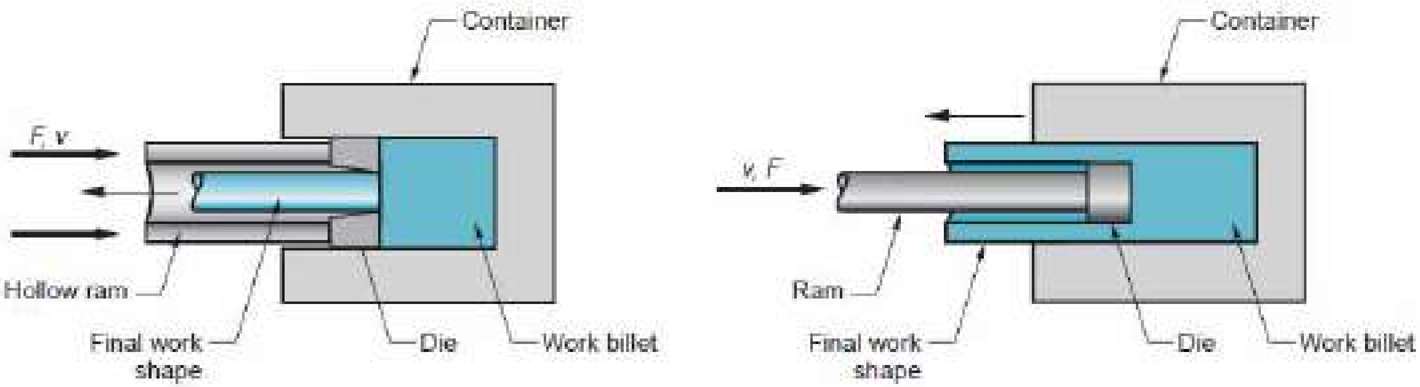
Making hollow shapes using direct extrusion

Hollow sections like tubes can be made using direct extrusion setup shown in above figure. The starting billet is prepared with a hole parallel to its axis. As the billet is compressed, the material will flow through the gap between the mandrel and the die opening.

Indirect extrusion: - In this type, the die is mounted to the ram and not on the container. As the ram compresses the metal, it flows through the die hole on the ram side which is in opposite direction to the movement of ram.

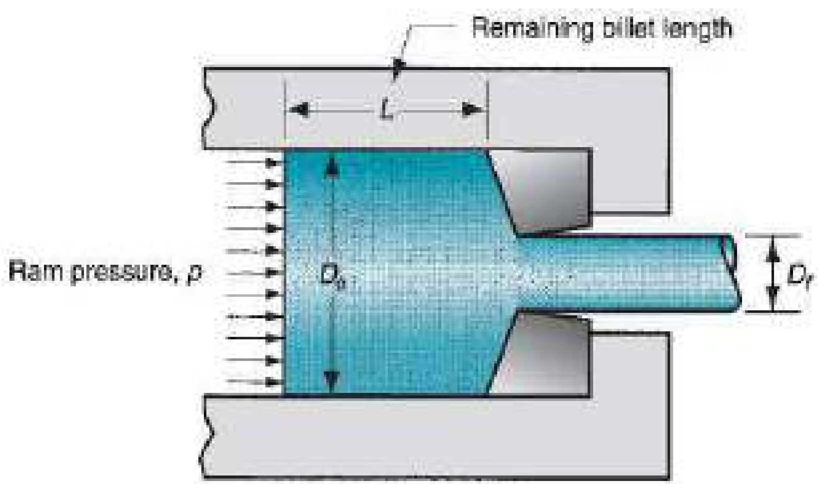
- Since there is no relative motion between the billet and the container, there is no friction at the interface, and hence the ram force is lower than in direct extrusion.

- Limitations: lower rigidity of the hollow ram, difficulty in supporting the extruded product at the exit



Indirect extrusion: solid billet and hollow billet

Simple analysis of extrusion



Pressure distribution and billet dimensions in direct extrusion

Assuming the initial billet and extrudate are in round cross-section. An important parameter, extrusion ratio (r_e), is defined as below:

$$r_e = \frac{A_0}{A_f}$$

A_0 - CSA of the initial billet
A_f - CSA of the extruded section

True strain in extrusion under ideal deformation (no friction and redundant work) is given by,

$$\varepsilon = \ln(r_e) = \ln(\frac{A_0}{A_f})$$

Under ideal deformation, the ram pressure required to extrude the billet through die hole is given by,

$$\boxed{p = \overline{Y}_f \ln(r_e) = \overline{Y}_f \ln(\frac{A_0}{A_f})} \quad \text{where} \quad \overline{Y}_f = \frac{K\varepsilon^n}{1+n}$$

Note: The average flow stress is found out by integrating the flow curve equation between zero and the final strain defining the range of forming

Where Y_f is average flow stress, and ε is maximum strain value during the extrusion process.

The actual pressure for extrusion will be greater than in ideal case, because of the friction between billet and die and billet and container wall.

There are various equations used to evaluate the actual true strain and associated ram pressure during extrusion. The following relation proposed by Johnson is of great interest.

$$\varepsilon_x = a + b \ln r_e = a + b\varepsilon \Longrightarrow \boxed{p = \bar{Y}_f \varepsilon_x}$$

Where ε_x is extrusion strain; *a* and *b* are empirical constants for a given die angle. Typical values are: *a* = 0.8, *b* = 1.2 - 1.5.

In direct extrusion, assuming that friction exists at the interface, we can find the actual extrusion pressure as follows:

billet-container friction force = additional ram force to overcome that friction

$$\mu p_e \pi D_0 L = \frac{p_f \pi D_0^{\ 2}}{4}$$

Where p_f is additional pressure required to overcome friction, p_e is pressure against the container wall

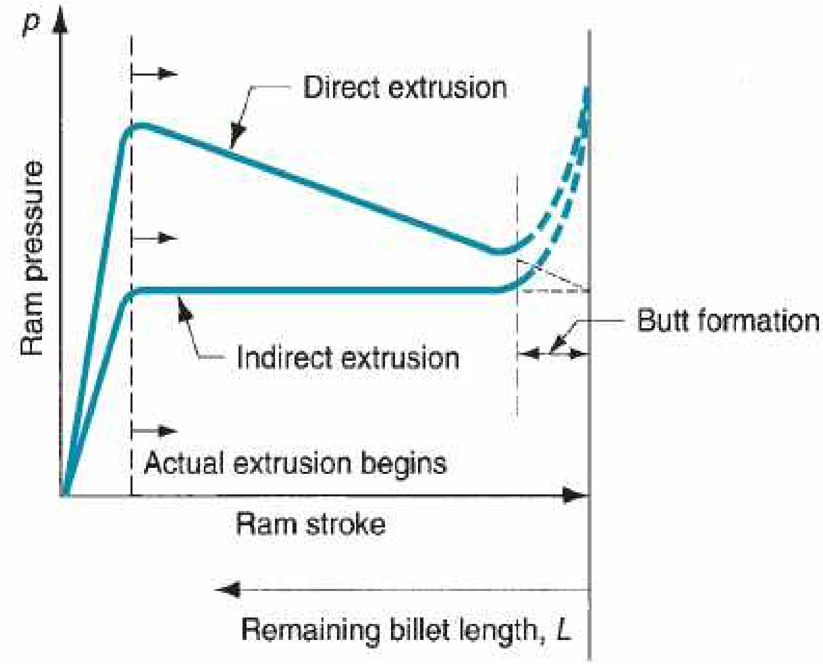
The above eqn. assume sliding friction condition. Assuming sticking friction at the interface, we can write:

$$K \pi D_0 L = \frac{p_f \pi D_0^{\ 2}}{4}$$

Where K is shear yield strength & m = 1

The above eqn. gives, $p_f = \dfrac{4KL}{D_0}$

Assuming, $K = \dfrac{\bar{Y}_f}{2}$ we get, $\boxed{p_f = \bar{Y}_f \dfrac{2L}{D_0}}$



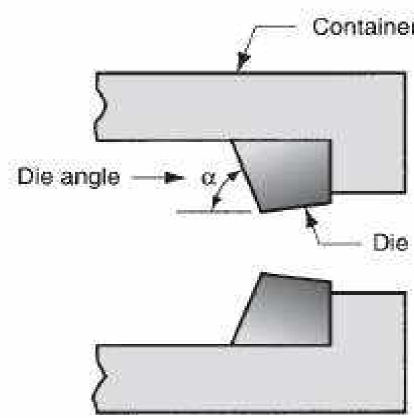
This is the additional pressure required to overcome friction during extrusion.

Now the actual ram pressure required for direct extrusion is given by,

$$\boxed{p = \bar{Y}_f \left(\varepsilon_x + \frac{2L}{D_0} \right)}$$

The shape of the initial pressure build up depends on die angle. Higher die angles cause steeper pressure buildups.

L is the billet length remaining to be extruded, and D_0 is the initial diameter of the billet. Here *p* is reduced as the remaining billet length decreases during the extrusion process.



Ram pressure variation with stroke for direct and indirect extrusion is shown in Figure.

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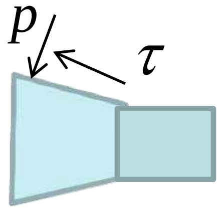
Sliding friction

The Coulomb friction stress (τ) between two surfaces is proportional to normal pressure (*p*).
The constant of proportionality is called friction coefficient (μ). This is assumed constant, but not mandatory. This condition exists when the forming tools are well lubricated and forming done at room temperature.

$$\tau = \mu p$$



Sticking friction

In this condition, a layer of material contacting the die-surface may stick onto the die and plastic flow may occur just under the surface layer. In this case, the friction stress (τ) is equal to shear yield strength (*K*), assuming friction factor '*m*' equal to 1.

This condition exists in hot forging, when no lubrication is used, in higher friction conditions. Mostly a part of contacting surface may be in slipping and another part in sticking condition.

$$\tau = mK$$

A billet 75 mm long and 25 mm in diameter is to be extruded in a direct extrusion operation with extrusion ratio r_e = 4.0. The extrudate has a round cross section. The die angle (half angle) is 90°. The work metal has a strength coefficient of 415 MPa, and strain-hardening exponent of 0.18. Use the Johnson formula with a = 0.8 and b=1.5 to estimate extrusion strain. Find the pressure applied to the end of the billet as the ram moves forward.

Empirical formulae for extrusion pressure

Hot extrusion of Al alloys:

For extrusion of pure Al, Al-Zn alloy, Al-Zn-Mg alloy in the temperature range of 50-500°C.

$$p_e / \sigma_0 = 0.52 + 1.32 \ln R$$ for values of R from 1 to 100

$$p_e / \sigma_0 = -13 + 4.78 \ln R$$ for values of R from 100 to 1000

Here *R = 1/(1-r)* where '*r*' is the relative reduction in area

Cold extrusion of steel:

$$p_e = 0.262 F (A_r)^{0.787} (2\alpha)^{0.375} \frac{N}{mm^2}$$

Where A_r = percent reduction in area = $\frac{A_1 - A_2}{A_1} \times 100$

$$\mathrm{F} = \frac{\text{Yield strength of steel}}{\text{Yield strength of lead}}$$

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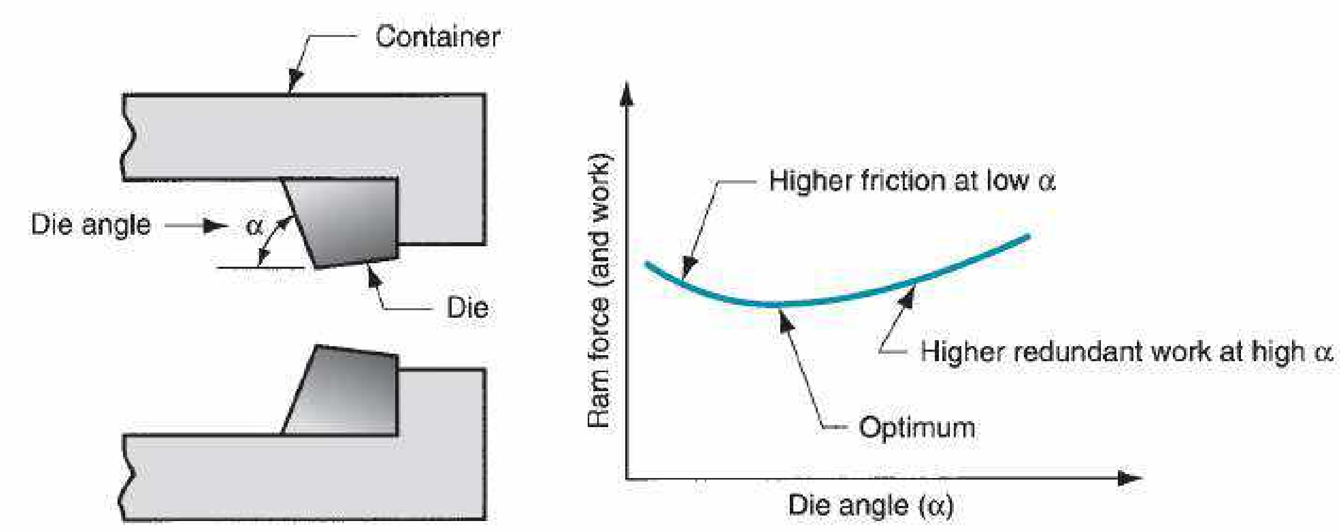
Extrusion dies

- Two important factors in an extrusion die are: die angle, orifice shape.

- For low die angles, surface area of the die is large, resulting in increased friction at the die-billet interface. Higher friction results in higher ram force.

- For a large die angle, more turbulence in the metal flow is caused during reduction, increasing the ram force required.

- The effect of die angle on ram force is a U-shaped function, shown in Figure. So, an optimum die angle exists. The optimum angle depends on various factors like work material, billet temperature, and lubrication.



- The extrusion pressure eqns. derived earlier are for a circular die orifice.

- The shape of the die orifice affects the ram pressure required to perform an extrusion operation, as it determines the amount of squeezing of metal billet.

-The effect of the die orifice shape can be assessed by the die shape factor, defined as the ratio of the pressure required to extrude a cross section of a given shape relative to the extrusion pressure for a circular cross section of the same area.

$$k_x = 0.98 + 0.02\left(\frac{c_x}{c_c}\right)^{2.25}$$

Where k_x is the die shape factor in extrusion; C_x is the perimeter of the extruded cross section, and C_c is the perimeter of a circle of the same area as the actual extruded shape.

$\frac{c_x}{c_c}$ varies from 1 to 6.

Die materials

For hot extrusion - tool and alloy steels.

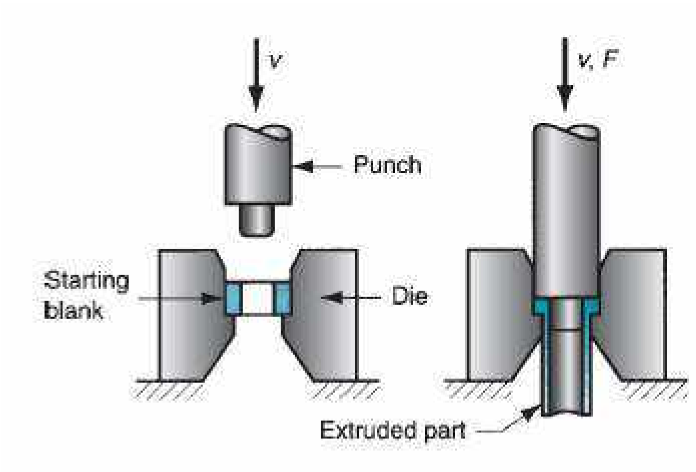
Important properties of die materials are high wear resistance, high thermal conductivity to remove heat from the process.

For cold extrusion - tool steels and cemented carbides.
Carbides are used when high production rates, long die life, and good dimensional control are expected.

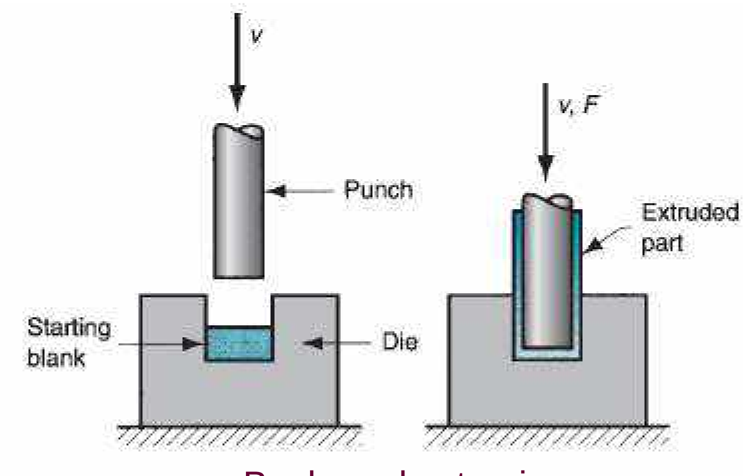
Other extrusion processes

Impact extrusion:

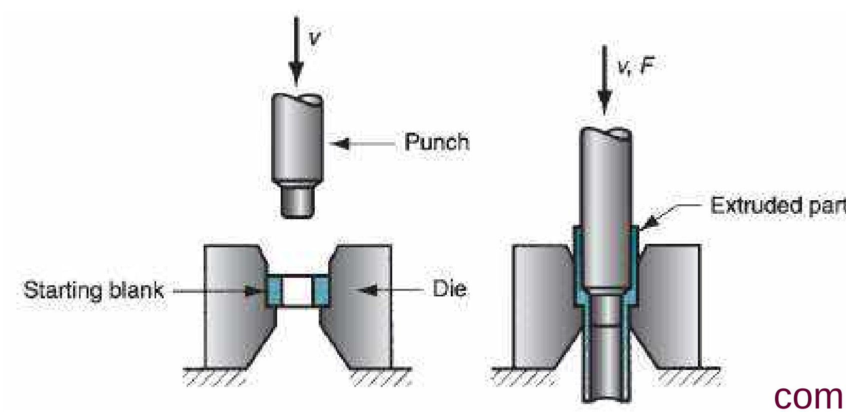
- It is performed at higher speeds and shorter strokes. The billet is extruded through the die by impact pressure and not just by applying pressure.
- But impacting can be carried out as forward extrusion, backward extrusion, or combination of these.



forward extrusion



Backward extrusion

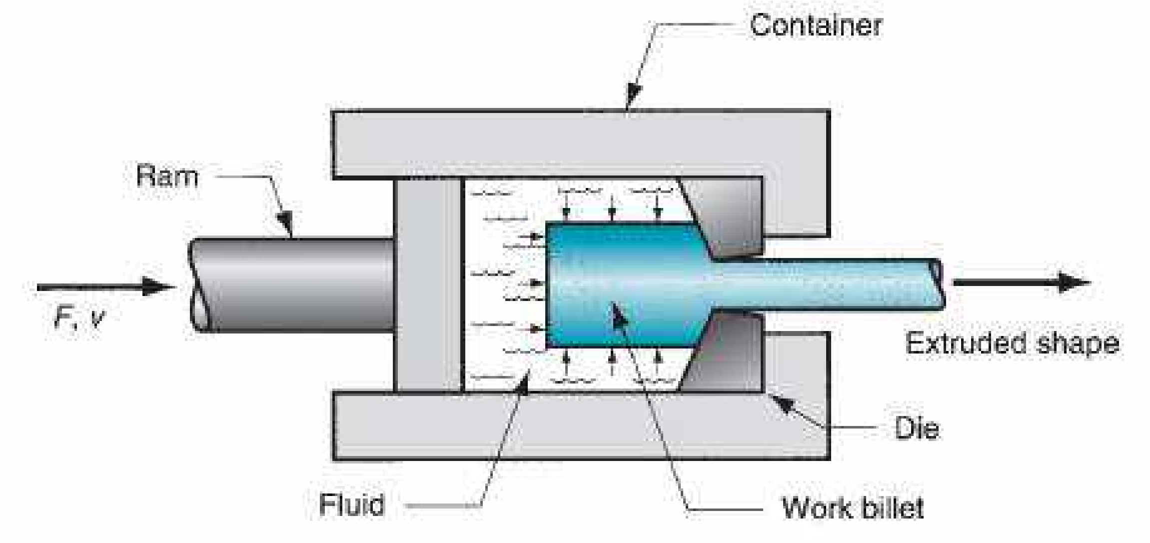


combined extrusion

- Impact extrusion is carried out as cold forming. Very thin walls are possible by backward impact extrusion method. Eg: making tooth paste tubes, battery cases.

- Advantages of IE: large reductions and high production rates

Hydrostatic extrusion:



Hydrostatic extrusion

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In hydrostatic extrusion, the billet is surrounded with fluid inside the container and the fluid is pressurized by the forward motion of the ram.

There is no friction inside the container because of the fluid, and friction is minimized at the die opening. If used at high temperatures, special fluids and procedures must be followed.

Hydrostatic pressure on the work and no friction situation increases the material's ductility. Hence this process can be used on metals that would be too brittle for conventional extrusion methods.

This process is also applicable for ductile metals, and here high reduction ratios are possible.

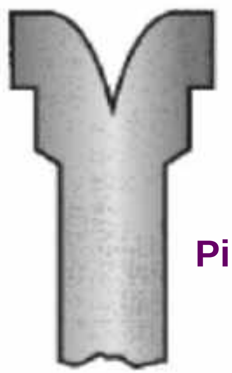
The preparation of starting work billet is important. The billet must be formed with a taper at one end to fit tightly into the die entry angle, so that it acts as a seal to prevent fluid leakage through die hole under pressure.

Defects during extrusion

Centerburst:
- This is an internal crack that develops as a result of tensile stresses along the center axis of the workpiece during extrusion. A large material motion at the outer regions pulls the material along the center of the work. Beyond a critical limit, bursting occurs.
- Conditions that promote this defect are: higher die angles, low extrusion ratios, and impurities in the work metal. This is also called as Chevron cracking.

Centerburst

Piping: It is the formation of a sink hole in the end of the billet. This is minimized by the usage of a dummy block whose diameter is slightly less than that of the billet.



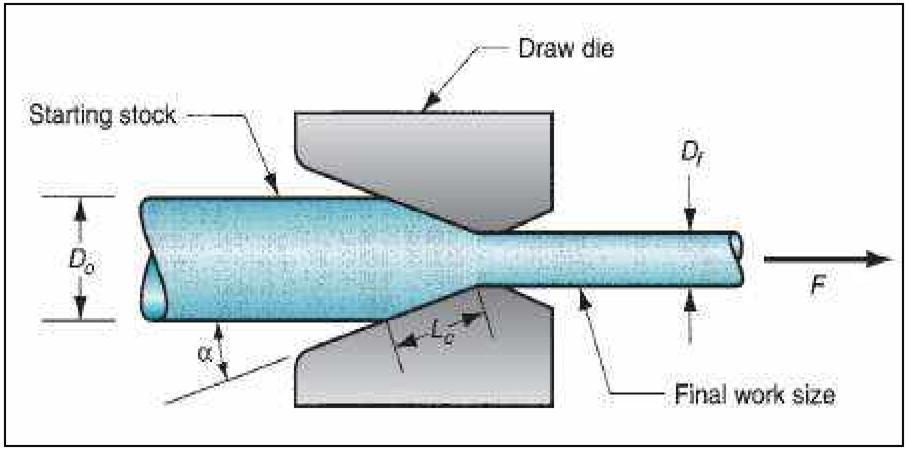
Piping

Surface cracking: This defect results from high workpiece temperatures that cause cracks to develop at the surface. They also occur at higher extrusion speeds, leading to high strain rates and heat generation. Higher friction at the surface and surface chilling of high temperature billets in hot extrusion also cause this defect.

Surface cracking

Wire, rod, bar drawing

- In this bulk forming process, a wire, rod, bar are pulled through a die hole reducing their cross-section area.



Wire, rod, bar drawing

Difference between wire drawing and rod drawing:

Initial stock size:

- The basic difference between bar drawing and wire drawing is the stock size that is used for forming. Bar drawing is meant for large diameter bar and rod, while wire drawing is meant for small diameter stock. Wire sizes of the order of 0.03 mm are produced in wire drawing.

Operating stages:

- Bar drawing is generally done as a single stage operation, in which stock is pulled through one die opening. The inlet bars are straight and not in the form of coil, which limits the length of the work that can be drawn. This necessitates a batch type operation.

- In contrast, wire is drawn from coils consisting of several hundred meters of wire and is drawn through a series of dies. The number of dies varies between 4 and 12. This is termed as ‘continuous drawing’ because of the long production runs that are achieved with the wire coils. The segments can be butt-welded to the next to make the operation truly continuous.

Simple analysis of wire drawing

True strain in wire drawing under ideal deformation (no friction and redundant work) is given by,

$$\varepsilon = \ln\left(\frac{A_0}{A_f}\right) = \ln\left(\frac{1}{1-r}\right)$$

Here $r = (A_0 - A_f) / A_0$

Under ideal deformation, the stress required in wire drawing is given by,

$$\sigma_d = \bar{Y}_f \ln\left(\frac{A_0}{A_f}\right)$$

Here $\bar{Y}_f = \frac{K\varepsilon^n}{1+n}$, $\bar{Y}_f$ is the average flow stress corresponding to ε mentioned in above equation.

In order to consider the effect of die angle and friction coefficient on the drawing stress, Schey has proposed another equation as shown below:

$$\sigma_d = \bar{Y}_f\left(1 + \frac{\mu}{\tan\alpha}\right)\phi \ln\left(\frac{A_0}{A_f}\right)$$

Here ϕ is a term that accounts for inhomogeneous deformation which is found by the following eqn. for round cross-section.

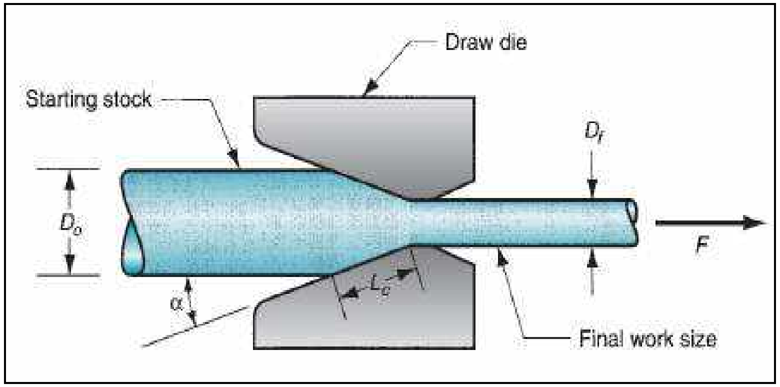
$$\phi = 0.88 + 0.12\frac{D}{L_c}$$

Here D is the average diameter of the workpiece, L_C is the contact length of the work with die given by,

$$D = \frac{D_0 + D_f}{2}; L_C = \frac{D_0 - D_f}{2\sin\alpha}$$

Finally the drawing force is given by, $F = A_f \sigma_d$

The power required for drawing is given by multiplying drawing force with exit velocity of the workpiece



Wire is drawn through a draw die with entrance angle 15°. Starting diameter is 2.5 mm and final diameter 2 mm. The coefficient of friction at the work–die interface is 0.07. The metal has a strength coefficient K = 205 MPa and a strain-hardening exponent n = 0.2. Determine the draw stress and draw force in this operation.

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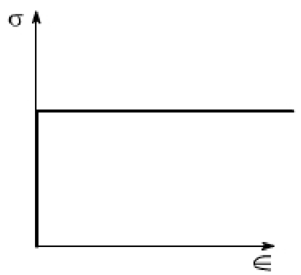
Maximum reduction per pass

Increase in reduction, increase the draw stress. If the reduction is large enough, draw stress will exceed the yield strength of the material. Then the wire will just elongate rather than new material being drawn into the die hole. To have a successful wire drawing operation, drawing stress should be less than yield strength of the drawn metal.

Assume a perfectly plastic material (n = 0), no friction and redundant work, then,

$$\sigma_d = \bar{Y}_f \ln\left(\frac{A_0}{A_f}\right) = Y \ln\left(\frac{A_0}{A_f}\right) = Y \ln\left(\frac{1}{1-r}\right) = Y$$



which means that

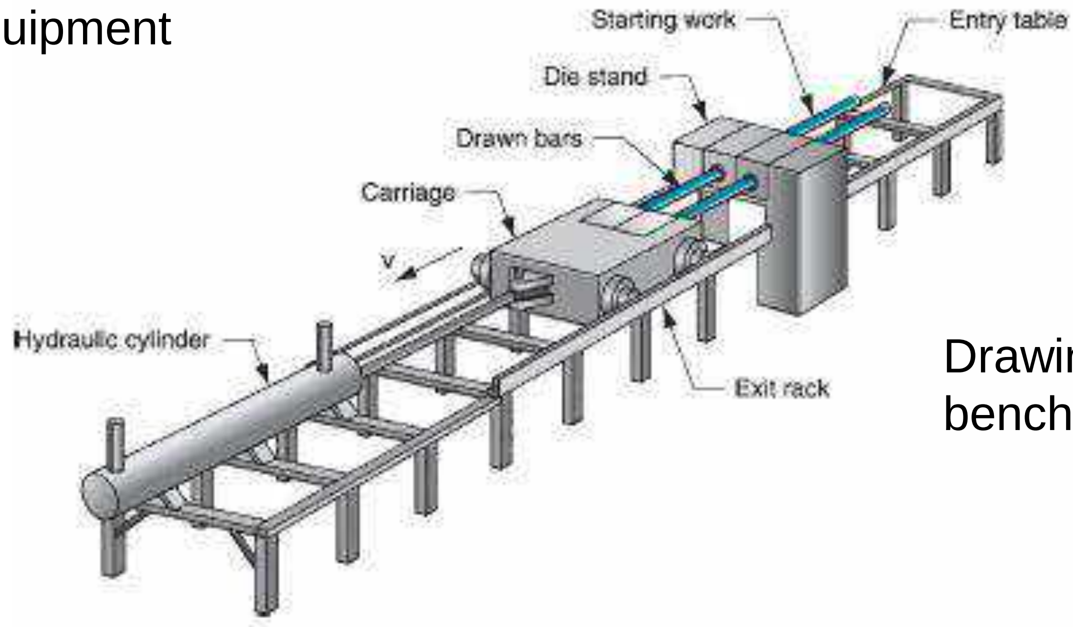
$$\ln\left(\frac{A_0}{A_f}\right) = \ln\left(\frac{1}{1-r}\right) = 1$$

This gives a condition that the maximum possible reduction, r_{max} is

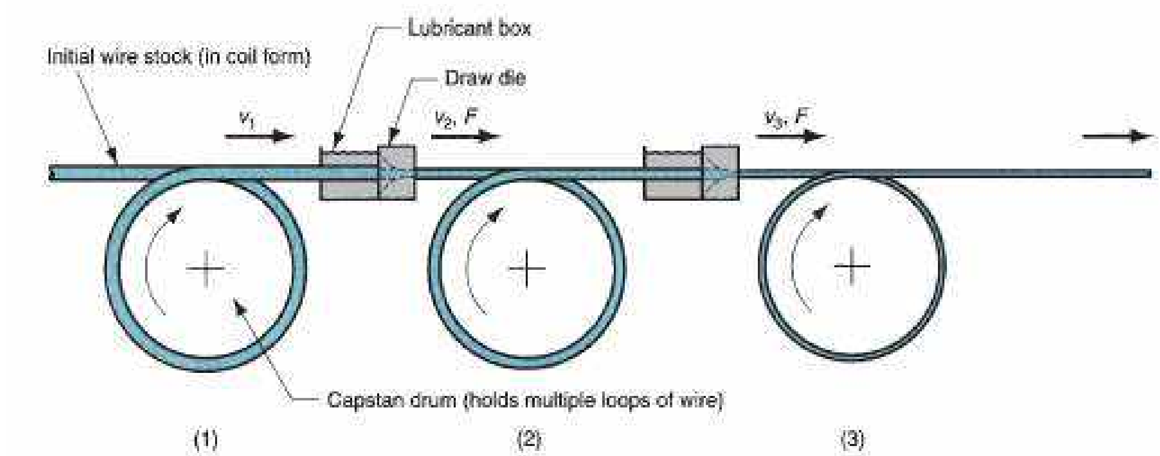
r_{max} = 0.632 (theoretical maximum limit)

This analysis ignores the effects of friction and redundant work, which would further reduce the maximum value, and strain hardening, which would increase the maximum reduction because of the stronger wire than the starting metal. **Reductions of 0.5-0.3 per pass seem to be possible in industrial operations.**

Drawing equipment



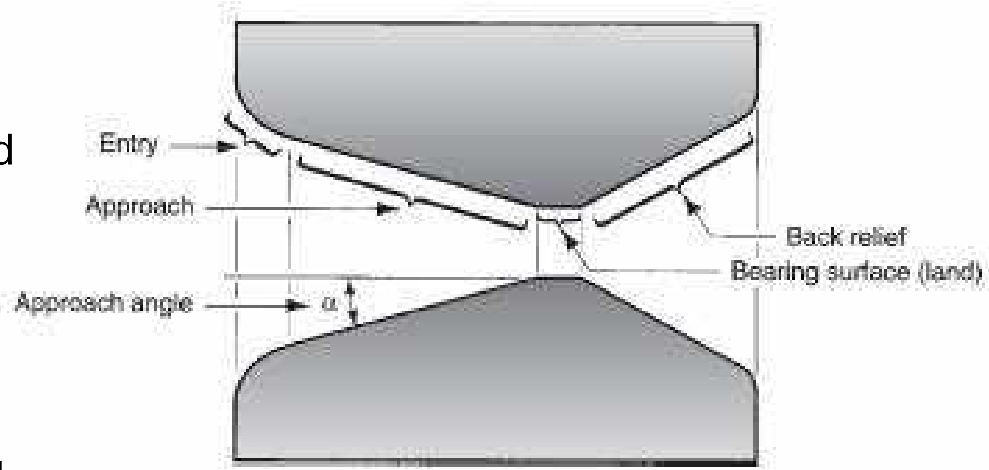
Drawing bar by draw bench



Continuous drawing of wire

Drawing dies

The entry region is generally a bell-shaped mouth that does not contact the work-piece. Its function is to contain and push the lubricant into the die and prevent wearing of work and die surfaces



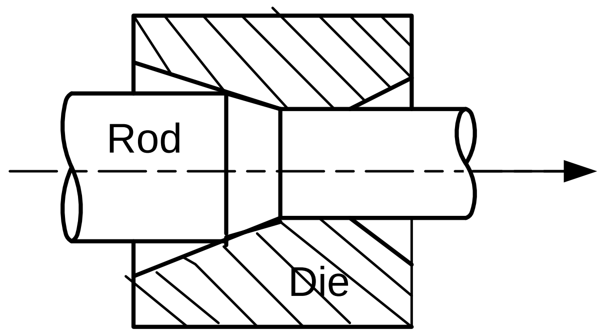
The approach region is where the drawing operation occurs. It is cone-shaped with an angle (half-angle) normally ranging from 6° to 20°.

The bearing surface or land, determines the size of the final drawn work-piece.

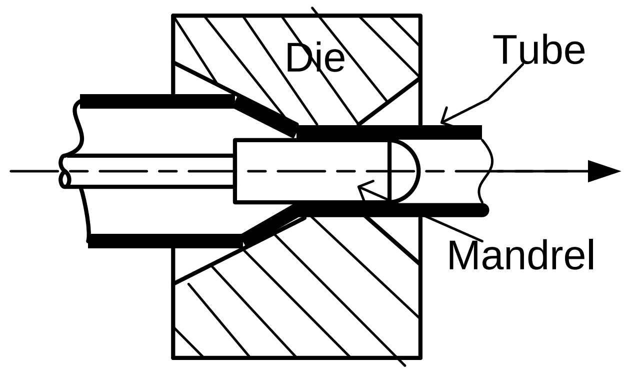
Finally, the back relief is the exit zone. It is provided with a back relief angle (half-angle) of about 25-30°.

Tube drawing

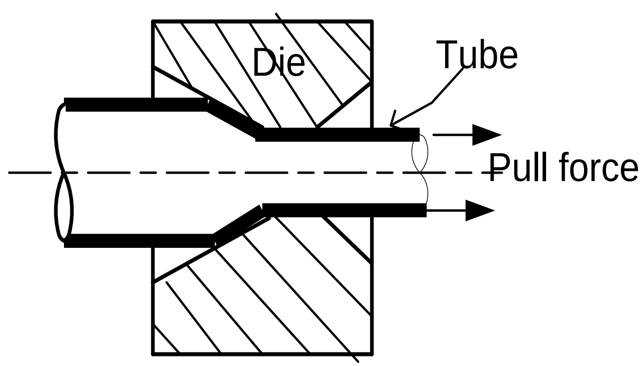
This operation is used to reduce the diameter or wall thickness of the seamless tubes and pipes. Tube drawing can be done either with or without mandrel. **The simplest method uses no mandrel and is used for diameter reduction called as tube sinking.** But inside diameter and wall thickness cannot be controlled. So mandrel is required.



(a) Rod drawing

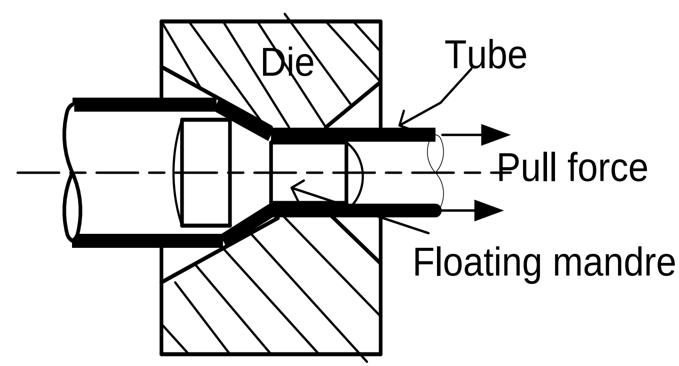


(c) Tube drawing with fixed mandrel



(b) Tube drawing without mandrel

(TUBE SINKING)



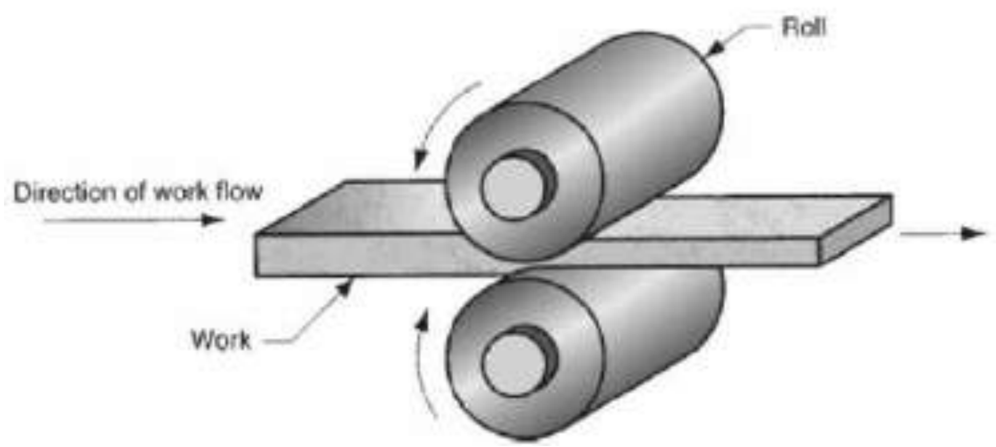
(d) Tube drawing with floating mandrel

Using a fixed mandrel: In this case, a mandrel is attached to a long support bar to control the inside diameter and wall thickness during the operation. The length of the support bar restricts the length of the tube that can be drawn.

Using a floating plug: As the name suggests the mandrel floats inside the tube and its shape is designed so that it finds a suitable position in the reduction zone of the die. There is no length restriction in this as seen with the fixed mandrel.

Rolling

Rolling is a metal forming process in which the thickness of the work is reduced by compressive forces exerted by two rolls rotating in opposite direction. Flat rolling is shown in figure. Similarly shape rolling is also possible like a square cross section is formed into a shape such as an I-beam, L-beam.



Flat rolling

Important terminologies:

Bloom: It has a square cross section 150 mm x 150 mm or more.

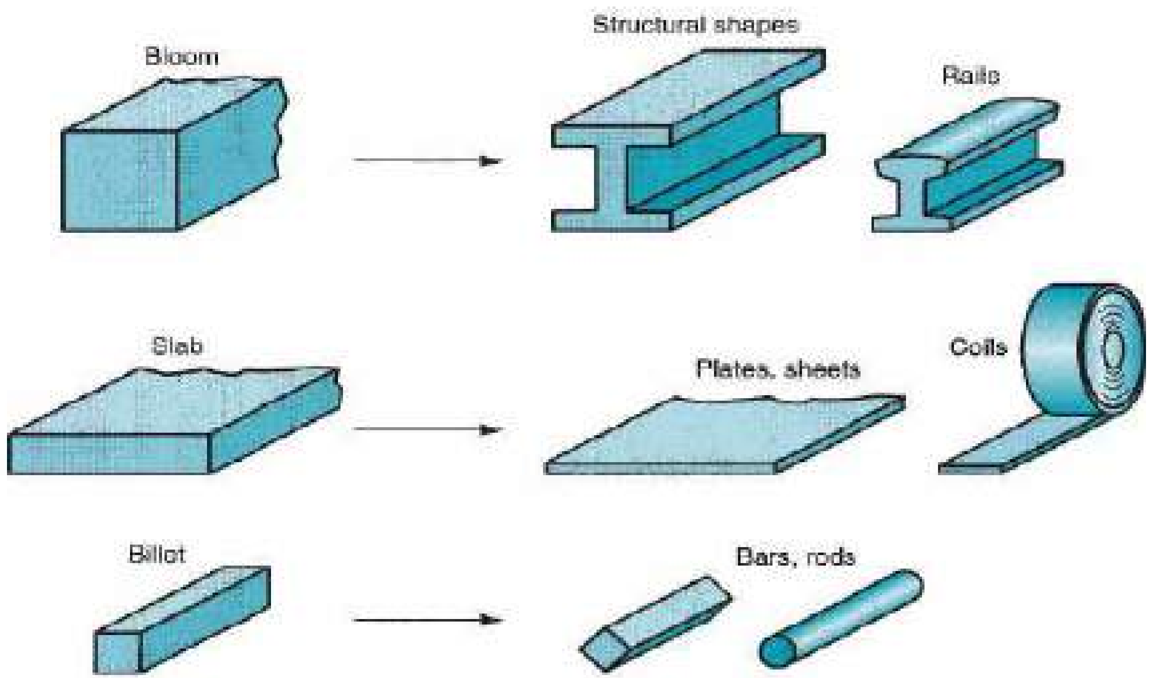
Slab: It is rolled from an ingot or a bloom and has a rectangular cross section of 250 mm width or more and thickness 40 mm or more.

Billet: It is rolled from a bloom and is square in cross-section with dimensions 40mm on a side or more.

Blooms are rolled into structural shapes like rails for railroad tracks.

Billets are rolled into bars, rods. They become raw materials for machining, wire drawing, forging, extrusion etc.

Slabs are rolled into plates, sheets, and strips. Hot rolled plates are generally used in shipbuilding, bridges, boilers, welded structures for various heavy machines, and many other products.



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The plates and sheets are further reduced in thickness by cold rolling to strengthen the metal and permits a tighter tolerance on thickness.

Important advantage is that the surface of the cold-rolled sheet does not contain scales and generally superior to the corresponding hot rolled product.

Later the cold-rolled sheets are used for stampings, exterior panels, and other parts used in automobile, aerospace and house hold appliance industries.

Simple analysis of flat strip rolling

The schematic of flat rolling is shown in previous slides. It involves rolling of sheets, plates having rectangular cross section in which the width is greater than the thickness.

In flat rolling, the plate thickness is reduced by squeezing between two rolls. The thickness reduction is quantified by draft which is given by,

$$d = t_0 - t_f$$

here t_0 and t_f are initial thickness and final thickness of the sheet used for rolling.

Draft is also defined as, $r = d / t_0$. Here r is reduction.

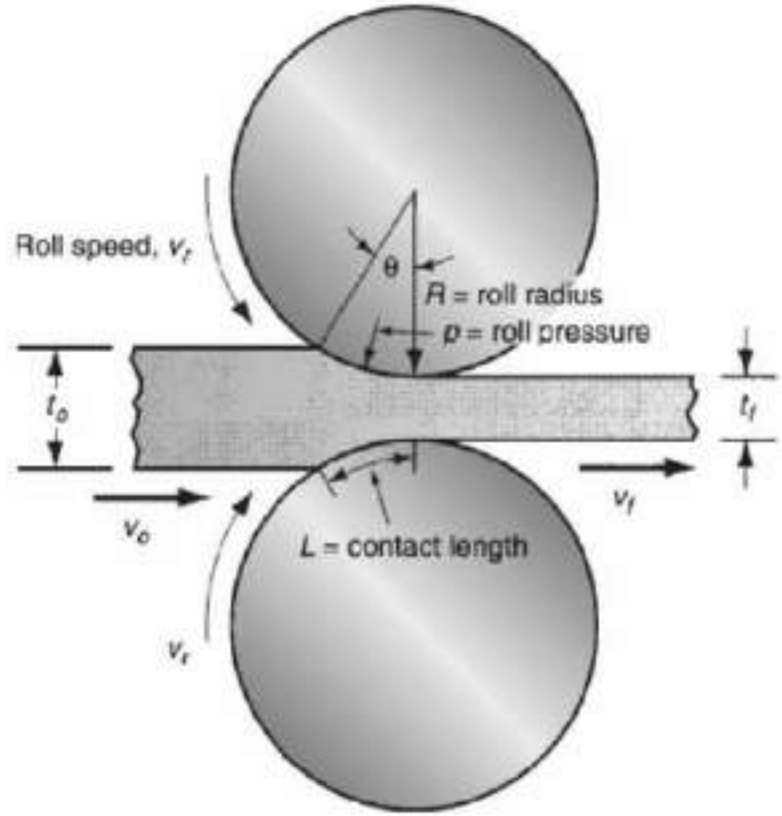
During rolling, the workpiece width increases which is termed as spreading. It will be large when we have low width to thickness ratio and low friction coefficient.

In strip rolling, $t_0 w_0 l_0 = t_f w_f l_f$ and hence $t_0 w_0 v_0 = t_f w_f v_f$

Here w_o and w_f are the initial and final work widths, l_0 and l_f are the initial and final work lengths. v_o and v_f are the entry and exit velocities of the work.

In strip rolling, the width will not change much after rolling. From the previous equation, it is observed that the exit velocity v_f is greater than entry velocity v_0. In fact, the velocity of the rolled sheet continuously increases from entry to exit.

The rolls contact the rolling sheet along an arc defined by angle θ. Each roll has radius R, and its has surface velocity v_r. This velocity is in between entry and exit velocity.



However, there is one point or zone along the contact arc where work velocity equals roll velocity. This is called the no-slip point, or neutral point.

On either side of the neutral point, slipping and friction occur between roll and sheet. The amount of slip between the rolls and the sheet can be quantified by forward slip, S,

$$S = \frac{v_f - v_r}{v_r}$$

v_f is the final velocity, v_r is the roll velocity

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The true strain during rolling is given by, $\varepsilon = \ln(\frac{t_0}{t_f})$

The true strain is used to find the average flow stress (Y_f) and further rolling power, force.

$$\bar{Y}_f = \frac{K\varepsilon^n}{1+n}$$

On the entry side of the neutral point, friction force is in one direction, and on the other side it is in the opposite direction, i.e., the friction force acts towards the neutral point. But the two forces are unequal.

The friction force on the entry side is greater, so that the net force pulls the sheet through the rolls. Otherwise, rolling would not be possible.

The limit to the maximum possible draft that can be accomplished in flat rolling is given by,

$$d_{\max} = \mu^2 R$$

The equation indicates that if friction were zero, draft is zero, and it is not possible to accomplish the rolling operation.

The friction coefficient in rolling depends on lubrication, work material, and working temperature.

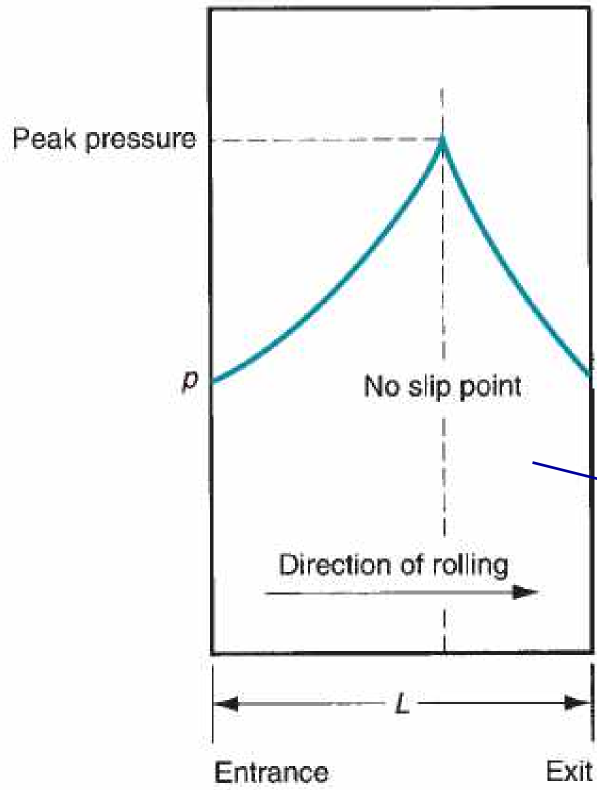
In cold rolling, the value is app. 0.1, in warm rolling, a typical value is around 0.2; and in hot rolling, it is around 0.4.

Hot rolling is characterized by sticking friction condition, in which the hot work surface adheres to the rolls over the contact region. This condition often occurs in the rolling of steels and high-temperature alloys.
When sticking occurs, the coefficient of friction can be as high as 0.7.

The roll force (*F*) is calculated by, $F = \bar{Y}_f wL$, *wL* is the contact area

The contact length (projected) is approximated by, $L = \sqrt{R(t_0 - t_f)}$

The rolling power required for two powered rolls is given by, $P = (2\pi N)FL$ (watts)



Area under the curve,
rolling force, *F*,

$$F = w\int_0^L p\,dL$$

Typical variation in roll pressure along the contact length in flat rolling

A 300 mm wide strip, 25 mm thick, is fed through a rolling mill with two powered rolls each of radius 250 mm. The work thickness is to be reduced to 22 mm in one pass at a roll speed of 50 rev/min. The work material has a flow curve defined by K = 275 MPa and n = 0.15, and the coefficient of friction between the rolls and the work is 0.12. Determine if the friction is sufficient to permit the rolling operation to be accomplished. If so, calculate the roll force, and horsepower (or rolling power).

Inference from equations: The strip rolling force and/or power of a given width and work material can be reduced by the following methods: (1) using hot rolling rather than cold rolling to reduce strength and strain hardening (*K* and *n*) of the work material; (2) reducing the draft in each rolling pass; (3) using a smaller roll radius 'R' to reduce force; and (4) using a lower rolling speed 'N' to reduce power.

Rolling mills

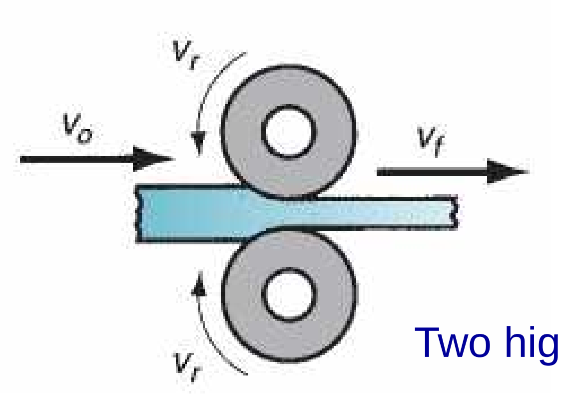
Two high rolling mill: This type of rolling mill consists of two rolls rotating in opposite directions.

Roll diameters: 0.6 to 1.4 m

Types: either reversing or non-reversing.

Non-reversing mill: rolls rotate only in one direction, and the slab always move from entry to exit side.

Reversing mill: direction of roll rotation is reversed, after each pass, so that the slab can be passed through in both the directions. This permits a continuous reductions to be made through the same pairs of rolls.

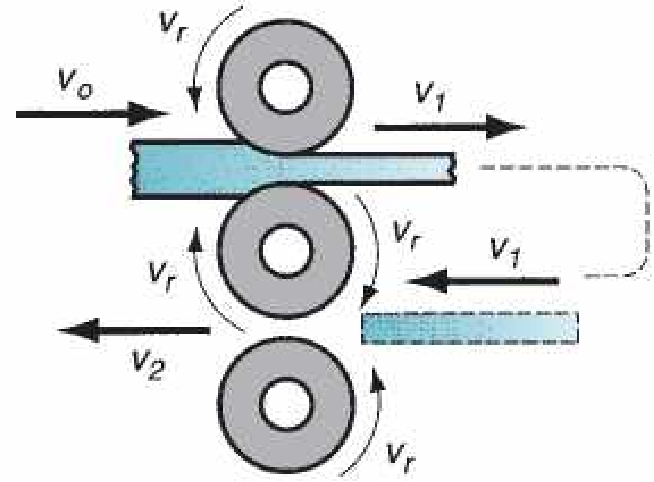


Two high rolling mill

Three high rolling mill: In this case, there are three rolls one above the other. At a time, for single pass, two rolls will be used. The roll direction will not be changed in this case.

The top two rolls will be used for first reduction and the sheet is shifted to the bottom two rolls and further reduction is done. This cycle is continued till actual reduction is attained.

Disadvantage: automated mechanism is required to shift the slab

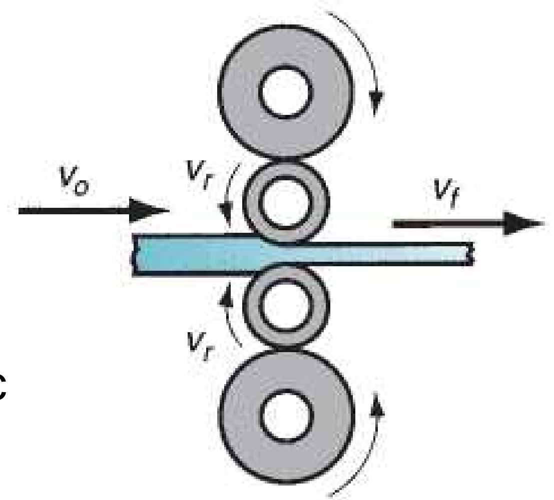


Three high rolling mill

Four high rolling mill: This consists of two small rolls for thickness reduction and two large backing rolls to support the small rolls.

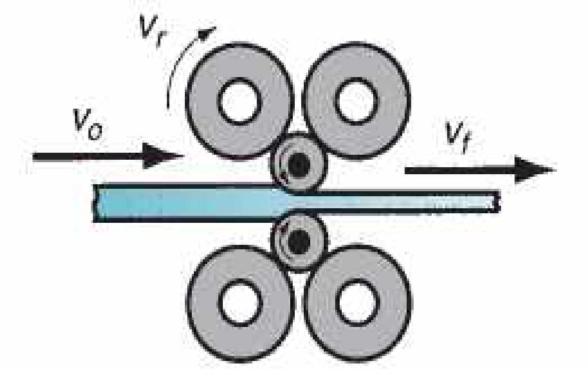
The small rolls will reduce the roll force required as the roll-sheet contact area will be reduced.

The large backing rolls are required to reduce the elastic deflection of small rolls when sheet passes between them.



Four high rolling mill

Cluster rolling mill: This uses smaller rolls for rolling

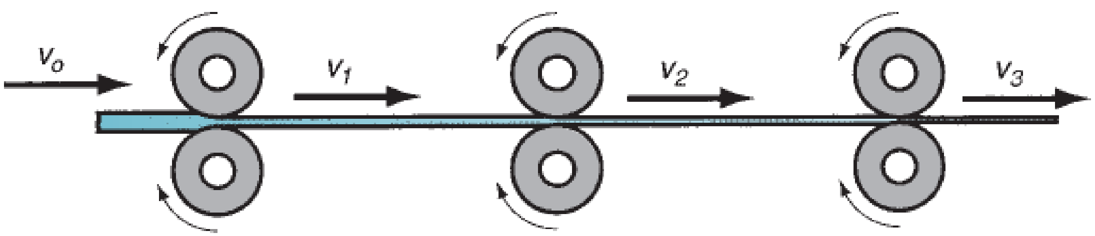


Cluster rolling mill

Tandem rolling mill:

This consists of series of rolling stations of the order of 8 to 10. In each station, thickness reduction is given to the sheet. With each rolling station, the work velocity increases.

This is fully used in industry practice, along with continuous casting operation. This results in reduction in floor space, shorter manufacturing lead time.



Tandem rolling mill

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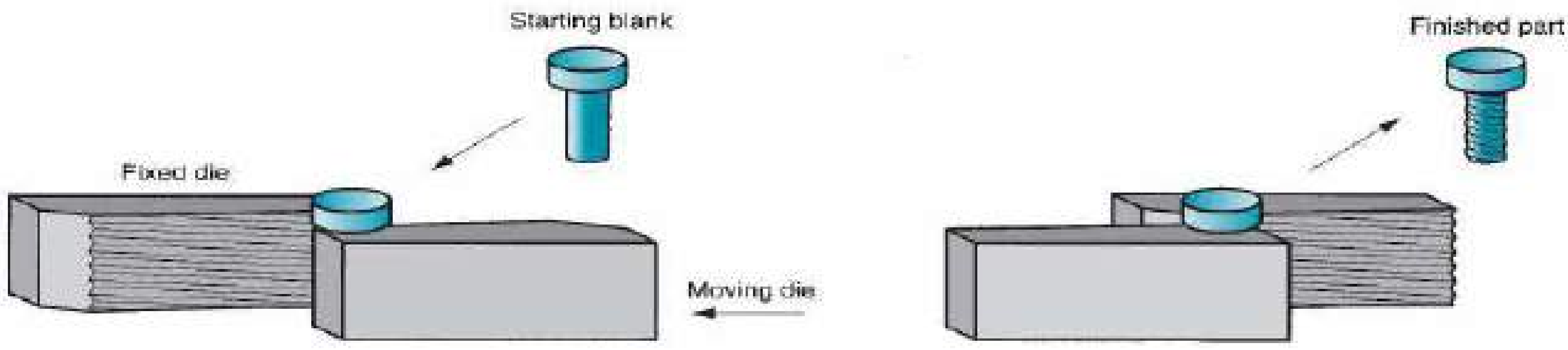
Thread rolling



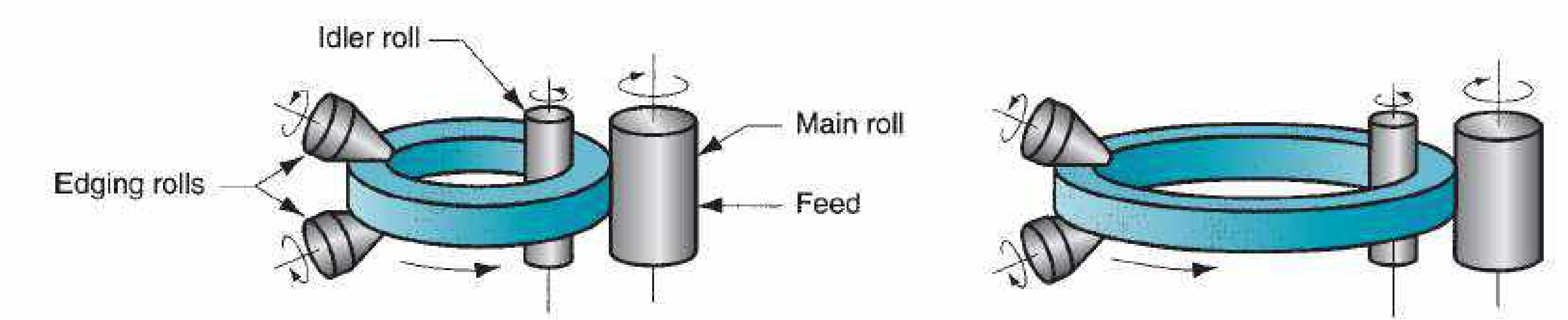
Thread rolling is used to create threads on cylindrical parts by rolling them between two dies as shown in figure.

It is used for mass production of external threaded parts like bolts and screws.

Ring rolling

Ring rolling is a forming process in which a thick walled ring part of smaller diameter is rolled into a thin walled ring of larger diameter.
As the thick walled ring is compressed, the deformed material elongates, making the diameter of the ring to be enlarged.

Application: ball and roller bearing races, steel tires for railroad wheels, rings for pipes, pressure vessels, and rotating machinery



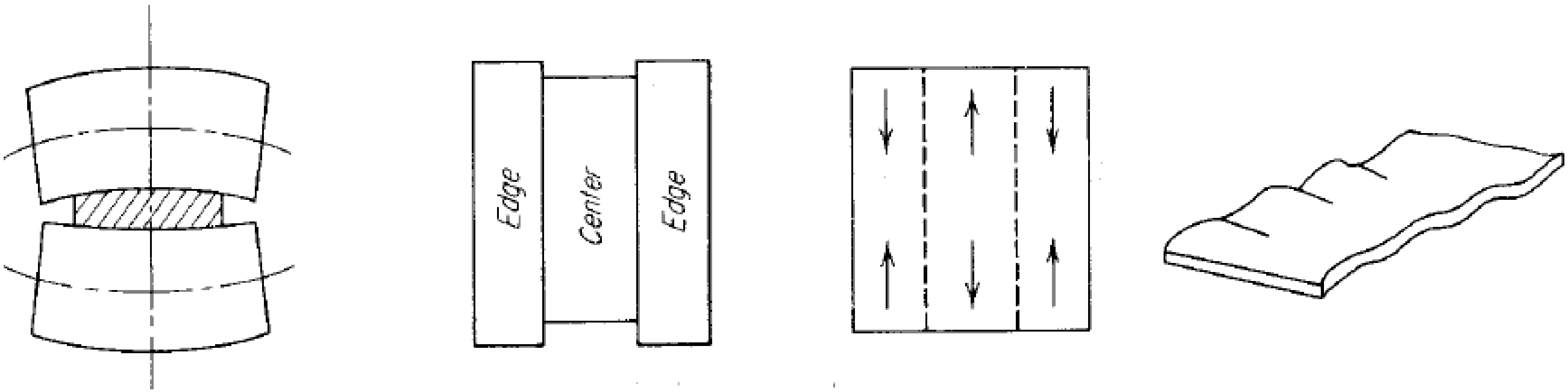
Start of process (thick walled, small diameter)

Completion of process (thin walled, large diameter)

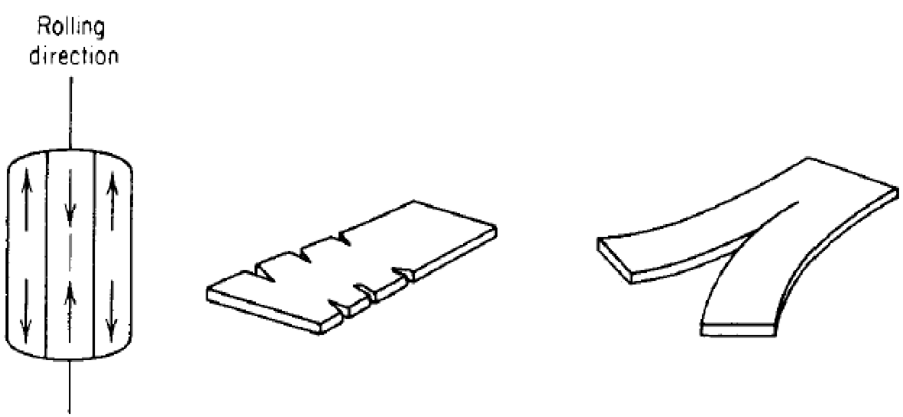
Ring rolling

Defects in strip rolling

Waviness



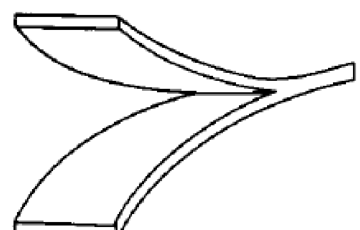
Cracking



Edge defect

Light reduction

Heavy reduction



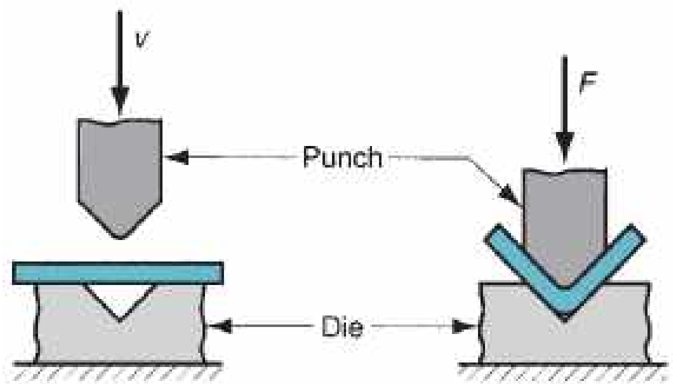
Aligatoring

G.E.Dieter, *Mechanical Metallurgy*

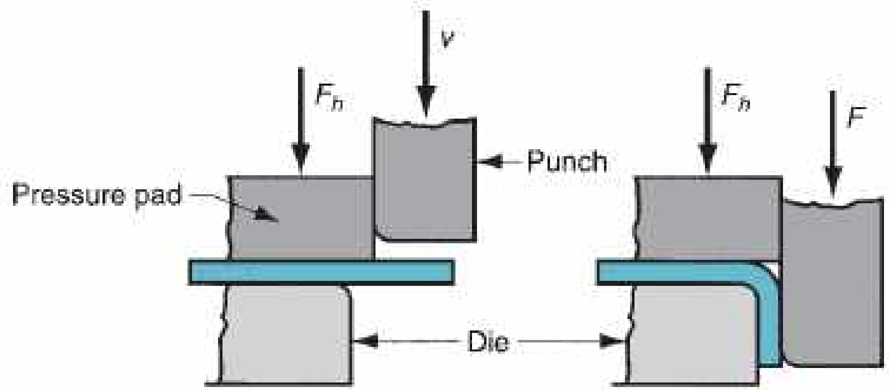
Sheet forming operations

Sheet forming:

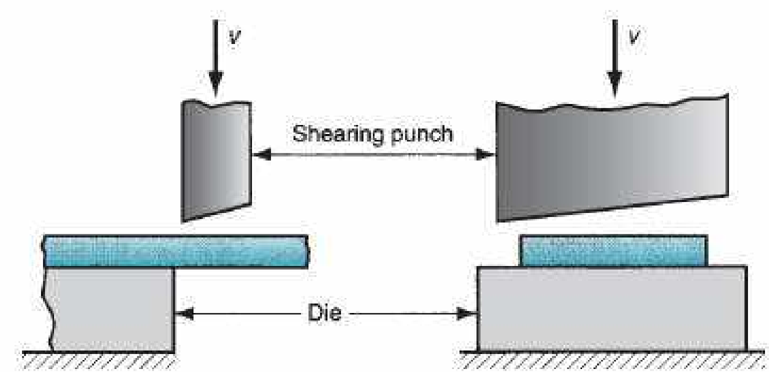
Involves plastic deformation of sheets like deep drawing, cutting, bending, hemming, flanging, curling, stretch forming/stretching, stamping etc.



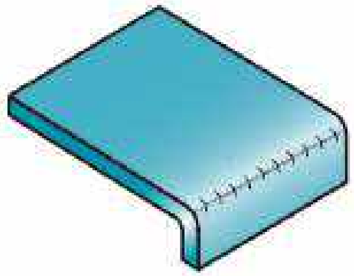
V-bending



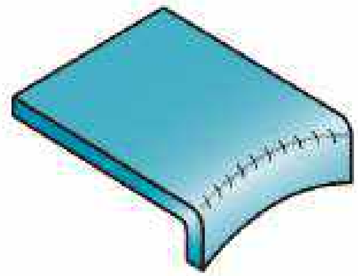
Edge bending



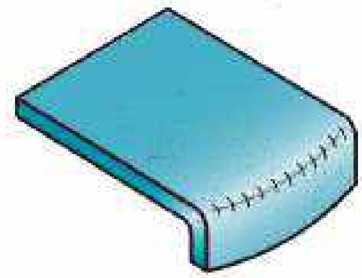
shearing



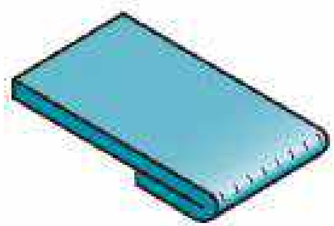
Straight flanging



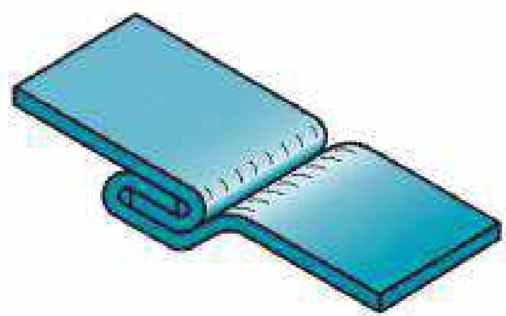
stretch flanging



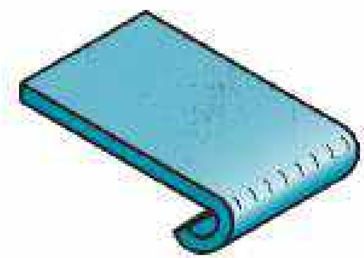
shrink flanging



Hemming



seaming



curling

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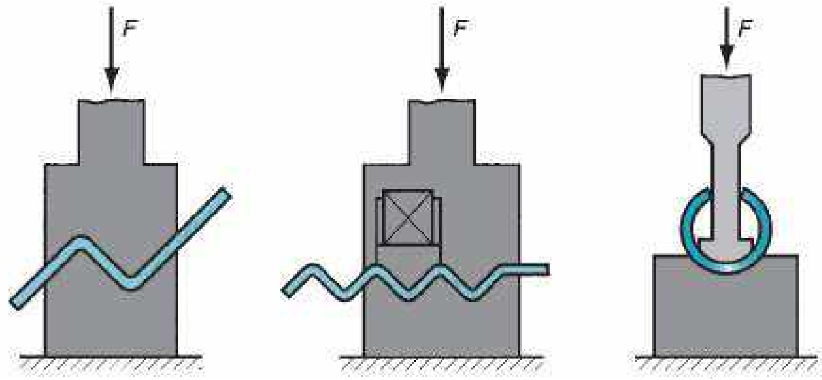
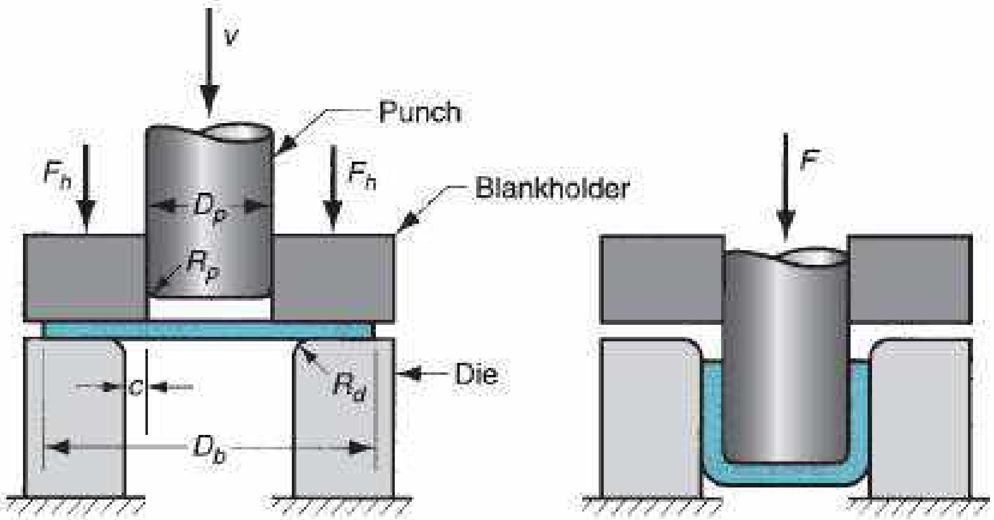


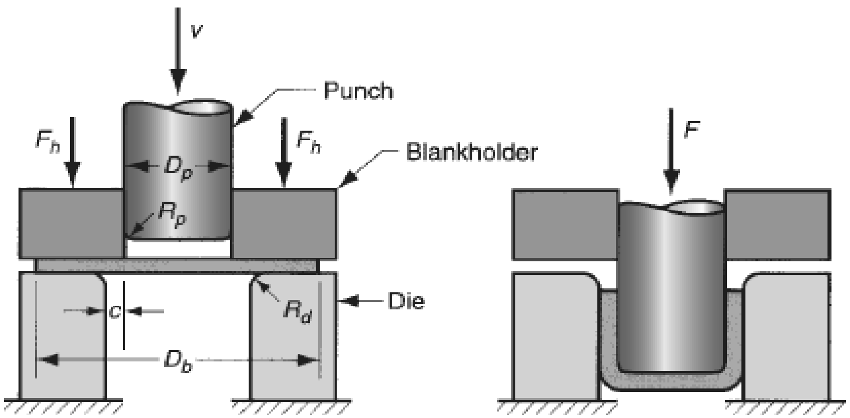
Other bending operations



Cup deep drawing

Cup deep drawing

It is a sheet forming operation, in which the sheet is placed over the die opening and is pushed by punch into the opening. The sheet is held flat on the die surface by using a blank holder.



c – clearance
D_b – blank diameter
D_p – punch diameter
R_d – die corner radius
R_p – punch corner radius
F – drawing force
F_h – holding force

The clearance '*c*' is defined to equal to 10% more than the sheet thickness '*t*'. If the clearance between the die and the punch is less than the sheet thickness, then ironing occurs.

$$c = 1.1t$$

Stages in deep drawing:

(i) As the punch pushes the sheet, it is subjected to a bending operation. Bending of sheet occurs over the punch corner and die corner. The outside perimeter of the blank moves slightly inwards toward the cup center.

(ii) In this stage, the sheet region that was bent over the die corner will be straightened in the clearance region at this stage, so that it will become cup wall region. In order to compensate the presence of sheet in cup wall, more metal will be pulled from the sheet edge, i.e., more metal moves into the die opening.

(iii) Friction between the sheet and the die, blank holder surfaces restricts the movement of sheet into the die opening. The blank holding force also influences the movement. Lubricants or drawing compounds are generally used to reduce friction forces.

(iv) Other than friction, compression occurs at the edge of the sheet. Since the perimeter is reduced, the sheet is squeezed into the die opening. Because volume remains constant, with reduction in perimeter, thickening occurs at the edge.

In thin sheets, this is reflected in the form of wrinkling. This also occurs in case of low blank holding force. If BHF very small, wrinkling occurs. If it is high, it prevents the sheet from flowing properly toward the die hole, resulting in stretching and tearing of sheet.

(v) The final cup part will have some thinning in side wall.

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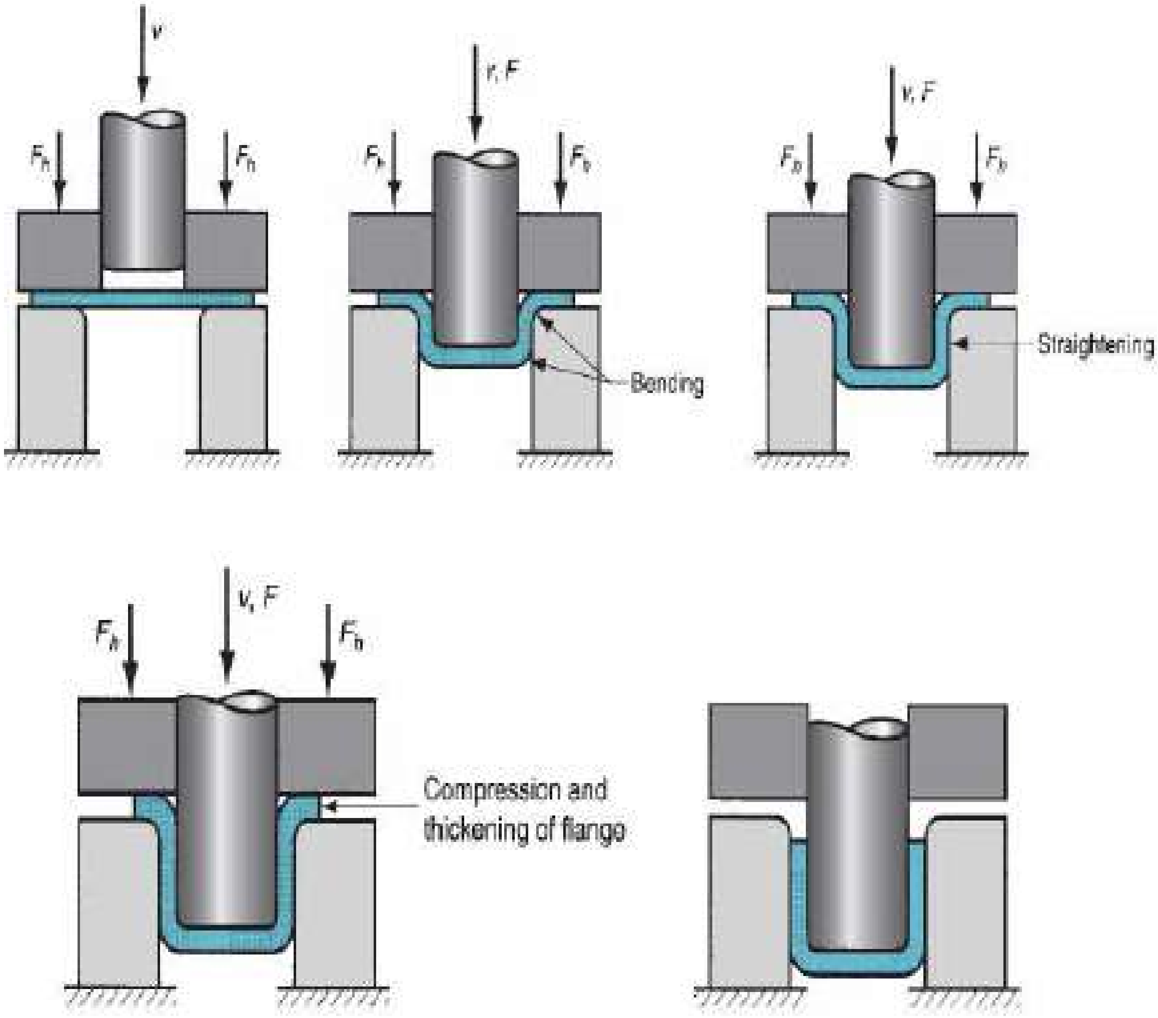
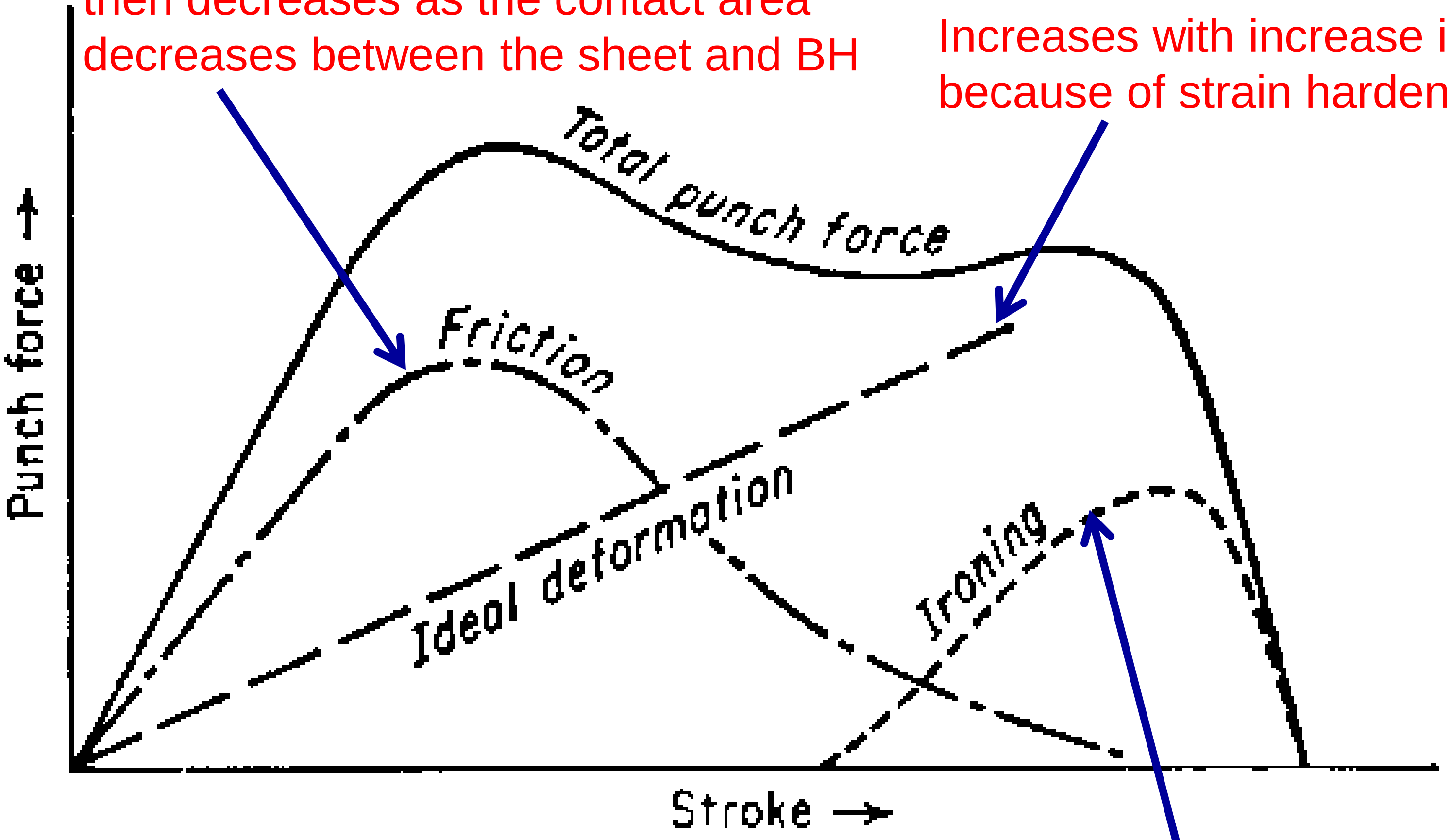


Stages in cup deep drawing

Friction force reaches peak early and then decreases as the contact area decreases between the sheet and BH

Increases with increase in strain because of strain hardening



Punch force-stroke for cup deep drawing: contribution from three important factors

Ironing occurs late in the process once the cup wall has reached the maximum thickness

G.E.Dieter, *Mechanical Metallurgy*

Quantification of cup drawability

Drawing ratio: ratio of blank diameter, D_b, to punch diameter, D_p. The greater the ratio, the more severe the drawing operation.

$$DR = \frac{D_b}{D_P}$$

The limiting value for a given operation depends on punch and die corner radii, friction conditions, draw depth, and quality of the sheet metal like ductility, degree of directionality of strength properties in the metal.

Reduction, R, is defined as, $$R = \frac{D_b - D_P}{D_b}$$

Limiting values: $DR \leq 2$; $R \leq 0.5$

Thickness to diameter ratio, $t/D_b > 1\%$;

As the ratio decreases, tendency for wrinkling increases.

The maximum drawing force, *F* , can be estimated approximately by the following equation .

$$F = \pi D_p t \sigma_{UTS} \left(\frac{D_b}{D_p} - 0.7 \right)$$

Correction factor for friction

The holding force, F_h, is given by,

$$F_h = 0.015 \sigma_{ys} \pi \left\{ D_b^{\ 2} - \left(D_p + 2.2t + 2R_d \right)^2 \right\}$$

$$F_h = \frac{F}{3}$$ (approx. holding force is one-third of drawing force)

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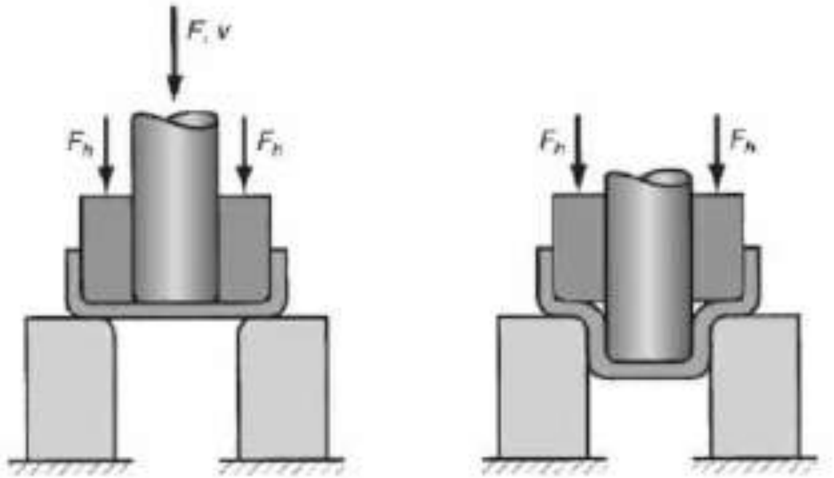
A cup drawing operation is performed in which the inside diameter = 80 mm and the height = 50 mm. The stock thickness = 3 mm, and the starting blank diameter = 150 mm. Punch and die radii = 4 mm. Tensile strength = 400 MPa and a yield strength = 180 MPa for this sheet metal. Determine: (a) drawing ratio, (b) reduction, (c) drawing force, and (d) blankholder force.

Redrawing

In many cases, the shape change involved in making that part will be severe (drawing ratio is very high). In such cases, complete forming of the part requires more than one deep drawing step.

Redrawing refers to any further drawing steps that is required to complete the drawing operation.



Redrawing

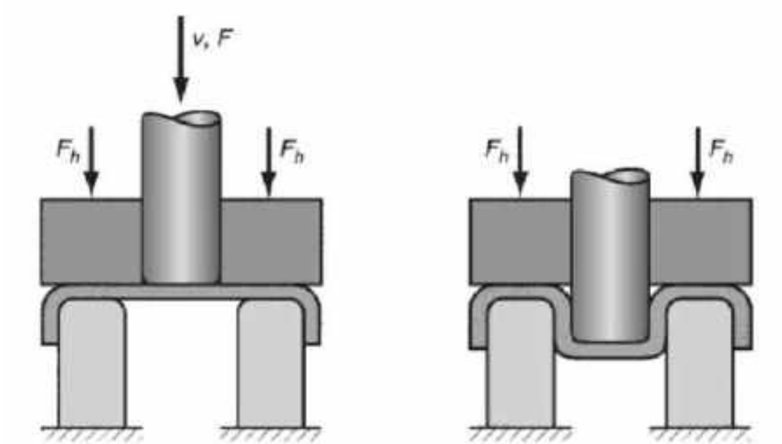
Guidelines for successful redrawing:

First draw: Maximum reduction of the starting blank - 40% to 45%

Second draw: 30%

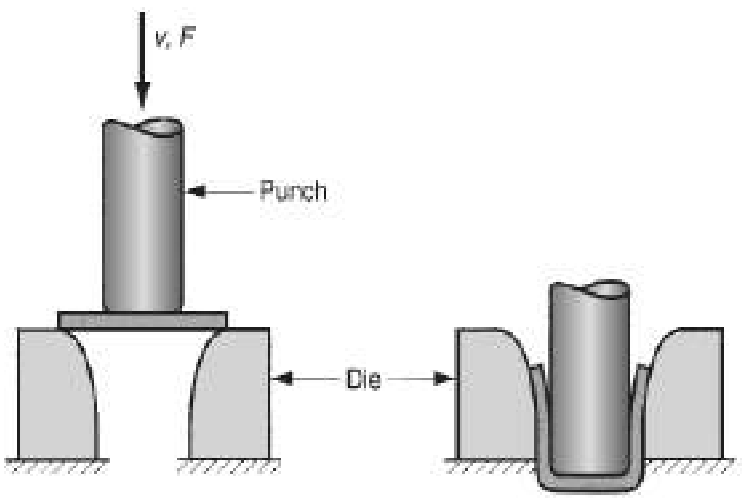
Third draw : 16%

Reverse redrawing



In reverse redrawing, the sheet part will face down and drawing is completed in the direction of initial bend.

Drawing without blank holder



The main function of BH is to reduce wrinkling. The tendency of wrinkling decreases with increase in thickness to blank diameter ratio (t/D_b). For a large t/D_b ratio, drawing without blank holder is possible.

The die used must have the funnel or cone shape to permit the material to be drawn properly into the die cavity.

Limiting value for drawing without BH:

$$D_b - D_p = 5t$$

Plastic anisotropy

The main cause of anisotropy of plastic properties is the preferred orientation of grains, i.e., tendency for grains to have certain orientations. This is cause mainly by mechanical forming of metals.

A useful parameter to quantify anisotropy is *R*, the plastic strain ratio, which is the ratio of true plastic strain in width direction to that in thickness direction. Higher R, large resistance to thinning.

$$R = \frac{\varepsilon_w}{\varepsilon_t}$$

For isotropic materials, *R* = 1; for anisotropic materials: *R* > 1 or *R* < 1

In many sheet forming operations like deep drawing, the materials exhibit some anisotropy in the sheet plane. So averaging is done to find a value quantifying all the variations in the sheet surface as given by the following equation. But this is practically impossible.

$$\overline{R} = \int_{\theta=0}^{\theta=360^\circ} R_\theta \, d\theta$$

(Average plastic strain ratio)

Usually the following equation is used by considering orthotropy is accurate.

$$\overline{R} = \frac{R_0 + 2R_{45} + R_{90}}{4}$$

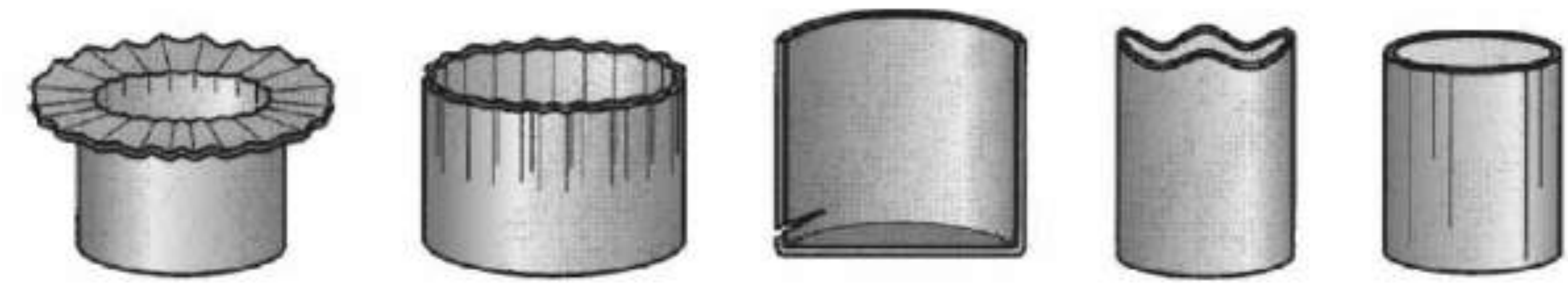
(normal anisotropy)

Another parameter that takes care of planar anisotropy is ΔR given by,

$$\Delta R = \frac{R_0 + R_{90} - 2R_{45}}{2}$$

This is a measure of how different the 45° directions are from the symmetry axes.

Defects in deep drawing



wrinkling in flange and cup wall **tearing** **earing** **surface scratches**

Wrinkling in flange and cup wall: This is like ups and downs or waviness that is developed on the flange. If the flange is drawn into the die hole, it will be retained in cup wall region.

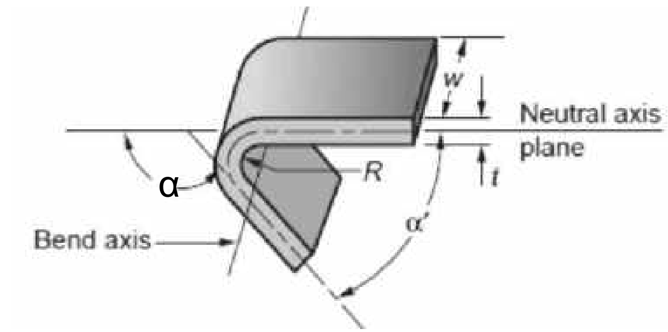
Tearing: It is a crack in the cup, near the base, happening due to high tensile stresses causing thinning and failure of the metal at this place. This can also occur due to sharp die corner.

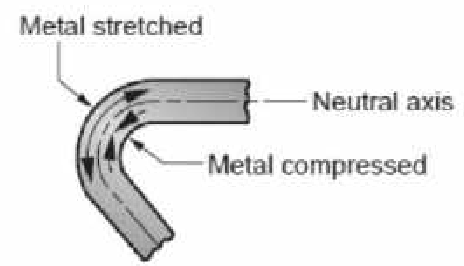
Earing: The height of the walls of drawn cups have peaks and valleys called as earing. There may be more than four ears. Earing results from planar anisotropy (ΔR), and ear height and angular position correlate well with the angular variation of R.

Surface scratches: Usage of rough punch, dies and poor lubrication cause scratches in a drawn cup.

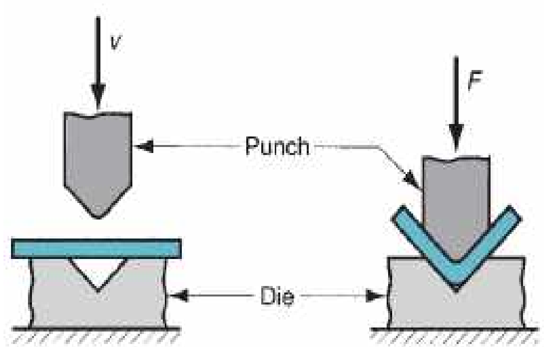
Sheet bending

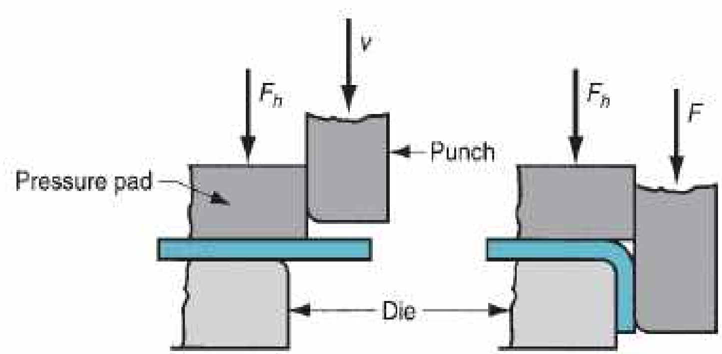
Sheet bending is defined as the straining of the metal around a straight axis as shown in figure. During bending operation, the metal on the inner side of the neutral plane is compressed, and the metal on the outer side of the neutral plane is stretched. Bending causes no change in the thickness of the sheet metal.



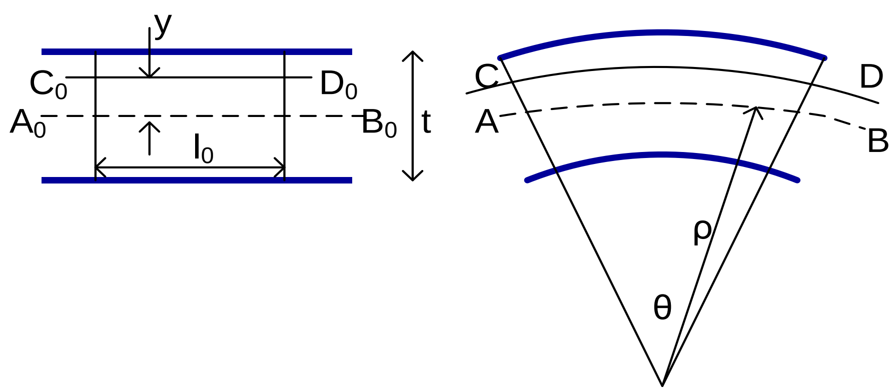


In V-bending, the sheet metal is bent between a V-shaped punch and die set up. The included angles range from very obtuse to very acute values.
In edge bending, cantilever loading of the sheet is seen. A pressure pad is used to apply a force to hold the sheet against the die, while the punch forces the sheet to yield and bend over the edge of the die.





Deformation during bending



For our analysis, it may be assumed that a plane normal section in the sheet will remain plane and normal and converge on the center of curvature as shown in Figure. The line A_0B_0 at the middle surface may change its length to AB, if the sheet is under stretching during bending. The original length l_o becomes, $l_s = \rho\theta$. A line C_0D_0 at a distance y from the middle surface will deform to a length,

$$l = \theta(\rho + y) = \rho\theta(1 + \frac{y}{\rho}) = l_s(1 + \frac{y}{\rho})$$ where ρ is the radius of curvature.

The axial strain of the fiber CD is,

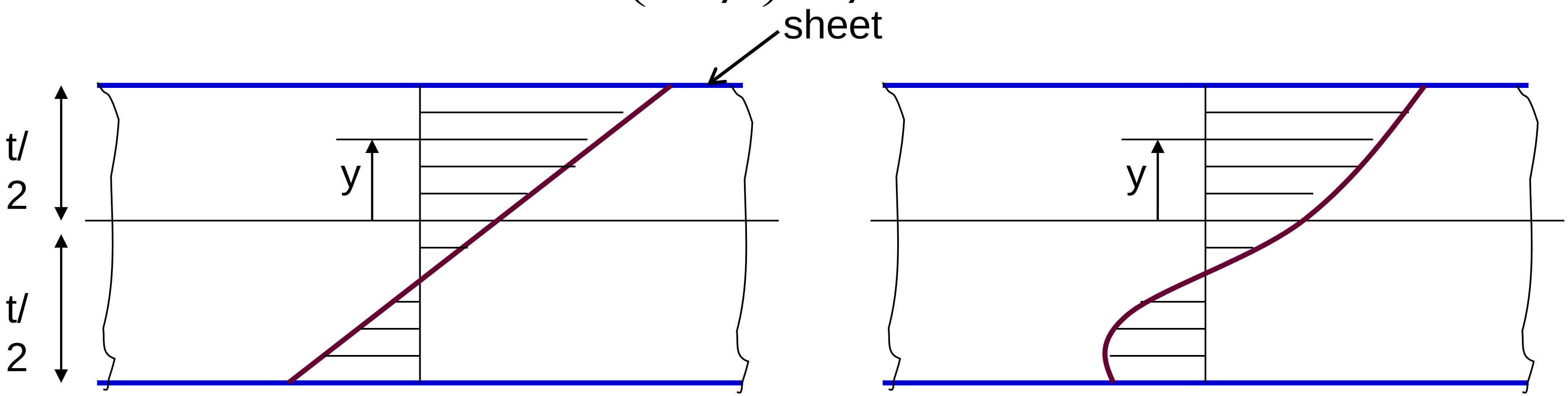
$$\varepsilon_1 = \ln\frac{l}{l_0} = \ln\frac{l_s}{l_0} + \ln\left(1 + \frac{y}{\rho}\right) = \varepsilon_a + \varepsilon_b \qquad (1)$$

R. Ganesh Narayanan, IITG

Marciniak, Duncan, Hu, *Mechanics of sheet metal forming* where 'ε_a' and 'ε_b' are the strains at the middle surface and bending strain respectively.

In the case of bending with radius of curvature larger compared to the thickness, the bending strain is approximated as,

$$\varepsilon_b = \ln\left(1 + \frac{y}{\rho}\right) \approx \frac{y}{\rho}$$



Strain distribution in bending

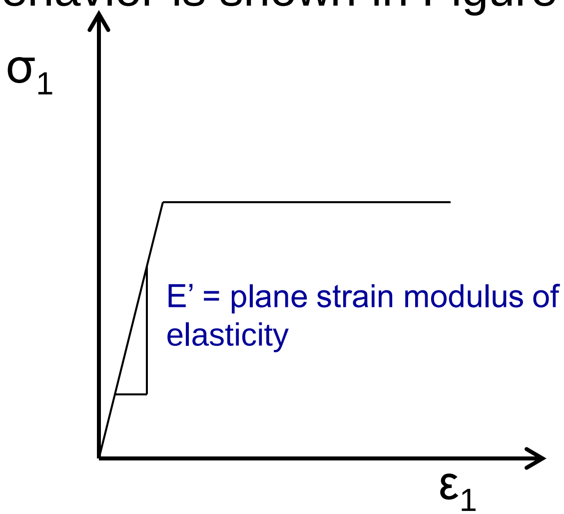
Typical stress distribution in bending

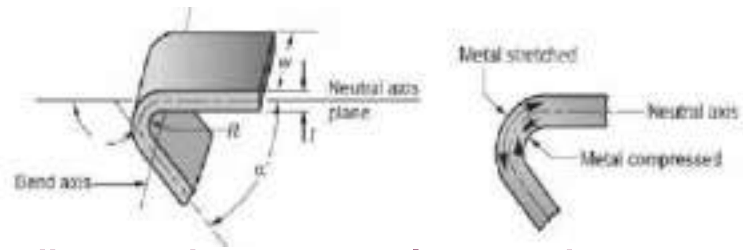
Choice of material model

For the strain distribution given by equation (1) for bending, the stress distribution on a section can be found out by knowing a stress-strain law.

Generally elastic-plastic strain hardening behavior is seen in sheet bending. But there are other assumptions also.

Elastic, perfectly plastic model: Strain hardening may not be important for a bend ratio (ρ/t) (radius of curvature/thickness) of about 50. For this case the stress-strain behavior is shown in Figure below.





Bending can be seen as plane strain deformation as strain along bend can be zero

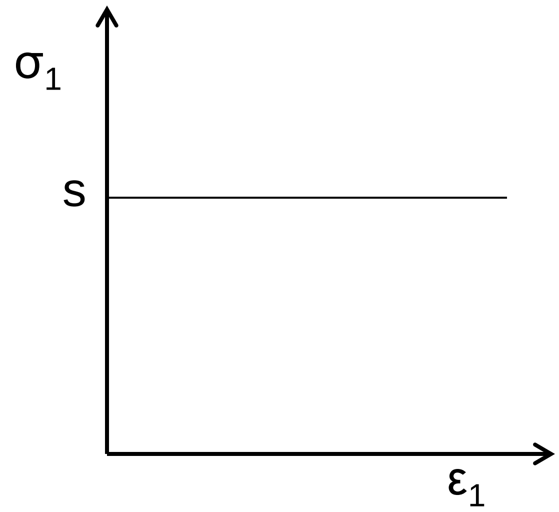
For elastic perfectly plastic model, for stress less than plane strain yield stress, S,

$$\boldsymbol{\sigma_1 = E' \varepsilon_1} \quad \text{where } E' = E/1\text{-}\gamma^2$$

For strains greater than yield strains, $\boldsymbol{\sigma_1 = S}$ *where* $S = \sigma_f\,(2/\sqrt{3})$

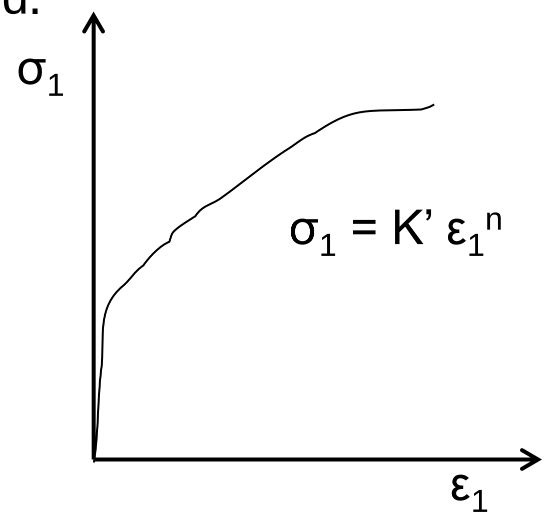
Rigid, perfectly plastic model: For smaller radius bends, where elastic springback is not considered, the elastic strains and strain hardening are neglected. So,

$$\sigma_1 = S$$



Strain hardening model: When the strains are large, elastic strains can be neglected, and the power hardening law can be followed.

$$\sigma_1 = K' \varepsilon_1^n$$



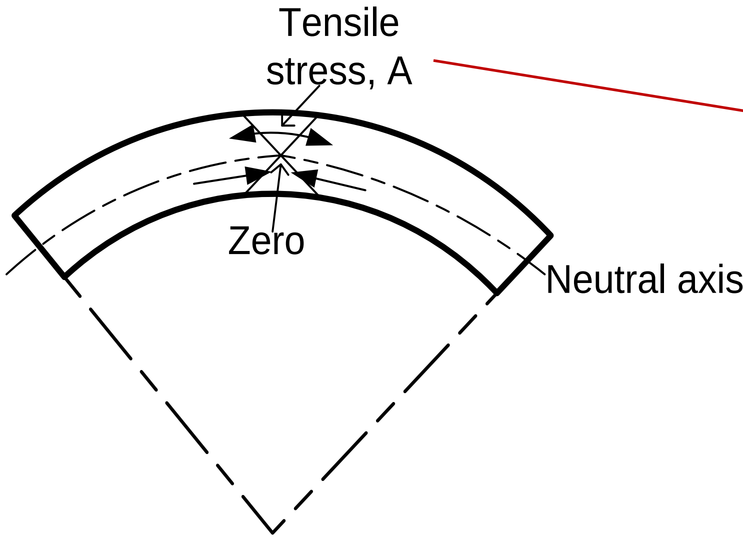
Spring back

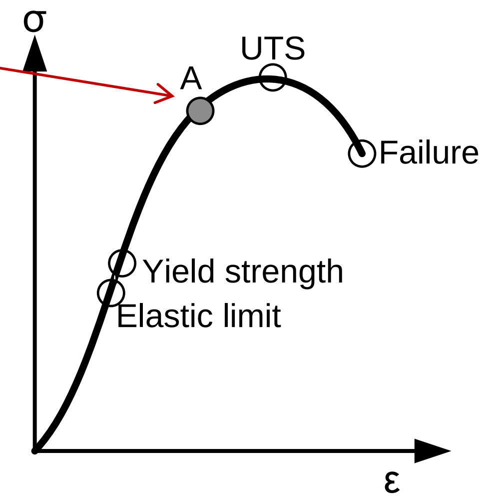
•*Spring back* occurs because of the variation in bending stresses across the thickness, i.e., from inner surface to neutral axis to outer surface. The tensile stresses decrease and become zero at the neutral axis.

•Since the tensile stresses above neutral axis cause plastic deformation, the stress at any point (say '*A*') in the tensile stress zone should be less than the ultimate tensile strength in a typical tensile stress-strain behavior. The outer surface will crack, if the tensile stress is greater than ultimate stress during bending.

•The metal region closer to the neutral axis has been stressed to values below the elastic limit. This elastic deformation zone is a narrow band on both sides of the neutral axis, as shown in Fig. The metal region farther away from the axis has undergone plastic deformation, and obviously is beyond the yield strength.

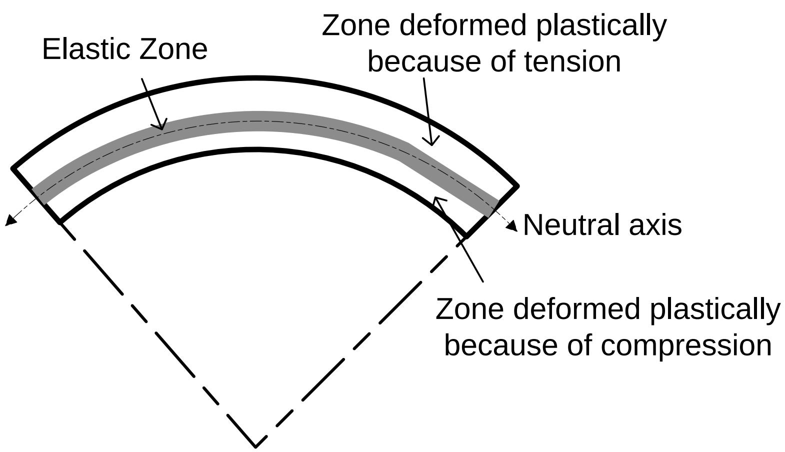
•Upon load removal after first bending, the elastic band tries to return to the original flat condition but cannot, due to the restriction given by the plastic deformed regions. Some return occurs as the elastic and plastic zones reach an equilibrium condition and this return is named as *spring back*.



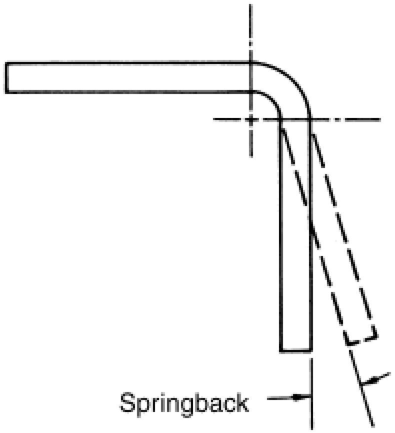


Changing stress patterns in a bend

ASM handbook, sheet metal forming



Elastic and plastic deformation zones during bending

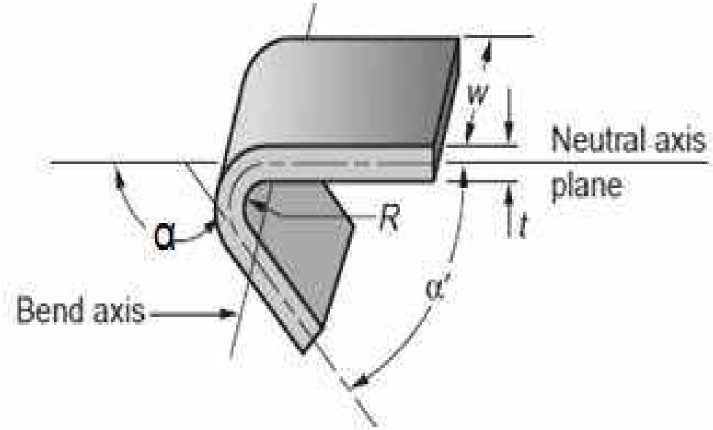


Springback

- Sprinback can be minimized by overbending, bottoming and stretch forming.
- In overbending, the punch angle and radius are made smaller than the specified angle on the final part so that the sheet metal springs back to the desired value.
- Bottoming involves squeezing the part at the end of the stroke, thus plastically deforming it in the bend region.

Spring back is defined by the equation:

$$SB = \frac{\alpha^{'} - \alpha_{tool}}{\alpha_{tool}}$$

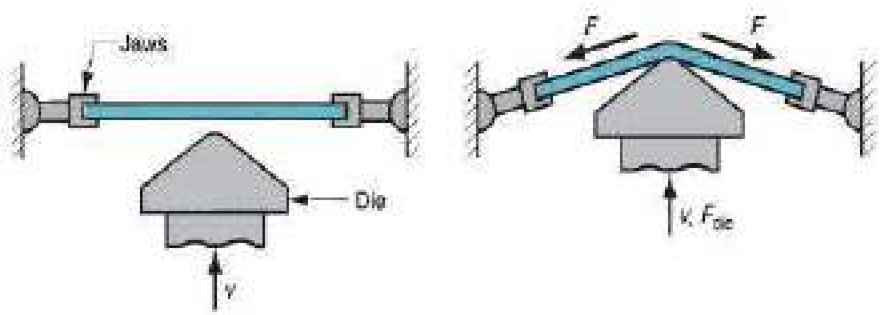


Stretching/stretch forming

- Stretch forming is a sheet metal forming process in which the sheet metal is intentionally stretched and simultaneously bent to have the shape change.

-The sheet is held by jaws or drawbeads at both the ends and then stretched by punch, such that the sheet is stressed above yield strength.

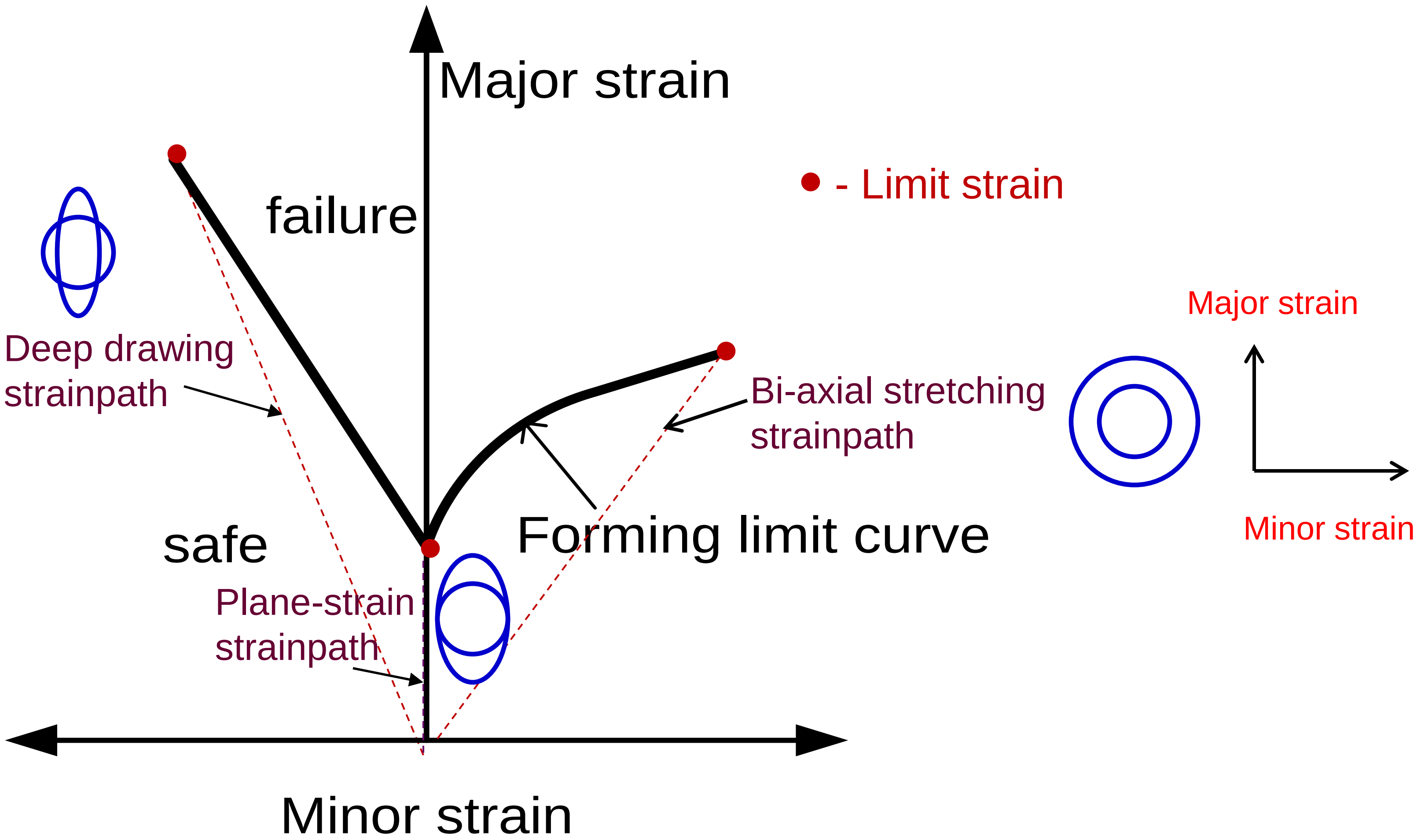
- When the tension is released, the metal has been plastically deformed. The combined effect of stretching and bending results in relatively less springback in the part.



Stretching/stretch forming

Photo from public resource

Forming limit diagram (FLD)

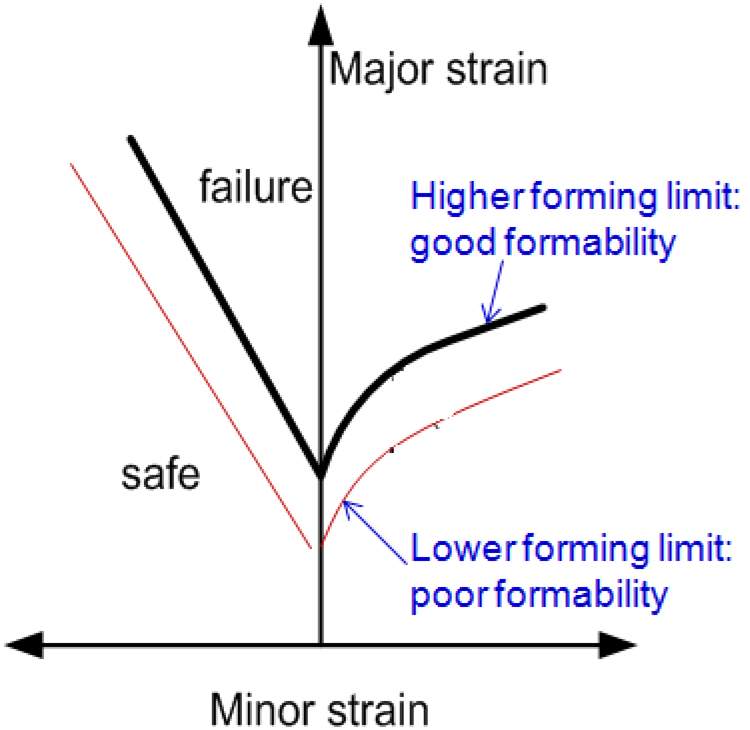


From tensile test we get only ductility, work hardening exponent, but it is in a uniaxial tension without friction, which cannot truly represent material behaviours obtained from actual sheet forming operations.

In sheet forming, mainly in stretching, FLD gives quantification about formability of sheet material. It tells about quality of the material.

In this diagram, *forming limit curve* (*FLC*), plotted between major strain (in Y-axis) and minor strain (in X-axis), is the index that says the amount of safe strains that can be incorporated into the sheet metal.

The FLC is the locus of all the limit strains in different strain paths (like deep drawing, biaxial stretching, plane strain) of the sheet material. The plane-strain condition possesses the least forming limit, when compared to deep drawing and stretching strain paths.



A sheet material with higher forming limit is considered good.

WELDING, BRAZING, SOLDERING

Metal joining process that uses melted metal as joints

Brazing & soldering: joining two different/similar metals using a third filler material into the joint in liquid state & allowed to solidify.

Brazing differs from soldering → in the melting temp. of the filler

Brazing - only the filler is melted → wets the materials to be joined
- temperature: 430^0 C – 800^0 C

Soldering – same as brazing; temperature range: 100^0 C – 450^0 C

Strength of joint determined by the adhesive quality of the filler

Welding – original materials are melted and joined → solidified

Mainly from Chapter 39:

Arranged according to the subject flow.

Joinability/Weldability

- Wettability: Hydrophobic or Hydrophilic
- Fluidity: Gap, Surface tension, material.
- Cleanliness: Oxide removal, etc.
- Prevention from further oxidation/Contamination

TABLE 37-3. Some Common Solders and Their Properties

Composition (wt %)	Freezing Temperature (°F)			Applications
	Liquidus	Solidus	Range	
Lead–tin solders				
98 Pb–2 Sn	611	601	10	Side seams in three-piece can
90 Pb–10 Sn	576	514	62	Coating and joining metals
80 Pb–20 Sn	531	361	170	Filling and seaming auto bodies
70 Pb–30 Sn	491	361	130	Torch soldering
60 Pb–40 Sn	460	361	99	Wiping solder, radiator cores, heater units
50 Pb–50 Sn	421	361	60	General purpose
40 Pb–60 Sn	374	361	13	Electronic (low temperature)
Silver solders				
97.5 Pb–1 Sn–1.5 Ag	588	588	0	Higher-temperature service
36 Pb–62 Sn–2 Ag	372	354	18	Electrical
96 Sn–4 Ag	430	430	0	Electrical
Other alloys				
45 Pb–55 Bi	255	255	0	Low temperature
43 Sn–57 Bi	281	281	0	Low temperature
95 Sn–5 Sb	464	450	14	Electrical
50 Sn–50 In	257	243	14	Metal-to-glass
37.5 Pb–25 In–37.5 Sn	280	280	0	Low temperature

TABLE 39-4. Some Common Solders and Their Properties

Composition (wt %)	Freezing Temperature (°C) Liquidus	Solidus	Range	Applications
Lead–tin solders				
98 Pb–2 Sn	322	316	6	Side seams in three-piece can
90 Pb–10 Sn	302	268	34	Coating and joining metals
80 Pb–20 Sn	277	183	94	Filling and seaming auto bodies
70 Pb–30 Sn	255	183	72	Torch soldering
60 Pb–40 Sn	238	183	55	Wiping solder, radiator cores, heater units
50 Pb–50 Sn	216	183	33	General purpose
40 Pb–60 Sn	190	183	7	Electronic (low temperature)
Silver solders				
97.5 Pb–1 Sn–1.5 Ag	308	308	0	Higher-temperature service
36 Pb–62 Sn–2 Ag	189	179	10	Electrical
96 Sn–4 Ag	221	221	0	Electrical
Other alloys				
45 Pb–55 Bi	124	124	0	Low temperature
43 Sn–57 Bi	138	138	0	Low temperature
95 Sn–5 Sb	240	234	6	Electrical
50 Sn–50 In	125	117	8	Metal-to-glass
37.5 Pb–25 In–37.5 Sn	138	138	0	Low temperature
95.5 Sn–3.9 Ag–0.6 CO	217	217	0	Electrical

Soldering joints : soft → types:

1. Tin & Lead (60:40, 50:50, 40:60) – $t_f \cong 240^0$ C
2. Lead & Silver (97:3) → $t_f \cong 310^0$ C

For filling → 20/30 % tin – lead composition – cheaper

Cleanliness – Critical to the strength of the joint
Oxide have to be removed from the surfaces before joining

Cleaning methods 1. Using fluxes (chemical action)
2. Abrasive removal (mechanical action)
3. Ultrasonic cleaning (acoustic action)

Fluxless Soldering: Gold coated, Ultrasonic, Inert atmosphere.

Heating:- required to melt the filler (by any method: furnaces, torch, electrical resistance)

•Typical, the use of soldering iron heat is applied from the iron and solder is melted and it adheres to the surface of the joint (usually, as a wire)

•The joined parts should be also heated to improve the joining process

•Ultrasonic soldering →the soldering iron is actuated with 20KHz

SOLDERING JOINTS:

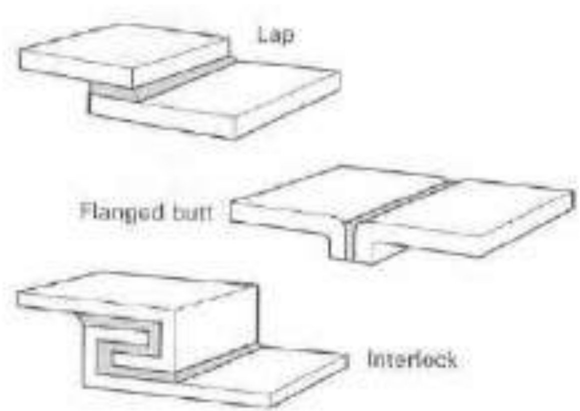


FIGURE 37-8 Some common designs for soldered joints. *(Courtesy of Lead Industries Association.)*

BRAZING: **Similar to soldering but at temp > 450^0 C, still lower than melting temperature of the brazed metal parts.**

Here, the capillary attraction is driving the filler metal into the joint (clearance is very small)

For different fillers →different recommended clearances to improve the strength of the joint

- **Copper → no clearance**
- **silver alloy → 0.04 – 0.05 mm**
- **brass → 0.5 – 0.75 mm**

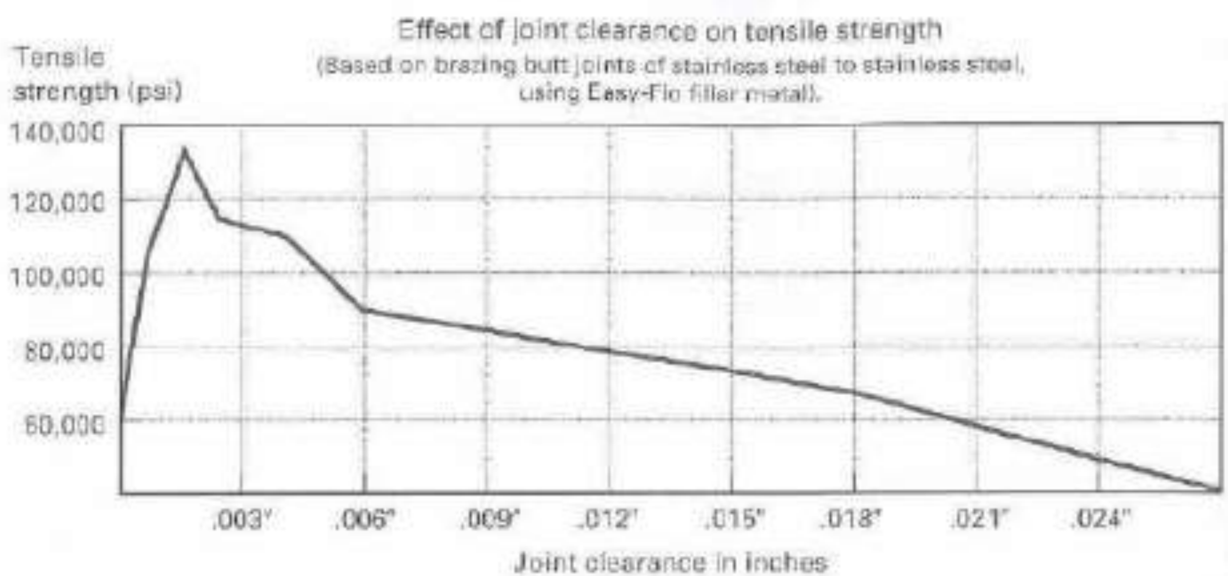
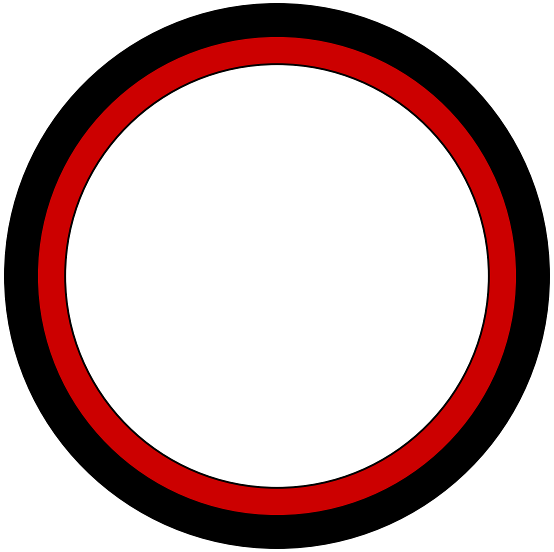


FIGURE 37-1 Typical variation of tensile strength with different joint clearances in a butt joint design. *(Courtesy of Handy & Harman).*

- The clearances are estimated at the brazing temperature.
- Estimate the initial dimensions based on the expansion coefficient→ gap or interference



BRAZE WELDING →a joining process where the capillary attraction is not used to distribute the filler metal. The molten filler is deposited before brazing is done.

→ special fluxes are used (Borax) to: remove the oxide
improve the fluidity of the fillers
wet the joint surfaces

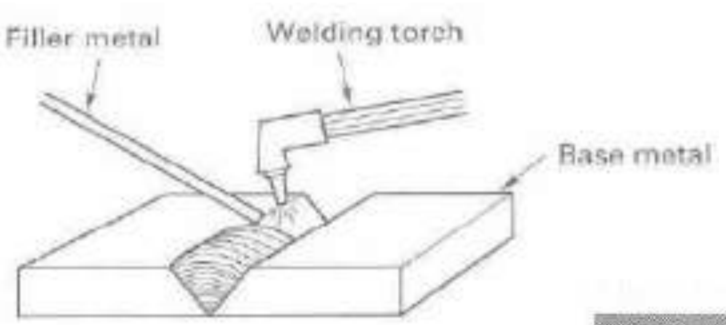


FIGURE 37-7 Schematic of the braze welding process.

TABLE 37-2. Engineering Materials and Their Compatibility with Brazing

Material	Brazing Recommendation
Cast iron	Somewhat difficult
Carbon and low-alloy steels	Recommended for low- and medium-carbon materials; difficult for high-carbon materials; seldom used for heat-treated alloy steels
Stainless steel	Recommended; Silver and nickel brazing alloys are preferred
Aluminum and magnesium	Common for aluminum alloys and some alloys of magnesium
Copper and copper alloys	Recommended for copper and high-copper brasses; somewhat variable with bronzes
Nickel and nickel alloys	Recommended
Titanium	Difficult, not recommended
Lead and zinc	Not recommended
Thermoplastics, thermosets, and elastomers	Not recommended
Ceramics and glass	Not recommended
Dissimilar metals	Recommended, but may be difficult, depending on degree of dissimilarity
Metals to nonmetals	Not recommended
Dissimilar nonmetals	Not recommended

TABLE 39-2. Some Common Braze Metal Families, Metals They Are Used to Join, and Typical Brazing Temperatures

Braze Metal Family	Materials Commonly Joined	Typical Brazing Temperature (°C)
Aluminum-silicon	Aluminum alloys	565–620
Copper and copper alloys	Various ferrous metals as well as copper and nickel alloys and stainless steel	925–1150
Copper-phosphorus	Copper and copper alloys	700–925
Silver alloys	Ferrous and nonferrous metals, except aluminum and magnesium	620–980
Precious metals (gold-based)	Iron, nickel, and cobalt alloys	900–1100
Magnesium	Magnesium alloys	595–620
Nickel alloys	Stainless steel, nickel, and cobalt alloys	925–1200

Brazing Materials:

copper alloys
silver alloys
aluminium alloys

Basic joint types in brazing:

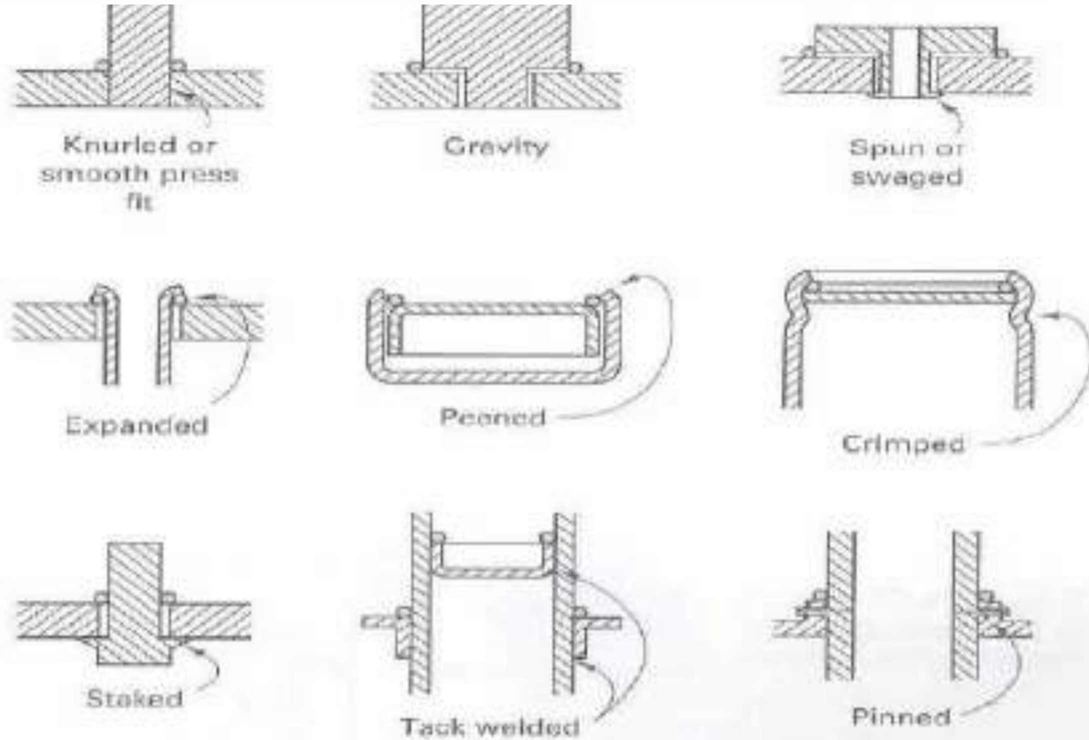


FIGURE 37-2 Methods of applying braze metal and positioning or fixturing various joints.

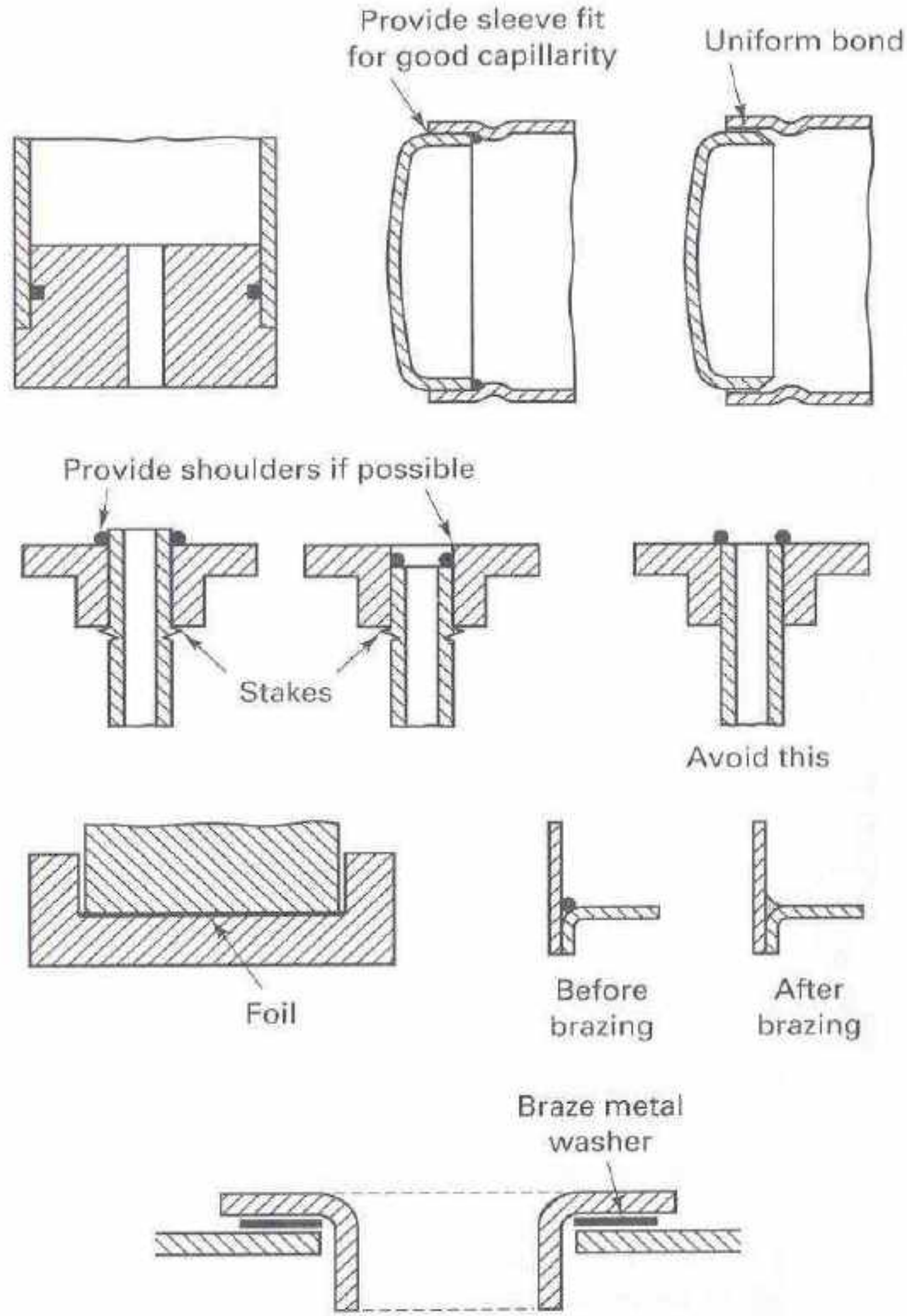


FIGURE 37-3 Techniques to apply brazing wire, foil, or sheet to assure proper flow into the joint.

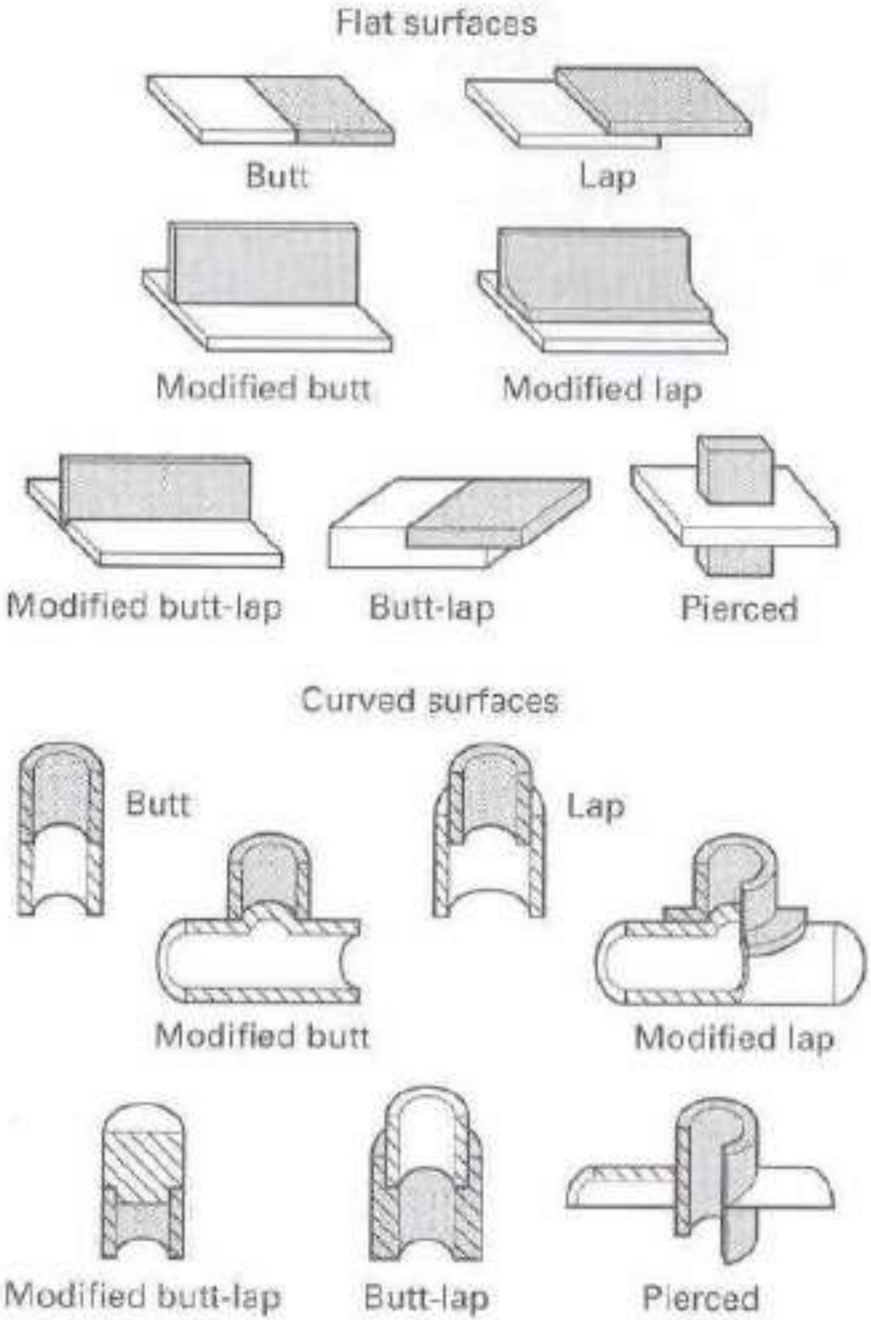


FIGURE 37-5 Some common designs of brazed joints for flat and curved surfaces. *(Adapted from* The Brazing Book, *Handy & Harman).*

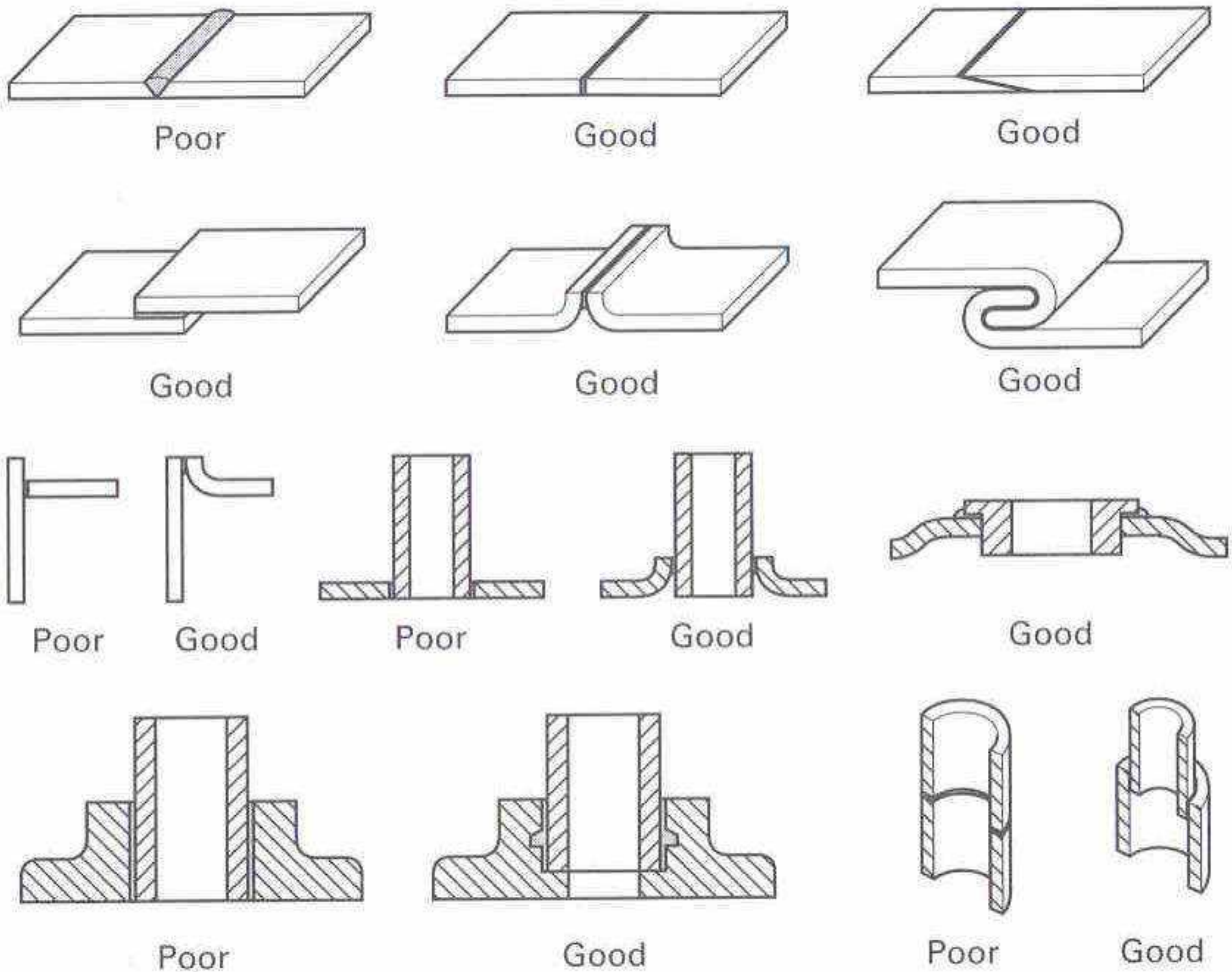


FIGURE 37-6 Examples of good and bad joint design for brazing.

Quality of joints:

Rule of thumb: **stronger joints for larger contact area**
stronger joints for optimal clearance
stronger joints for appropriate brazing material

Brazing of pipes – in hydraulic works, can be performed in different ways →

Induction brazing (brazing process named by the method that is used to heat assembly), furnace, dipping, torch, electric

The brazing operation must be preceded by cleaning and setting of the proper gap [jigs are used to hold the parts at their position during brazing]

Typical Process Assembly of pipes, carbide tips, radiators, heat exchangers, repair of casting

FIGURE 37-4 Typical furnace-brazed assemblies. *(Courtesy of Pacific Metals Company.)*

Chapter 35

WELDING

Metal joining process – without different metal added between.

Coalescence– can be obtained by heat and/or pressure, metallurgical conditions

BY HEAT → hot welding (melted partly at the joint)

BY PRESSURE →metallurgical process at the level of the intermolecular forces
→ cold welding (attraction forces between atoms at the contact surface)

PROBLEMS:

•Keeping weld clean – coalescence is improved by cleanliness of surface to be welded

•Surface oxides –removed before welding → fluxes are used during the welding, the fluxes burn and produce *slag* → because they float as slag on the molten metal and protect it from atmospheric contamination (made of SiO_2 + additives).

•In gas welding, the filler metal rod is often coated with flux

•In electrical arc – welding – the electrode is coated with flux or the flux is added as powder over the welding seem

•A non – oxidising atmosphere is created and the welding is shielded against oxygen (oxidation)

•Inert gasses used to protect the weld created from oxygen

CLASSIFICATION

FIGURE 33-1 Classification of common welding processes along with their AWS (American Welding Society) designations.

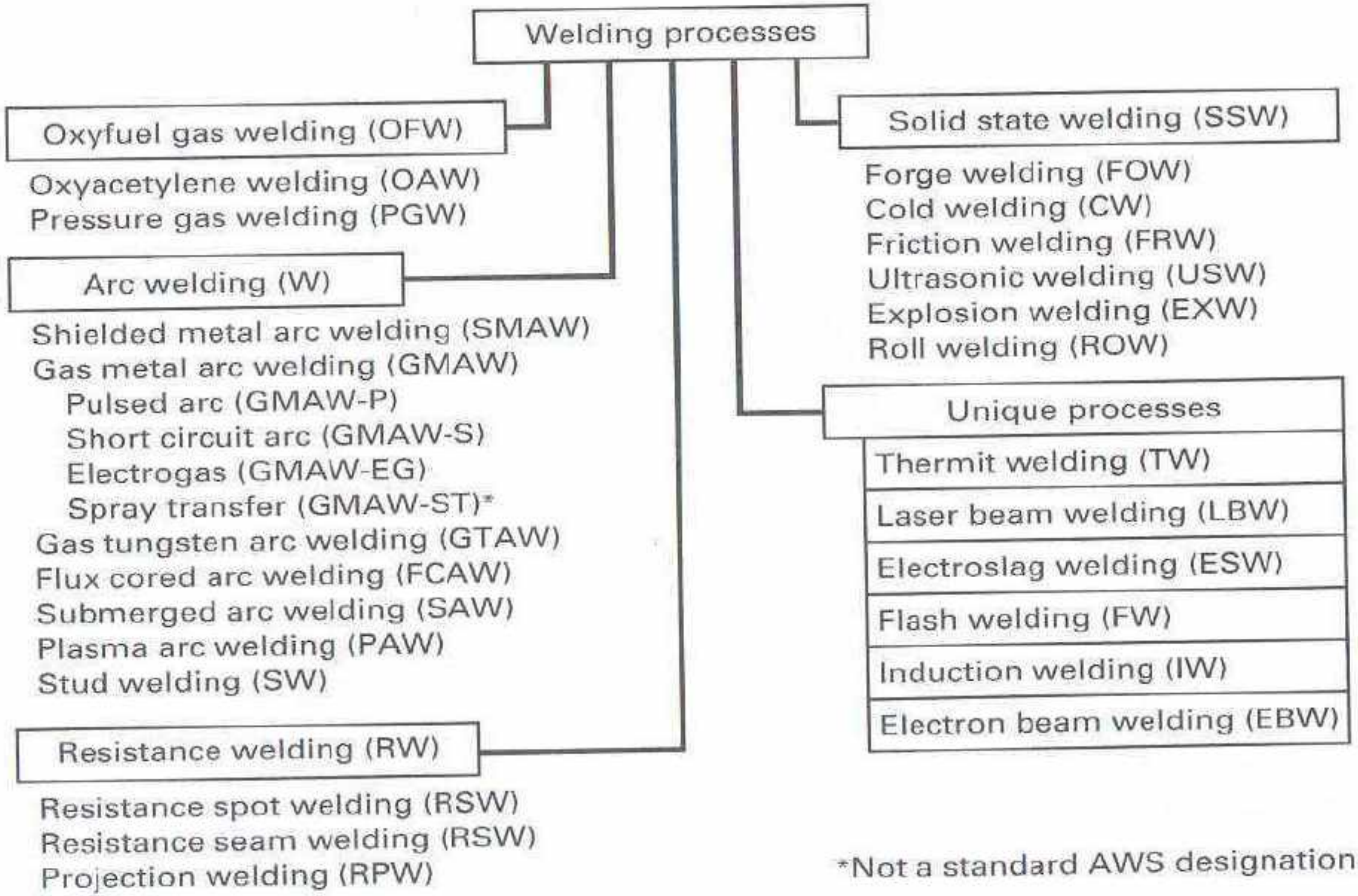
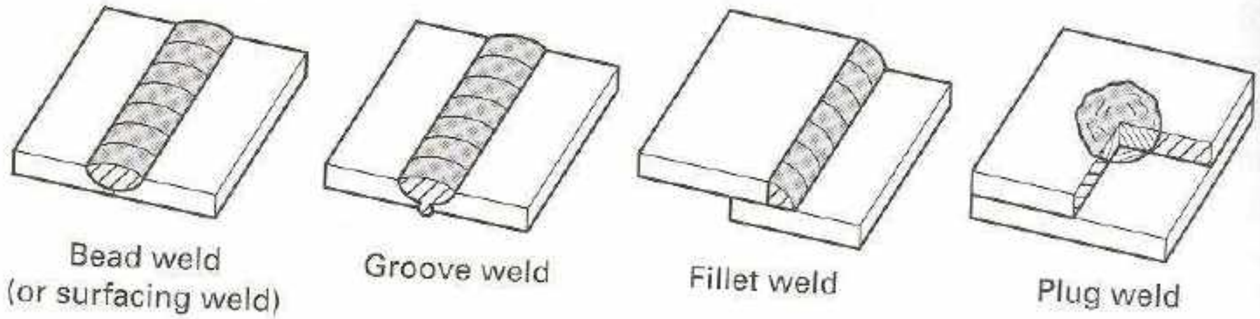


FIGURE 35-3 Four basic types of fusion welds.



... solidified from the molten state.

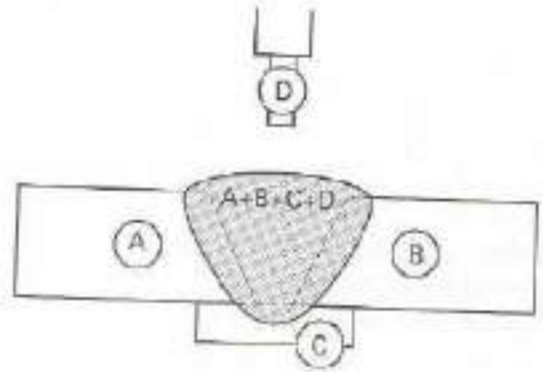
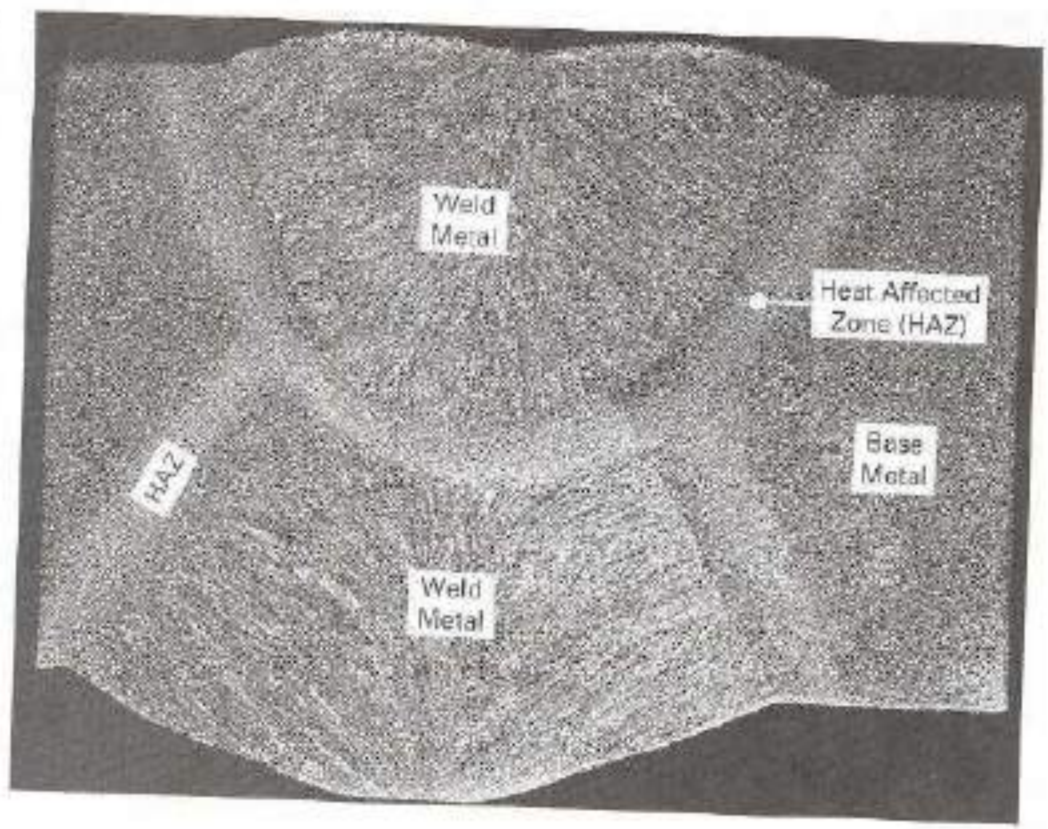


FIGURE 35-9 Schematic of a butt weld between a plate of metal A and a plate of metal B, with a backing plate of metal C and filler of metal D. The resulting weld nugget becomes a complex alloy of all four metals.



GURE 35-10 Grain structure d various zones in a fusion eld.

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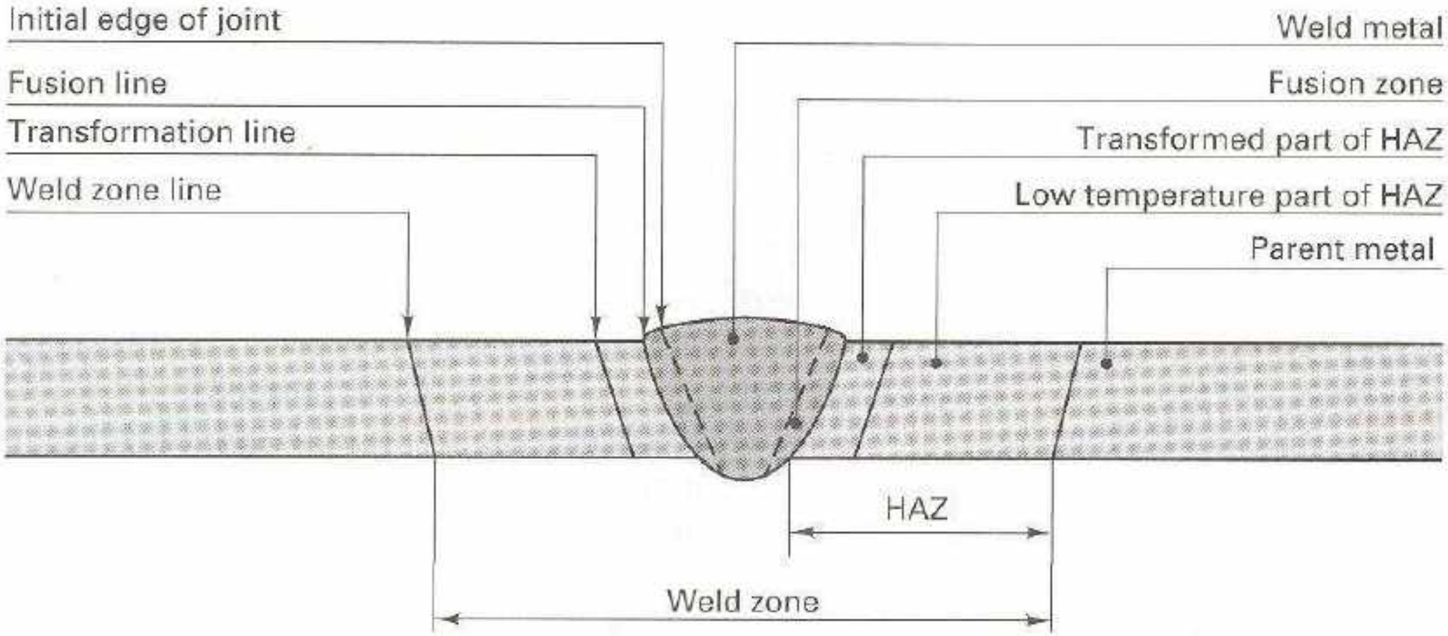


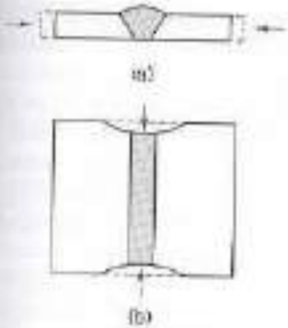


FIGURE 35-14 Shrinkage of a typical butt weld in the transverse (a) and longitudinal (b) directions as the material responds to the induced stresses. Note that restricting transverse motion will place the entire weld in transverse tension.

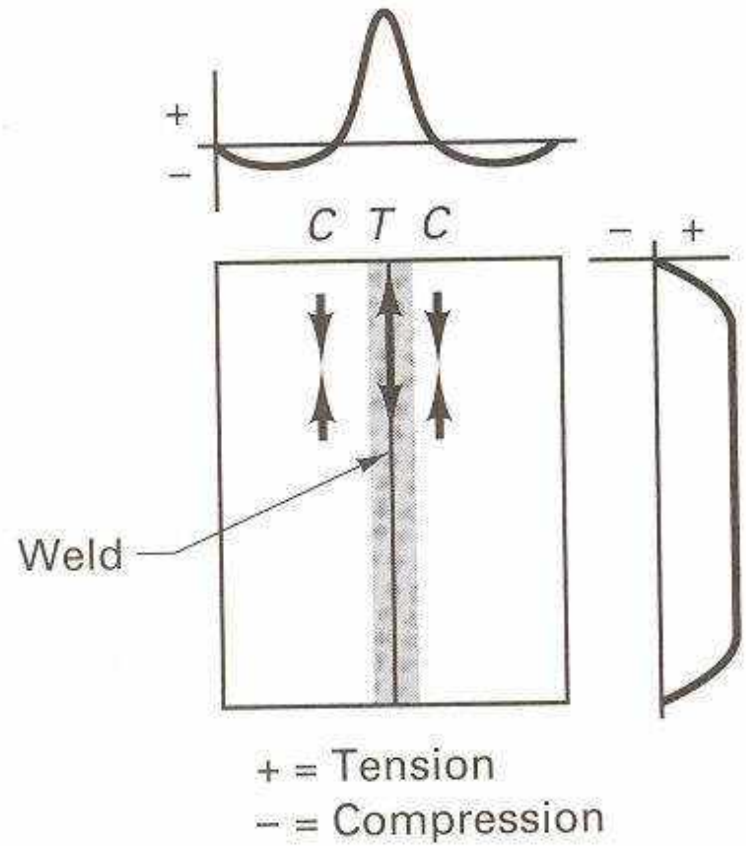


FIGURE 35-13 Schematic of the longitudinal residual stresses in a fusion-welded butt joint.

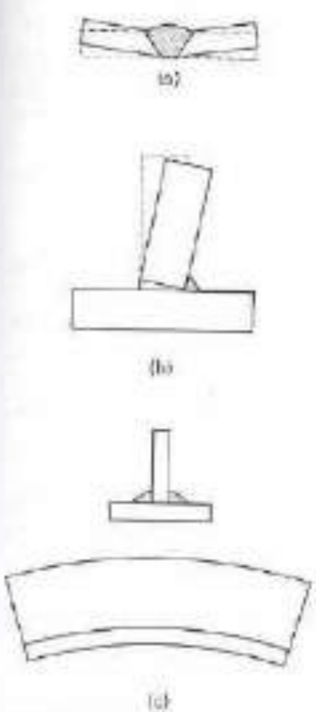


FIGURE 35-15 Distortions or warpage that may occur as a

TABLE 35-2 Weldability or Joinability of Various Engineering Materials[a]

Material	Arc Welding	Oxyacetylene Welding	Electron Beam Welding	Resistance Welding	Brazing	Soldering	Adhesive Bonding
Cast iron	C	R	N	S	D	N	C
Carbon and low-alloy steel	R	R	C	R	R	D	C
Stainless steel	R	C	C	R	R	C	C
Aluminum and magnesium	C	C	C	C	C	S	R
Copper and copper alloys	C	C	C	C	R	R	C
Nickel and nickel alloys	R	C	C	R	R	C	C
Titanium	C	N	C	C	D	S	C
Lead and zinc	C	C	N	D	N	R	R
Thermoplastics	Heated tool R	Hot gas R	N	Induction C	N	N	C
Thermosets	N	N	N	N	N	N	C
Elastomers	N	N	N	N	N	N	R
Ceramics	N	S	C	N	N	N	R
Dissimilar metals	D	D	C	D	D/C	R	R

[a] C, commonly performed; R, recommended (easily performed with excellent results); D, difficult; N, not used; S, seldom used.

Chapters 36, 37 and 38

WELDING PROCESSES

1. **FORGE WELDING (FOW)**

- **Welding with use of pressure & heat – not much in use today**
- **Hot metal are hammered together until welded (but not melted)**

2 **COLD WELDING (CW) – no heat is used → coalescence through rapid application of pressure**

- **Surface must be very clean, flat in order to bring the atoms of metal very close**
- **Done by a punch-press or hammer – a kind of cold working process**

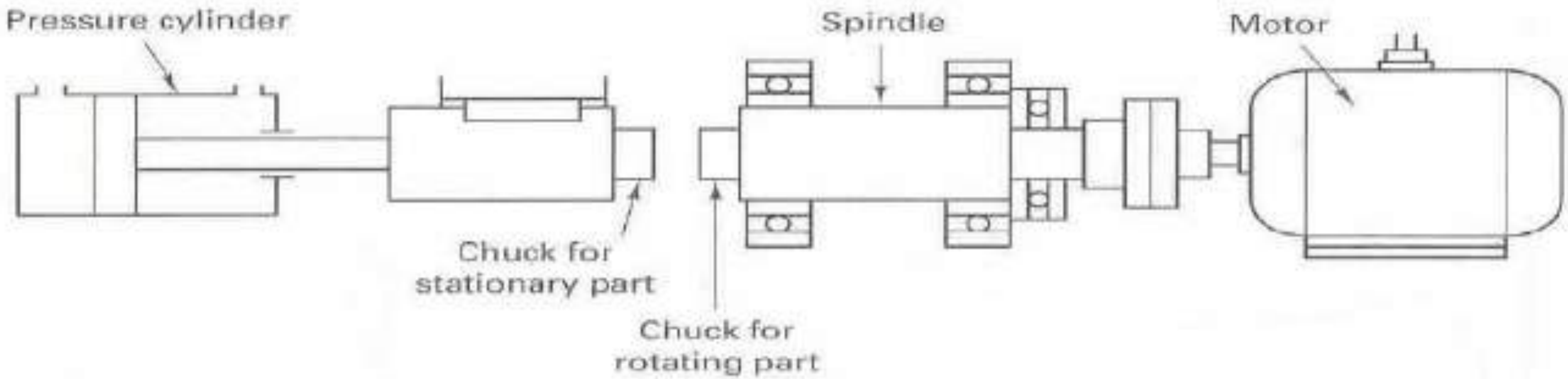
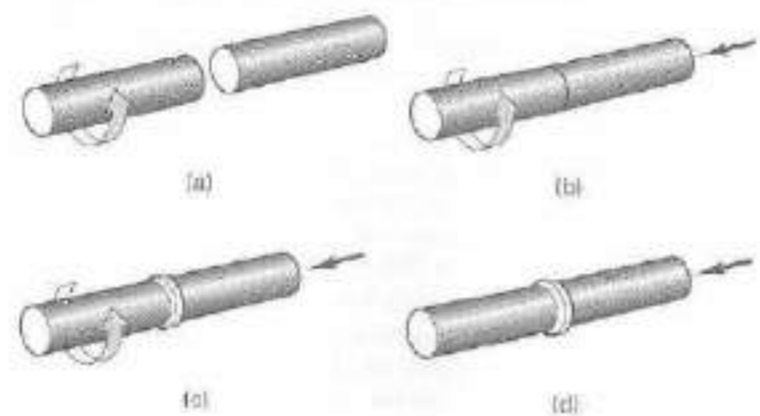


FIGURE 36-3 Schematic diagram of the equipment used for friction welding. *(Courtesy of Materials Engineering.)*

FIGURE 36-2 Sequence for making a friction weld. (a) Components with square surfaces are inserted into a machine where one part is rotated and the other is held stationary. (b) The components are pushed together with a low axial pressure to clean and prepare the surfaces. (c) The pressure is increased, causing an increase in temperature, softening, and possibly some melting. (d) Rotation is stopped and the pressure is increased rapidly, creating a forged joint with external flash.



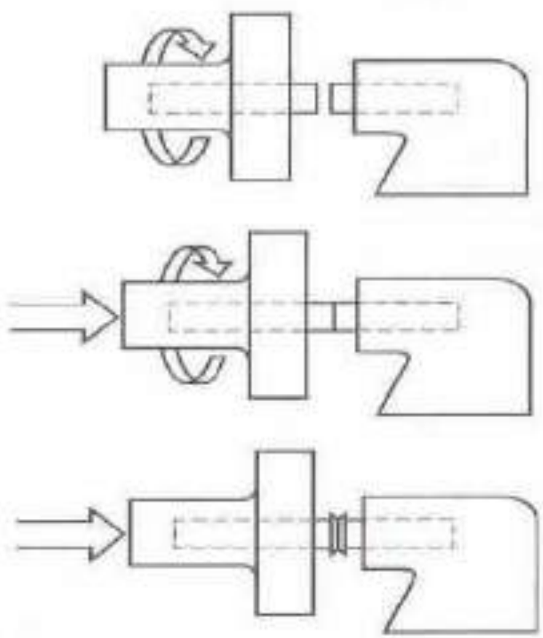


FIGURE 36-4 Schematic representation of the three steps in inertia welding.

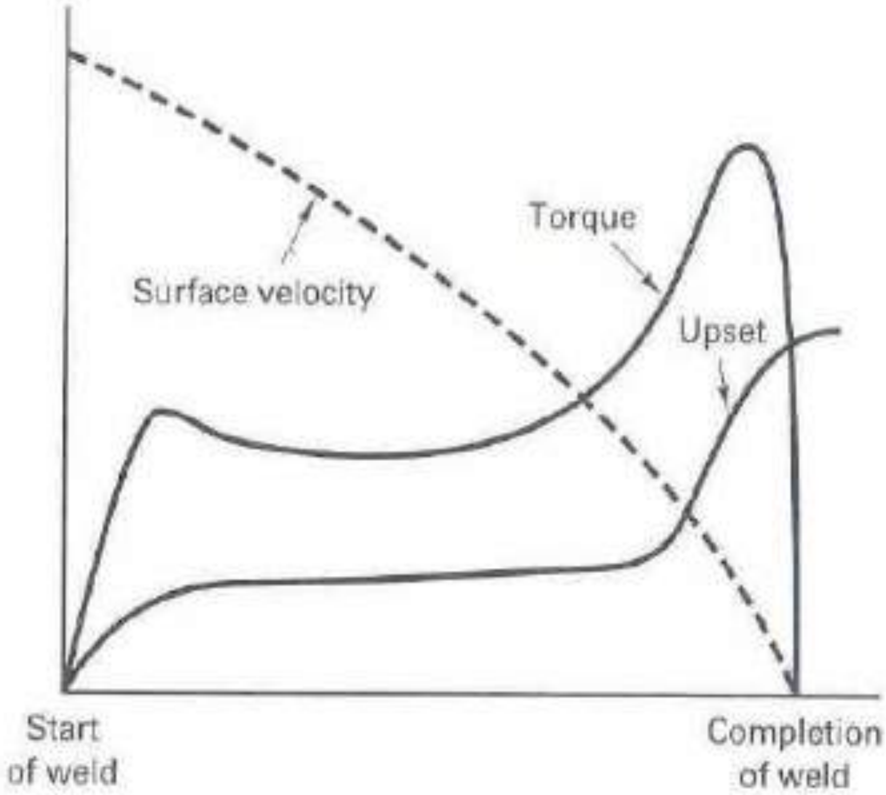


FIGURE 36-5 Relationship between surface velocity (speed), torque, and upset throughout the inertia welding process.

FIGURE 36-6 Some typical friction-welded parts. (*Left*) Impeller made by joining a chrome–moly steel shaft to a nickel–steel casting. (*Center*) Stud plate with two mild steel studs joined to a square plate. (*Right*) Tube component where a turned segment is joined to medium-carbon steel tubing. *(Courtesy of Newcor Bay City, Div. of Newcor, Inc.)*

3. OXYFUEL GAS WELDING (OFW):**old method → metals are heated with a flame produced from reaction of oxygen with acetylene**

+ use of a filler – metal to fill the gap (the same metal)

- to a state of fusion → no pressure is used
- Oxygen → from air → stored in steel cylinders at a pressure of 2000 psi (140 bar)
- acetylene gas (C_2H_2)- obtained from reaction between calcium carbide + water (or in bottles (cylinders) – 250 psi /17 bar)
- mixing & burning of acetylene + oxygen → torch (the flow controlled by valves)

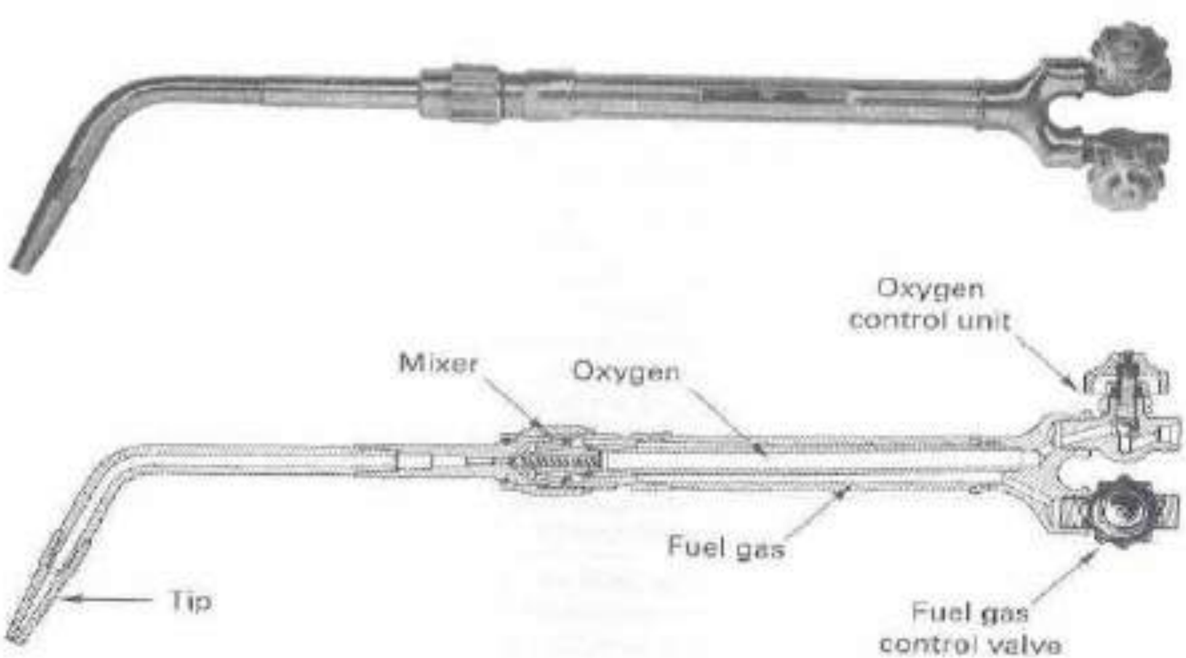


FIGURE 33-2 Typical oxyacetylene welding torch and cross-sectional schematic. *(Courtesy of Victor Equipment Company.)*

• **pure oxygen provides a flame with temperature much higher than using air (up to 3500^0 C)**

Combustion reactions:

Primary: 3500°C 1. $C_2H_2 + O_2 = 2CO + H_2$ -> very high temp. @ cone of flame

Secondary: 2. $2CO + O_2 = 2CO_2$ -> outside the cone

2'. $H_2 + 1/2\ O_2 = H_2O$ -> from atmosphere

- **Control of the flow rates of oxygen and acetylene – very important.**
  This affects the characteristic of the flame which depends on O_2/C_2H_2 ratio

- **Three types of flame can be obtained:**
  REDUCING, NEUTRAL & OXIDIZING

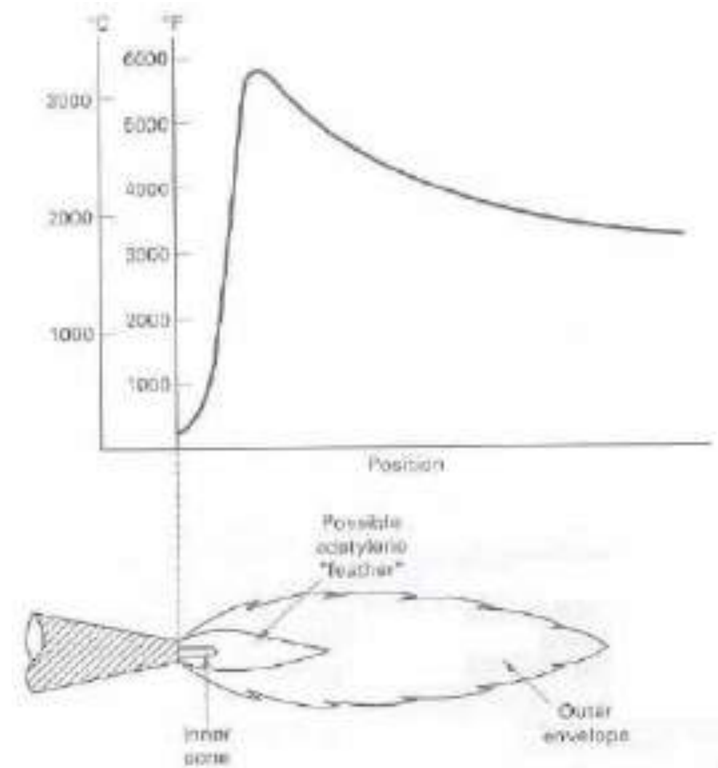


FIGURE 33-3 Typical oxyacetylene flame and the associated temperature distribution.

NEUTRAL flame → the widest application : the inner luminous cone has 1:1 ratio (stochiometric) of O_2 and C_2H_2

- **First part of reaction ($C_2H_2 + O_2 = 2CO + H_2$) occurs near the torch tip**

- **SAFETY – a real problem: eye protection from the radiation + explosion**
  Ex: C_2H_2 fitting has left hand valve and O_2 right hand thread, to avoid mistakes.

- **Utilisation: gas –flame welding largely replaced by arc or resistance welding except for repair work, field welding or some special applications (thin metal sheet welding, artistic welding)**

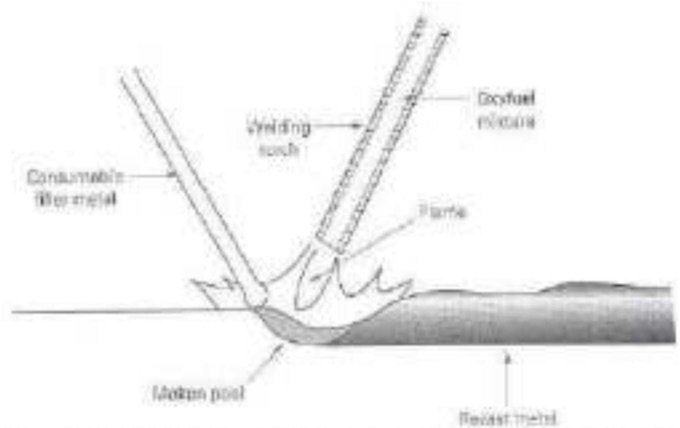


FIGURE 33-4 Schematic of oxyfuel gas welding with a consumable welding rod.

ADVANTAGES:

by gas welding even with thin materials, temperatures can be easily controlled

DISADVANTAGES:

exposure of heated metal to various gases from the atmosphere,
without shielding →contamination;

distortion of thin metal parts (non uniform heating)

more expensive→replaced by shielded metal arc welding & inert gas metal welding

TABLE 33-1 Engineering Materials and Their Compatibility with Oxyfuel Welding

Material	Oxyfuel Welding Recommendation
Cast iron	Recommended with cast iron filler rods; braze welding recommended if there are no corrosion objections
Carbon and low-alloy steels	Recommended for low-carbon and low-alloy steels, using rods of the same material; more difficult for higher carbon
Stainless steel	Common for thinner material; more difficult for thicker
Aluminum and magnesium	Common for aluminum thinner than 1 in.; difficult for magnesium alloys
Copper and copper alloys	Common for most alloys; more difficult for some types of bronzes
Nickel and nickel alloys	Common for nickel, Monels, and Inconels
Titanium	Not recommended
Lead and zinc	Recommended
Thermoplastics, thermosets, and elastomers	Hot-gas welding used for thermoplastics, not used with thermosets and elastomers
Ceramics and glass	Seldom used with ceramics, but common with glass
Dissimilar metals	Difficult; best if melting points are within 50°F; concern for galvanic corrosion
Metals to nonmetals	Not recommended
Dissimilar nonmetals	Difficult

4. Pressure – Gas Welding. (PGW) – To make butt joints between bars or ends heated with gas flame but below the melting point temperature, and then forced to join together under pressure

- **Can be considered as solid phase weld → this method requires special equipment**

5. Arc Welding – in general

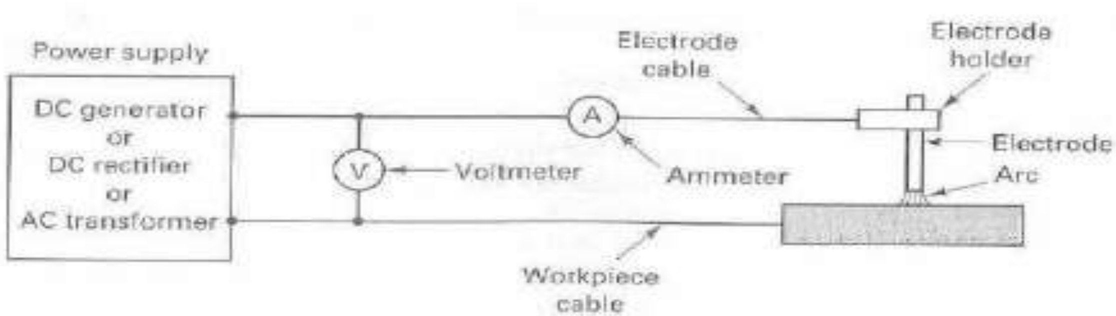
Process in which coalescence is obtained by heat produced from an electric arc created between the work piece and an electrode. – no pressure applied;

The electrode or filler metal is also heated to a liquid state and deposited into the joint to make the weld.

The two electrodes: 1. Workpiece and 2. Electrode → an electric circuit is created

- **By closing the electrodes, the arc is formed at low voltage (28V), high current (few hundreds of A)**
- **the electric energy is converted into an arc with intense heat release which creates high temperature, around 3900^0 C**
- **difficult to control the temperature → by on –off method only**
- **there is no possibility to control the temp. as in gas welding**
- **Traditionally, DC was used with heavy and expensive rectifiers**

FIGURE 34-1 Basic circuit for arc welding.



Two procedures:

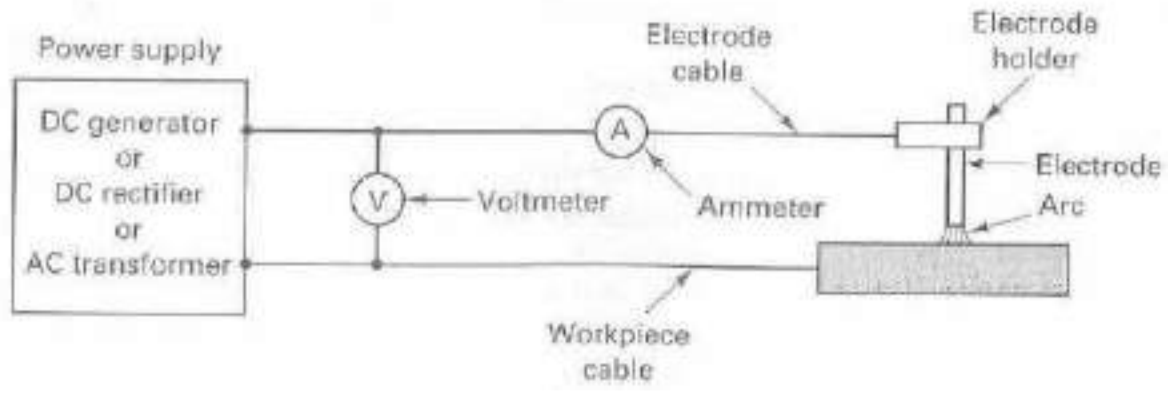
- **1. Straight polarity → electrode –**

  (e$^-$ pulled to job, Heavy ions to electrode, more heat at electrode → more melting and filling of electrode → but shallow weld penetration in job.

- **2. Reversed polarity → electrode +**

  The reverse happens, more heat at the job → more melting of job → heavier ions result in deeper weld penetration.

FIGURE 34-1 Basic circuit for arc welding.



- **Now: AC → more spread because of the simplicity of the equipment (no rectifiers but just an inexpensive transformer)**
- **the electrode used usually melts at temp. below the temp. of the arc**
  → electrodes consume in the welding process
  → this electrode is moved towards the workpiece when consumed.
- **also, not consumable electrode, made of tungsten are used.**
- **The method needs to feed the weld filler.**

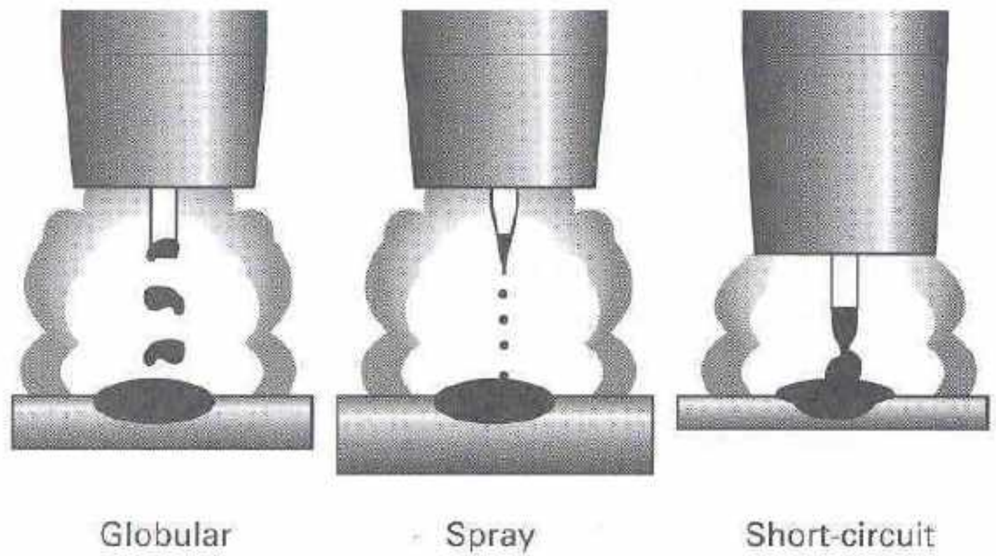


FIGURE 34-2 Three modes of metal transfer during arc welding. *(Courtesy of Republic Steel Corporation.)*

TYPES OF ELECTRODES

1. **Bare electrodes: limited use for iron and mild steel → low quality materials**

2. **Fluxed electrodes: with light coat of flux →eliminate undesirable oxides and prevent their formation**

3. **Heavy coated electrode:** very used presently for shielded metal arc welding (95%) →a gas shield is provided around the arc to eliminate the undesirable oxides and nitrides to be formed in weld metal. It also provides the weld metal with a protective slag coating, which prevents oxidation of the surface metal during cooling

*** the type of coating of the flux is considered in terms of the type of welding and the materials that must be welded: flux compounds Coating consists of slag forming compounds**

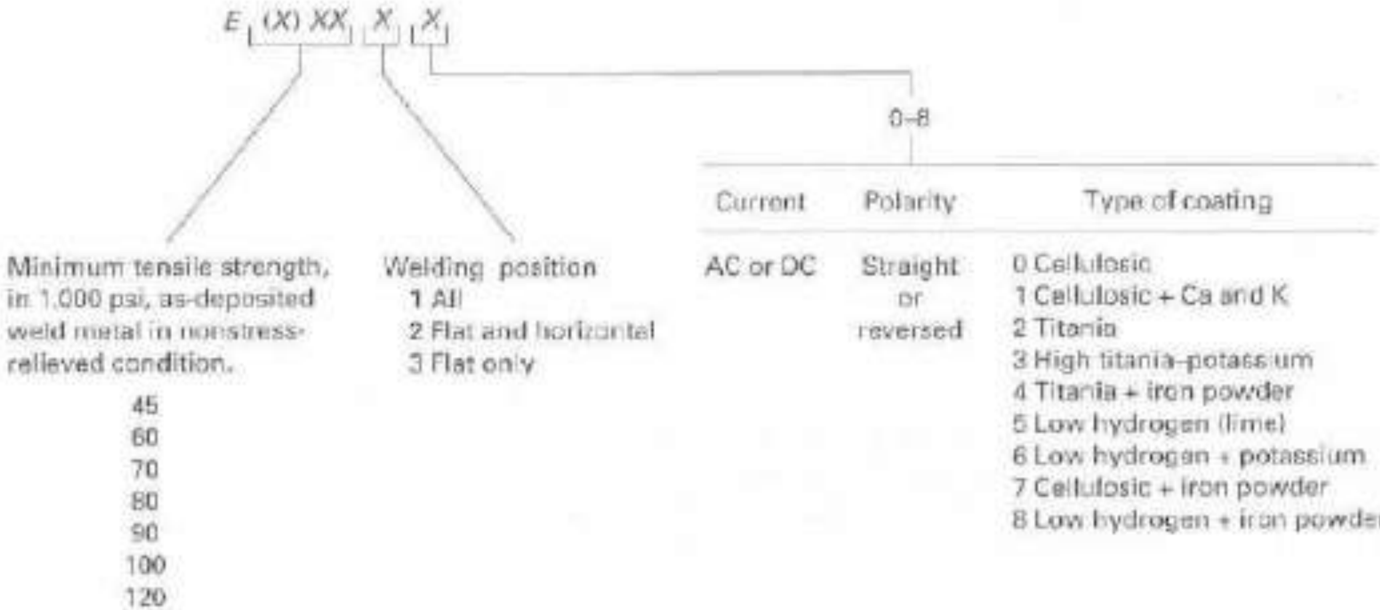


FIGURE 34-3 Designation system for arc-welding electrodes.

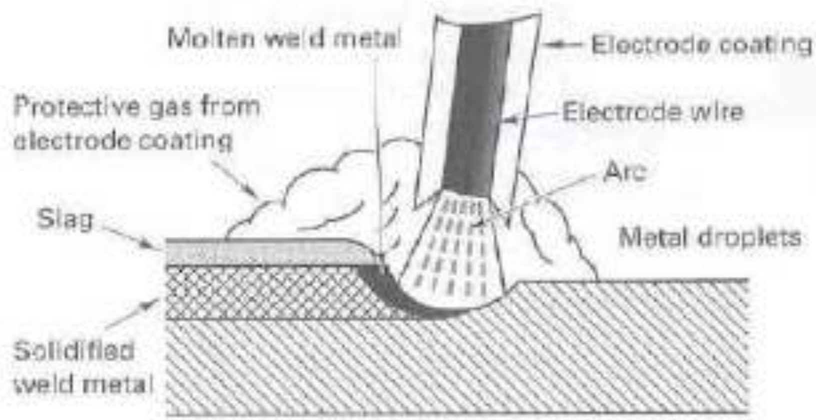


FIGURE 34-4 Schematic diagram of shielded metal arc welding (SMAW). *(Courtesy of American Iron and Steel Institute, Washington, D.C.)*

TYPES OF ARC WELDING PROCESS

5a. Shield Metal Arc Welding – (SMAW) – uses heavy –coated electrodes

5b. Gas Tungsten Arc Welding – (GTAW)

Special purpose such as stainless steel welding → to prevent oxidation

- **The inert gas substitutes for the shielded electrodes (Ar, He)**
- **Electrode – non consumable – by tungsten → NO SLAG**
- **Filler metal must be provided**

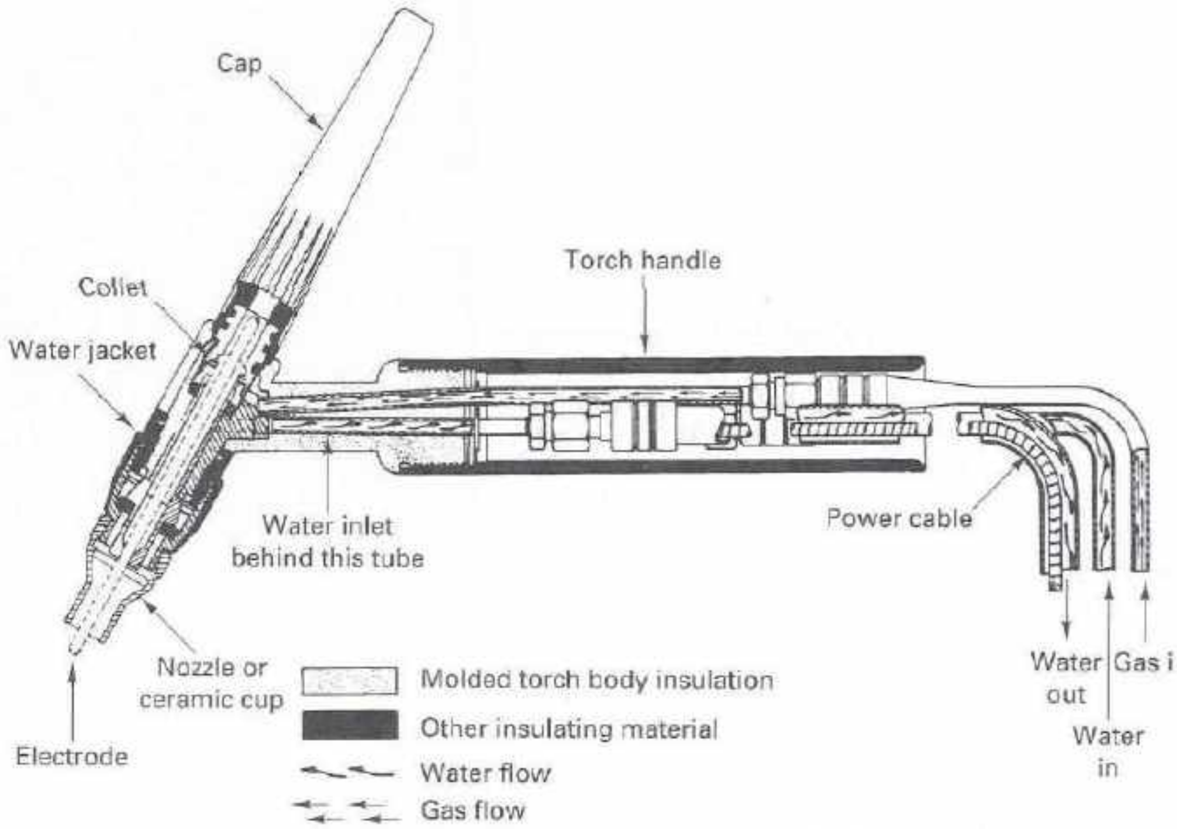


FIGURE 34-5 Welding torch used in nonconsumable-electrode, gas tungsten arc welding (GTAW), showing feed lines for power, cooling water, and inert gas flow. *(Courtesy of Linde Division, Union Carbide Corporation.)*

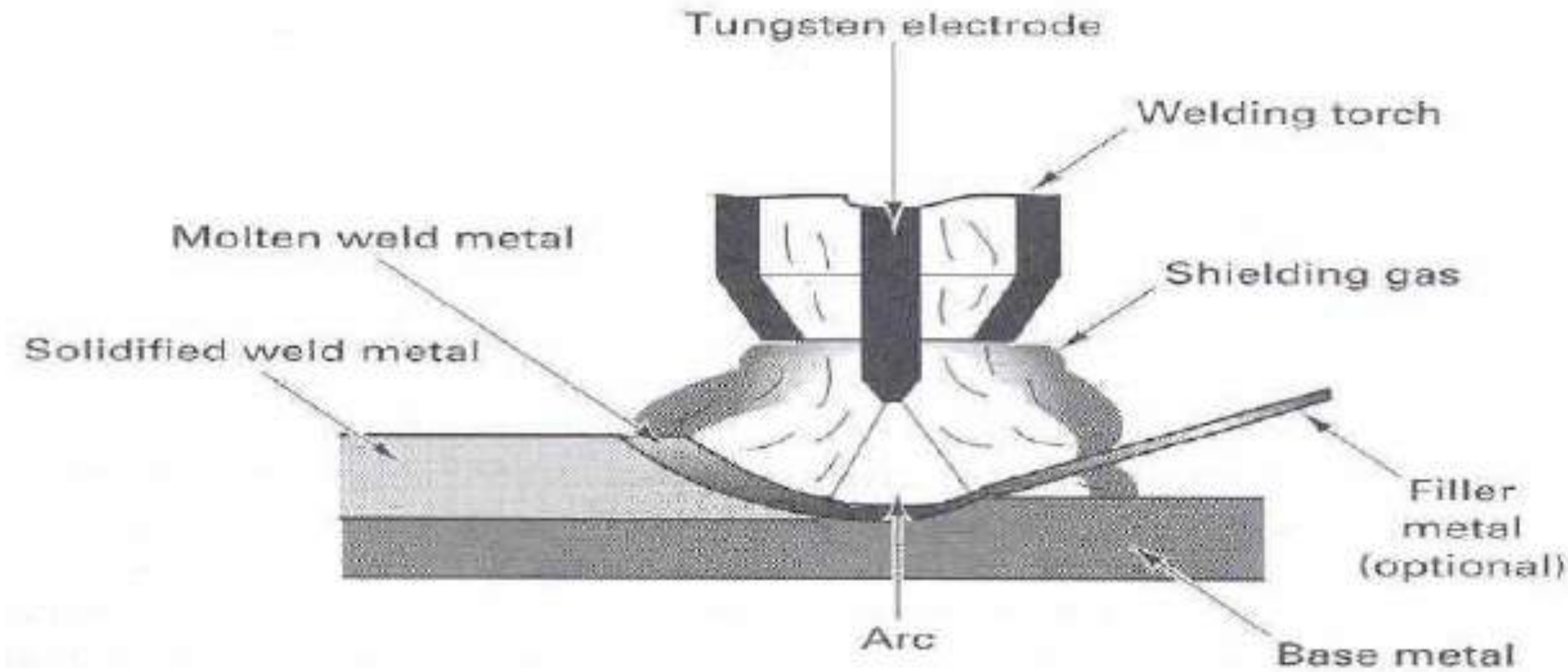


FIGURE 34-6 Schematic diagram of gas tungsten arc welding (GTAW). *(Courtesy of American Iron and Steel Institute, Washington, D.C.)*

5c. Gas Metal Arc Welding →

inert gas used for shielding against atmosphere (CO_2, N_2 - inexpressive)

- **consumable bare electrode are used**
- **for non – ferrous metals –(aluminium)**

→ NO SLAG

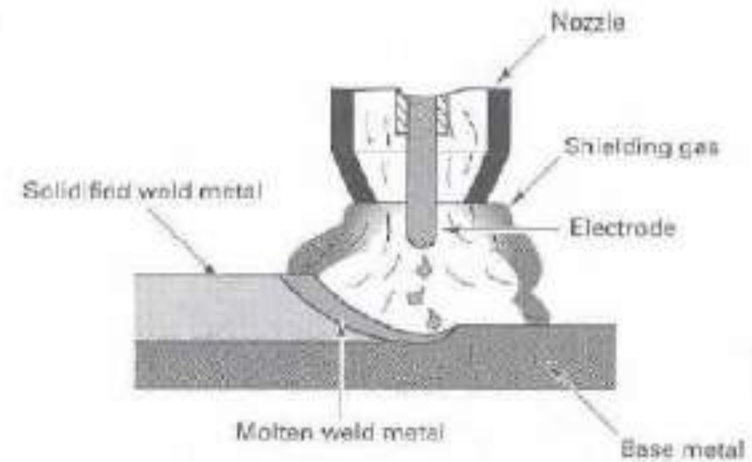


FIGURE 34-10 Schematic diagram of gas metal arc welding (GMAW). *(Courtesy of American Iron and Steel Institute, Washington, D.C.)*

5d. Flux Cored Arc Welding (FCAW)

- **Flux core – inside the electrode**
- **SLAG coats the hot weld**
- **gas produced from flux burning protects the weld**

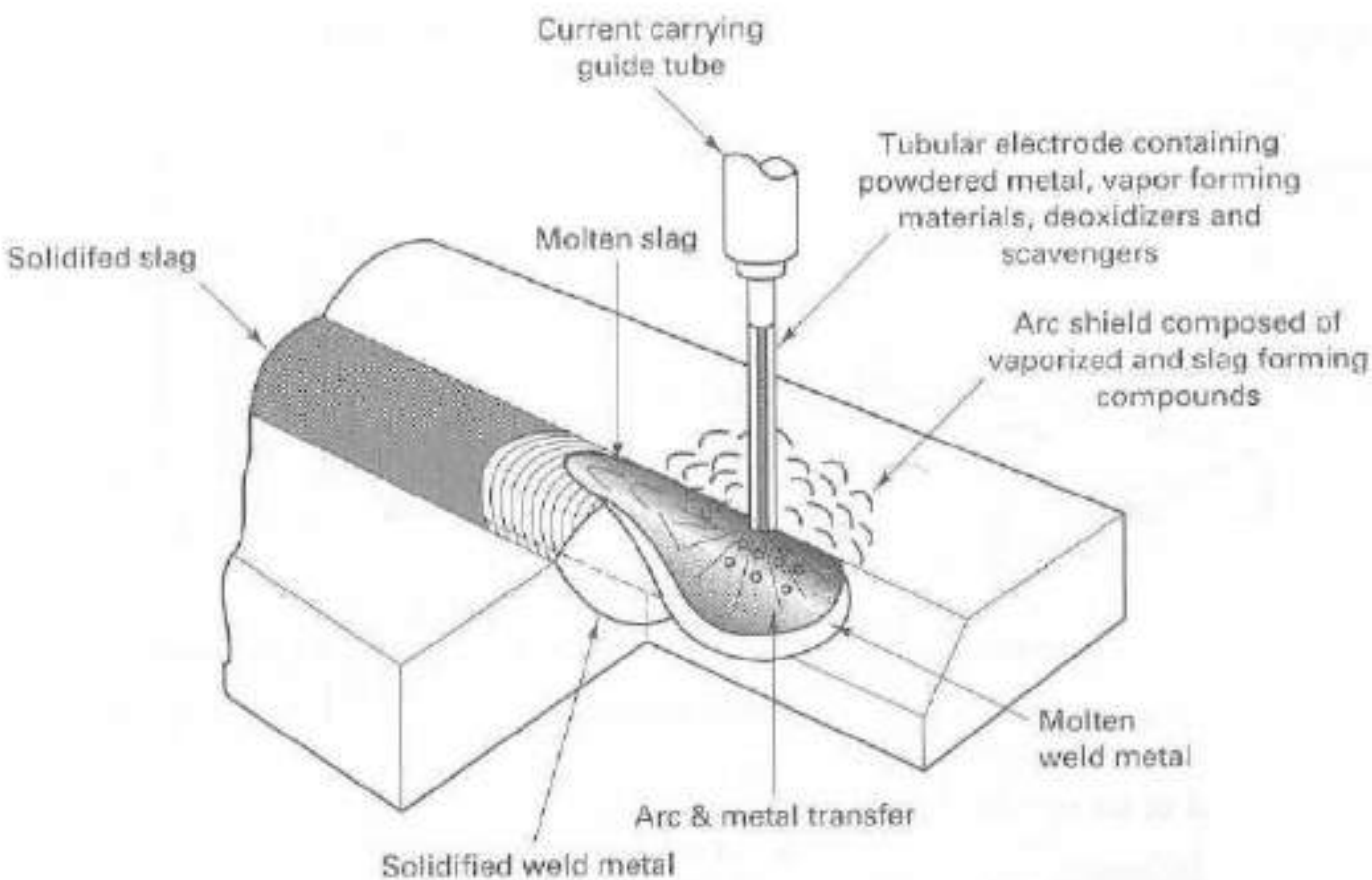


FIGURE 34-11 Schematic representation of the flux-cored arc welding process (FCAW). *(Courtesy of The American Welding Society, New York.)*

5e. Submerged – Arc welding (SAW)

- Suitable for automation →(automation process)

- Arc is shielded by a blanket of granular flux fed from a hopper during welding

- Bare electrode is fed into the granular flux which laid down along the seam to be welded

- Welding action takes place beneath the flux which laid down along the seam to be welded

- Welding action takes place beneath the flux cover

- Intense heat of the arc produces a pad of molten metal in the joint →the same time, a portion of the granular flux which will float on top of the molten metal will burn and produce slag → will protect the melted metal from the oxidation

- After cooling, the fused slag solidifies → is removed easily

- flux can be required

Ex: vessel welding →

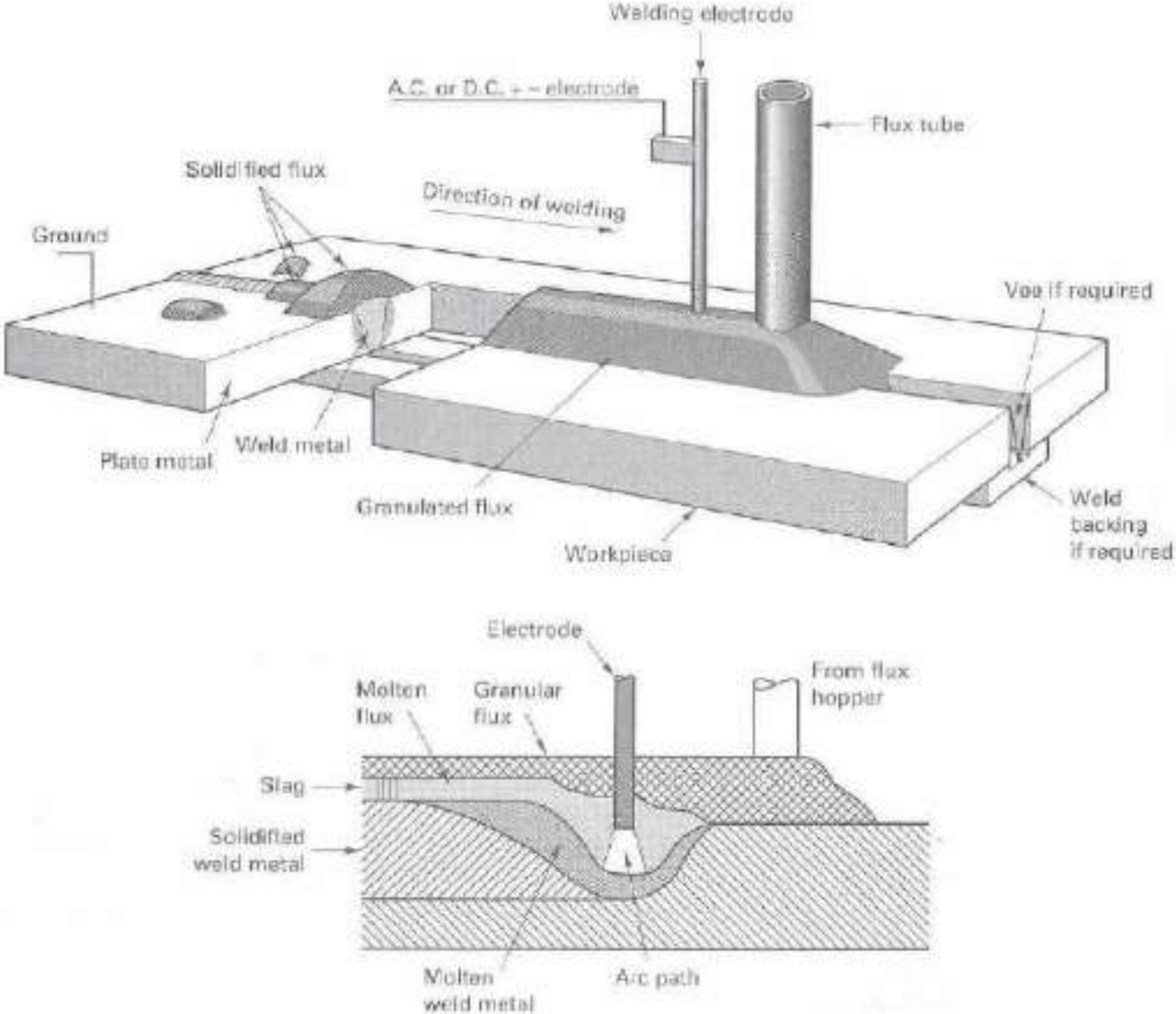


FIGURE 34-12 *(Top)* Basic features of the submerged arc welding process (SAW). *(Courtesy of Linde Division, Union Carbide Corporation.)* (Bottom) Cutaway schematic of submerged arc welding. *(Courtesy of American Iron and Steel Institute, Washington, D.C.)*

- Only flat surface or surfaces with large aperture can be welded
- high welding rate can be obtained with mechanised process
- good weld control obtained
- thick metal plates can be welded

5f. Stud Welding –(S.W) – arc welding process to end –weld metal studs to flat surfaces

- Special welding gun is used to hold the stud
- when the trigger is pressed, the stud is lifted to create an arc, and then, forced against molten pool by backing springs
- the operation – automatically controlled – no skill required
- frequency 60 operations/min

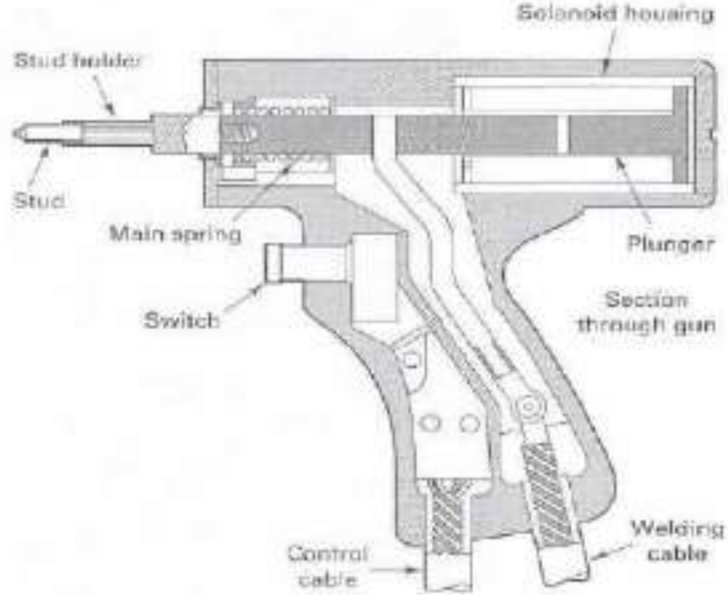


FIGURE 34-14 Schematic diagram of a stud welding gun. *(Courtesy of American Machinist.)*

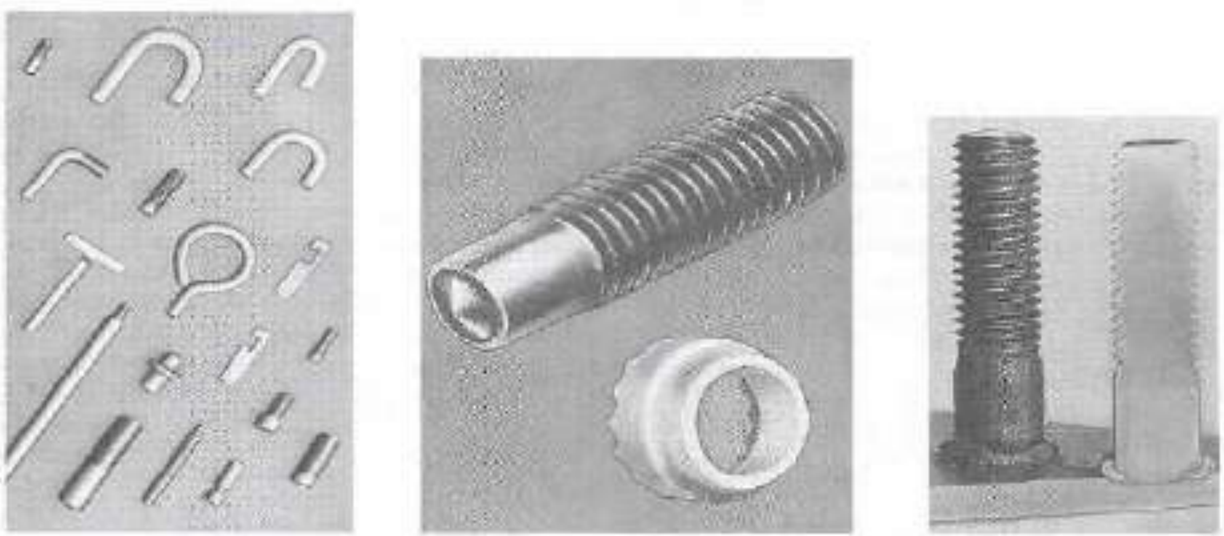


FIGURE 34-15 *(Left)* Types of studs used for stud welding. *(Center)* Stud and ceramic ferrule. *(Right)* Stud after welding and a section through a welded stud. *(Courtesy of Nelson Stud Welding Co.)*

6. Resistance Welding-

Phenomenon when high current is passed through a joint and heat is released

Joule's effect → E= I^2Rt

- **Heat and pressure are used to join parts: suitable for automation →robots perform this job.**
- **For plates and sheets => heavy current is passed through both parts causing local heating at the joint (the highest resistance)**
- **Welding is completed by application of pressure**
- **low voltages ~ 4-12 V at high flow (current) from transformers**
- **When the current passes through metal, most heat →at the joint point → greatest resistance (in the electrical path, which is at the interface of the sheets)**

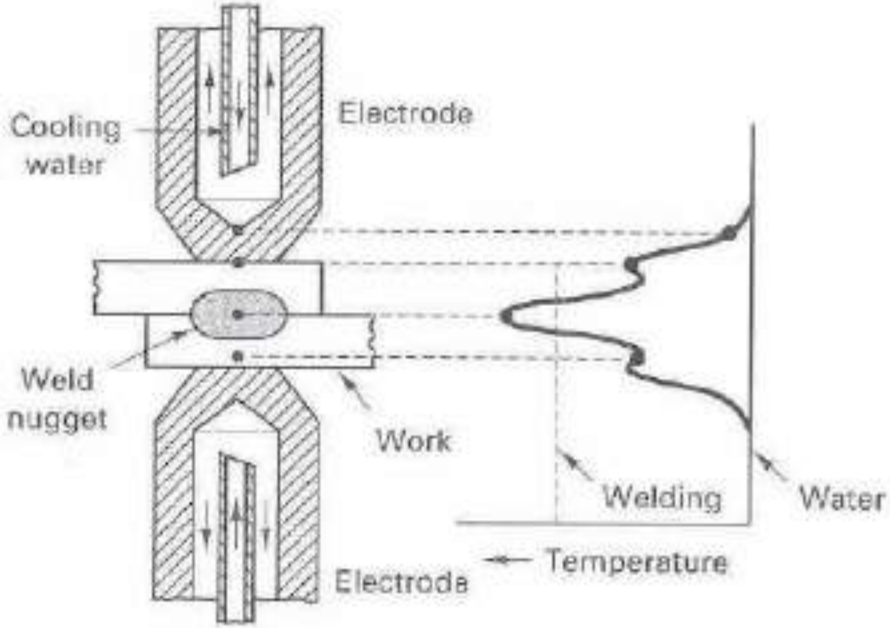


FIGURE 35-2 The des temperature distributio the electrodes and the workpieces in lap resist welding.

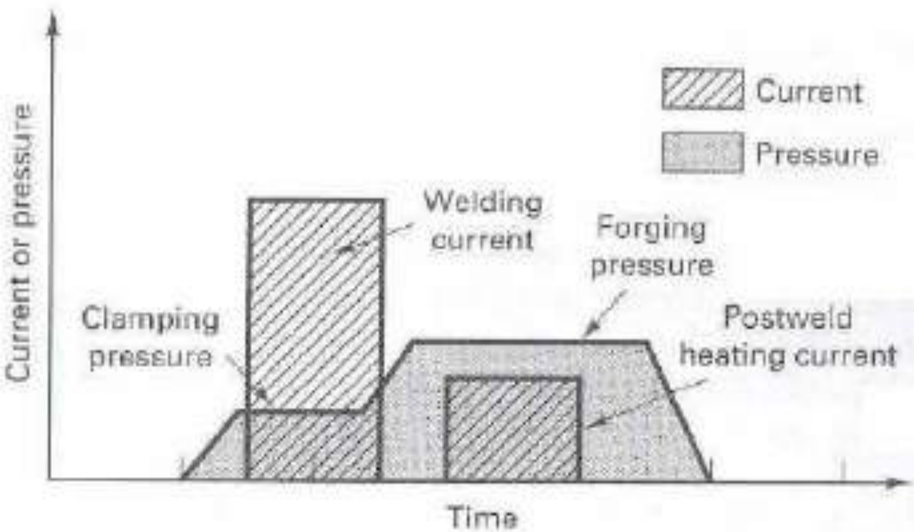


FIGURE 35-3 Typical current and pressure cycle for resistance welding. The cycle includes forging and postheating operations.

- Power flow 30-40 KVA/ in max. 10 sec. Time
- Pressure to complete the weld is 4000-8000 psi (28-55 MPa)
- Resistance of the workpiece is determined by the type of the metal and its thickness →it is usually small
- Electrodes – high conductivity → copper, do not melt, has cooling circuit
- Resistance between the surface depends on:
  - the finish of the surface
  - the contamination of surface
  - the pressure applied
  - the contact area of surface

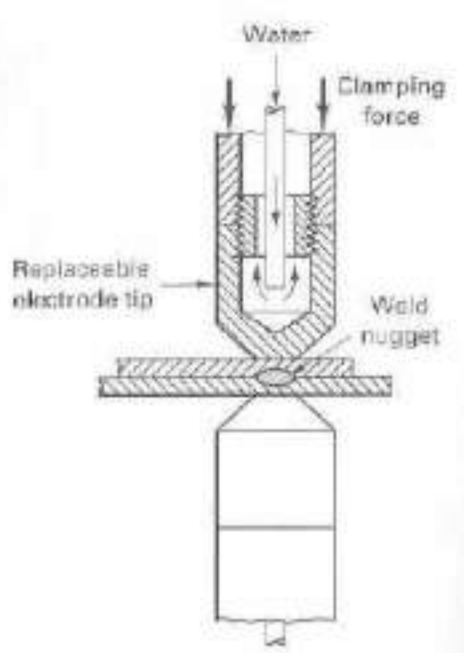


FIGURE 35-4 The arrangement of the electrodes and the work in spot welding, showing design for replaceable electrode tips.

6a. Resistance spot welding (RSW): **two or more sheets of metal are hold between metal electrodes.**

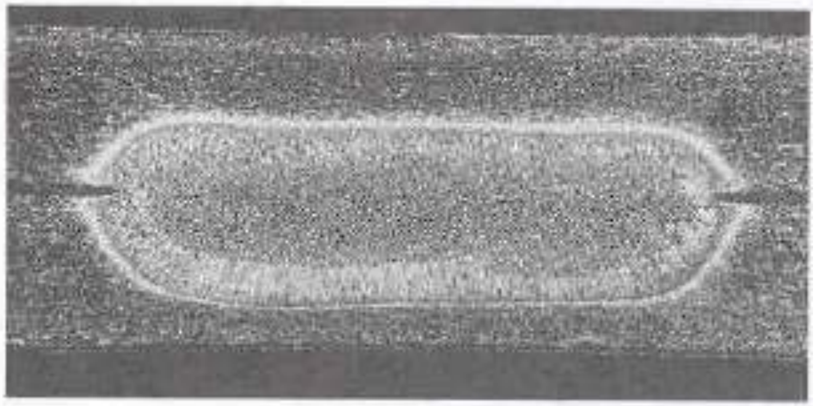


FIGURE 35-5 A spot-weld nugget between two sheets of 0.05-in. (1.3-mm) aluminum alloy. The nugget is not symmetrical because the radius of the upper electrode was greater than that of the lower electrode. *(Courtesy Locheed Aircraft Corporation.)*

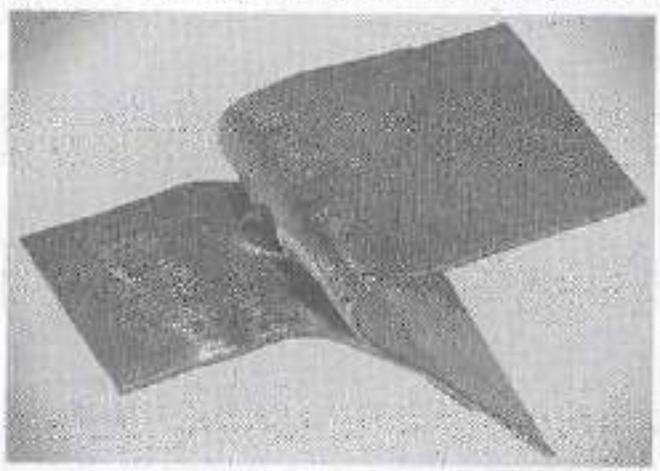


FIGURE 35-6 Tear test of a satisfactory spot weld, showing how failure occurs outside of the weld.

Welding cycle: **electrodes contact the metal (pressure is applied)**

⇒Known as squeeze time

- **Current is passed between electrodes →the temperature increases at the contact point → the metals melt → the electrodes squeeze the material → weld time**

- **Current is shut – down →pressure increased → hold time**

pressure is released →off time
weld nugget is formed

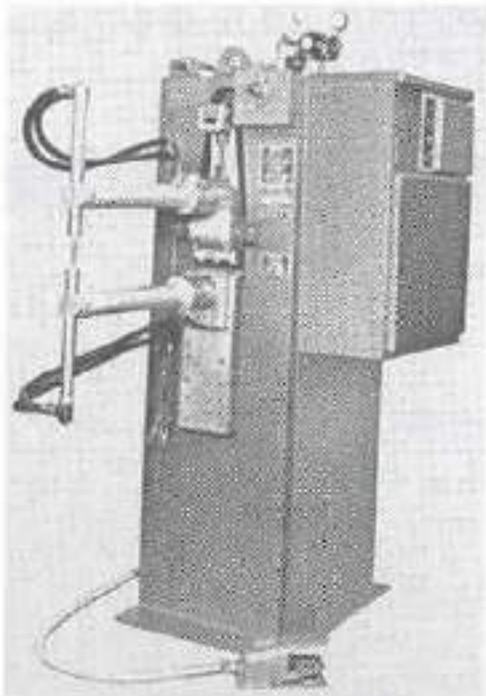


FIGURE 35-7 Foot-operated rocker-arm, spot-welding machine. *(Courtesy Sciaky Bros., Inc.)*

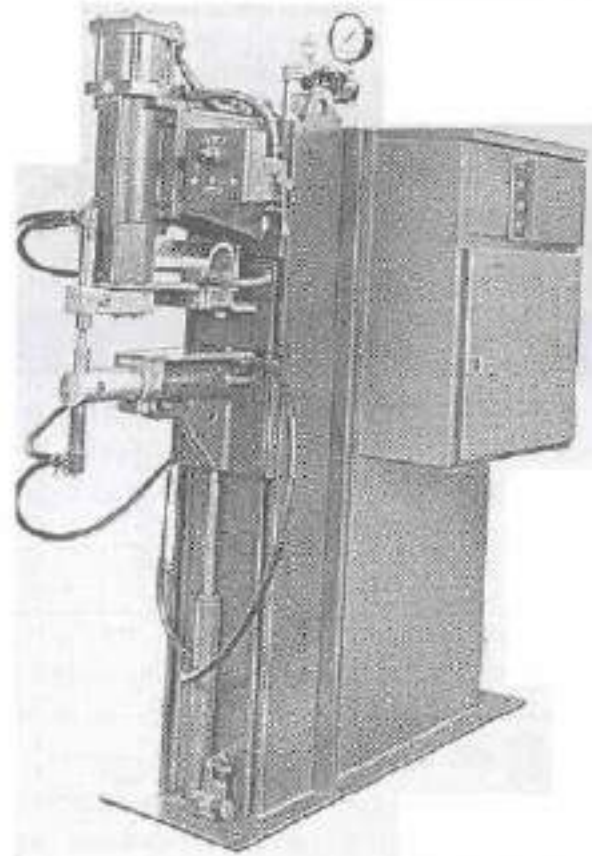


FIGURE 35-8 Single-phase, air-operated, press-type resistance welder with microprocessor control. *(Courtesy Sciaky Bros., Inc.)*

6b. Resistance Seam Welding (RSEW)

- Continuous weld on two overlapping pieces of sheet metal – can be leak proof (tanks, reservoirs)
- It is like frequency spot welding process, with the current applied periodically.
- Typical welding speed (~ 60 in/min)

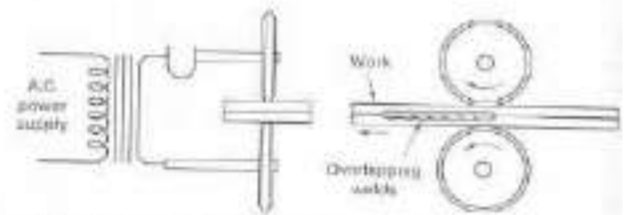


FIGURE 35-10 Schematic representation of seam welding.

Types of seam

- lap seam weld
- finish seam weld – only one side of the joint is visible

Water cooling of electrodes is needed

Seam welding used in manufacturing of metal containers, automobile parts, tanks, pipes.

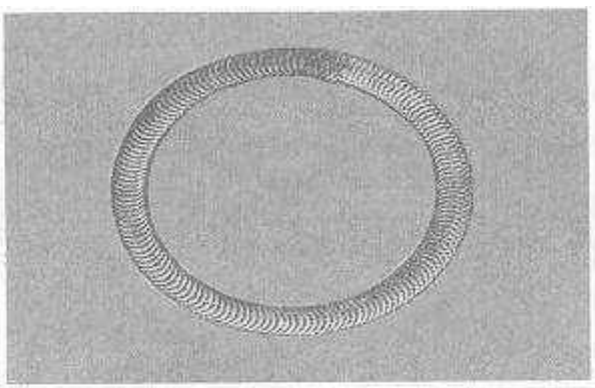
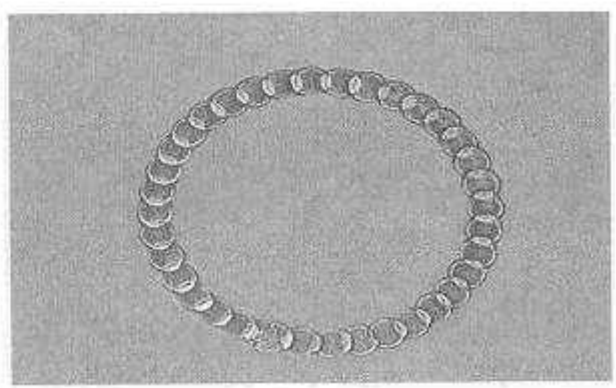



FIGURE 35-9 Seam welds made with overlapping spots of varied spacing.

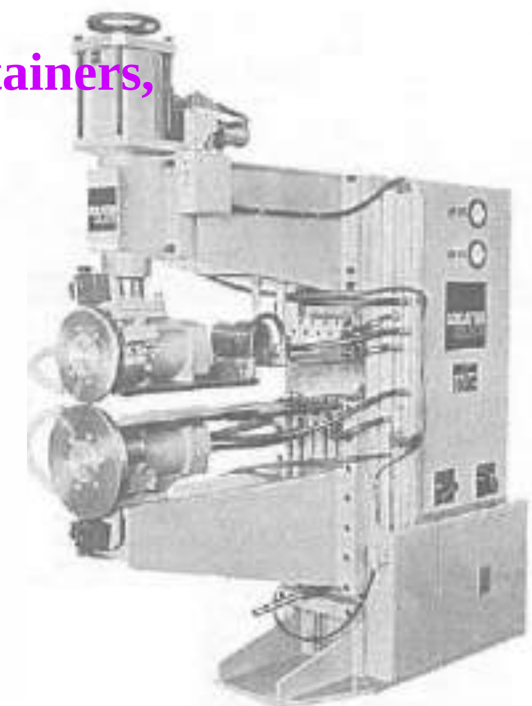


FIGURE 35-11 Typical commercial seam welder. (Courtesy H. A. Schlatter AG.)

6c. Butt welding → a sort of resistance welding → to weld two identical parts by pressure and heat generation just on the surface using high frequency current

6d. Pipe Welding → most of seam welding →
welding, in (shaping or forming)
Sides of the strips brought together and current is passed through
→ RESISTANCE BUTT WELDING

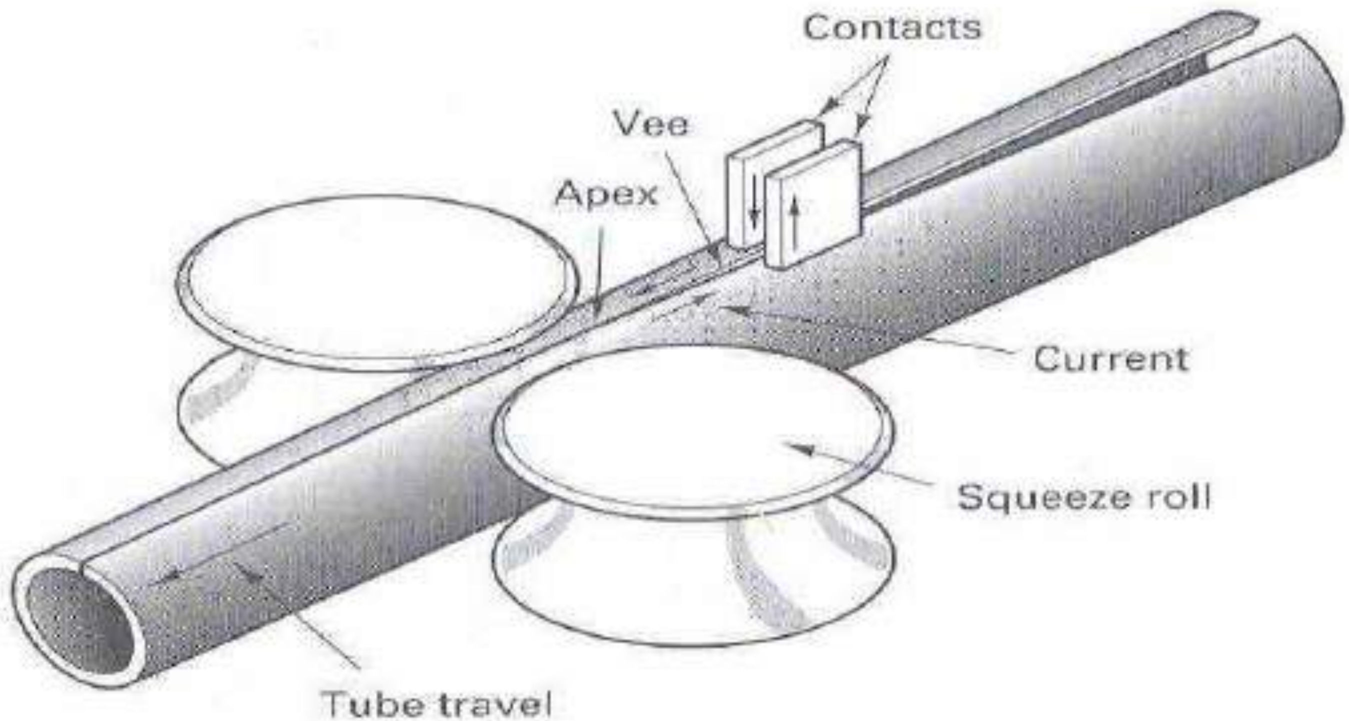


FIGURE 35-12 Using high-frequency ac current to produce a resistance seam weld in butt-welded tubing. Arrows from the contacts indicate the path of the high-frequency current.

Another method : high frequency induction heating of the surface before the material is squeezed together → **HIGH FREQUENCY WELDING OF PIPES**

MACHINES FOR RESISTANCE WELDING

- stationary single spot machine

- portable single spot machine

- multiple spot machine

- robots

PORTABLE SPOT WELDING MACHINES

- Different metals can be spot – welded together
- sheets can be welded to rolled shapes and castings
- practically →size limitation of 1/8 inch (~ 3 mm) for a sheet to be spot welded

6e Resistance Projection Welding (RPW) →similar to spot welding

- One of metal sheets to be welded, has to be put through a punch press which makes small projection or buttons in the metal sheet
- Projection welds are produced at localised points in work pieces help under pressure between suitable electrodes.
- Welds are made simultaneously

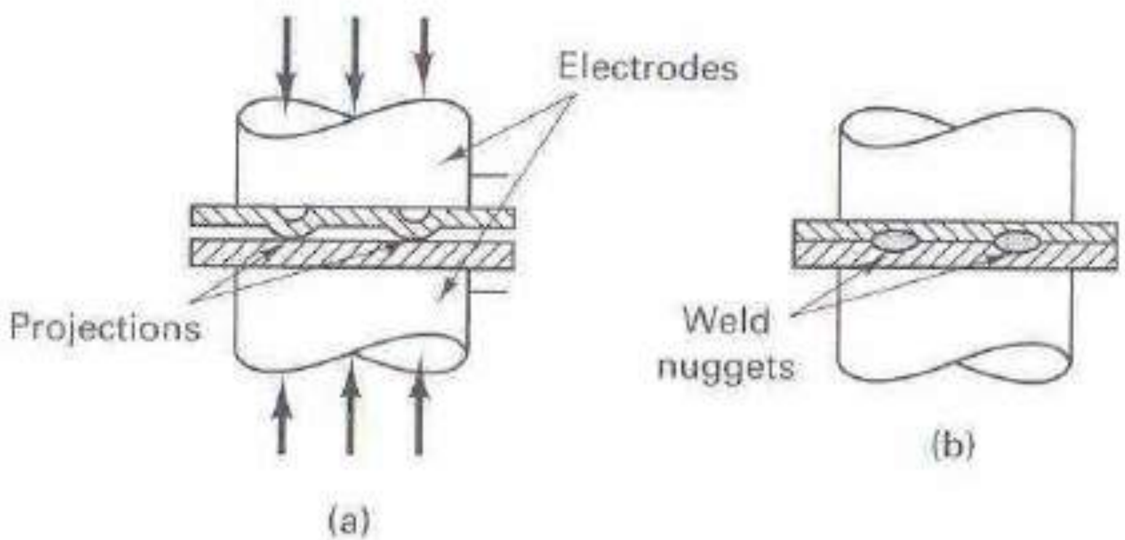


FIGURE 35-13 Principle of projection welding: prior to application of current and pressure (a) and after formation of the welds (b).

COMPARISON: Oxy-fuel, Arc, Resistance

Gas welding:

- **Functionally competitive to arc welding – but not as convenient from the equipment point of view (requires gases in bottles and expensive)**

Arc Welding:

- **Requires high skill operator**
- **Convenient supply of electric power**
- **New techniques of shielding, metal welding and submerged welding**

Resistance Welding:

- **High production process,**
- **Easy to automate**
- **Dependent on the skills of the operator**

QUALITY CONTROL OF WELDS

Cracks occurring in welds

hot cracks → in weld and fusion zone

cold cracks → in the heat affected zone

Due to the heating, the grain size of the weld is changing and so is the hardness → where hardness is the smallest, cracks can occur

WELD INSPECTION:

Visual

FPI

MPI

(cracks or internal defects → distorted magnetic fields. Current is passed through the weld seam →magnetic particles will gather at the crack)

X-ray (for safety reasons)

(not ultrasonic, which needs a flat datum)

NEW WELDING PROCESS

1. Electron Beam welding (EBW)

New technology for “clean welds”

- principles: high velocity e^- are emitted & directed towards the metal from, a tungsten that is heated to 2200^0 C → e^- pass through a magnetic field → centered by the anode and deflecting coils.
- The e^- beam is produced in vacuum. high purity of the weld. (also, fusion temperature is lower for the metal/ for all materials)
- High penetration of e-beam.
- Depth to width ratio of weld is 25:1 and the beam is 0.8 –3.2 mm DIA. (could be made much smaller).
- Low heat input, low distortion, narrow heat affected zone → high purity of weld is assured.

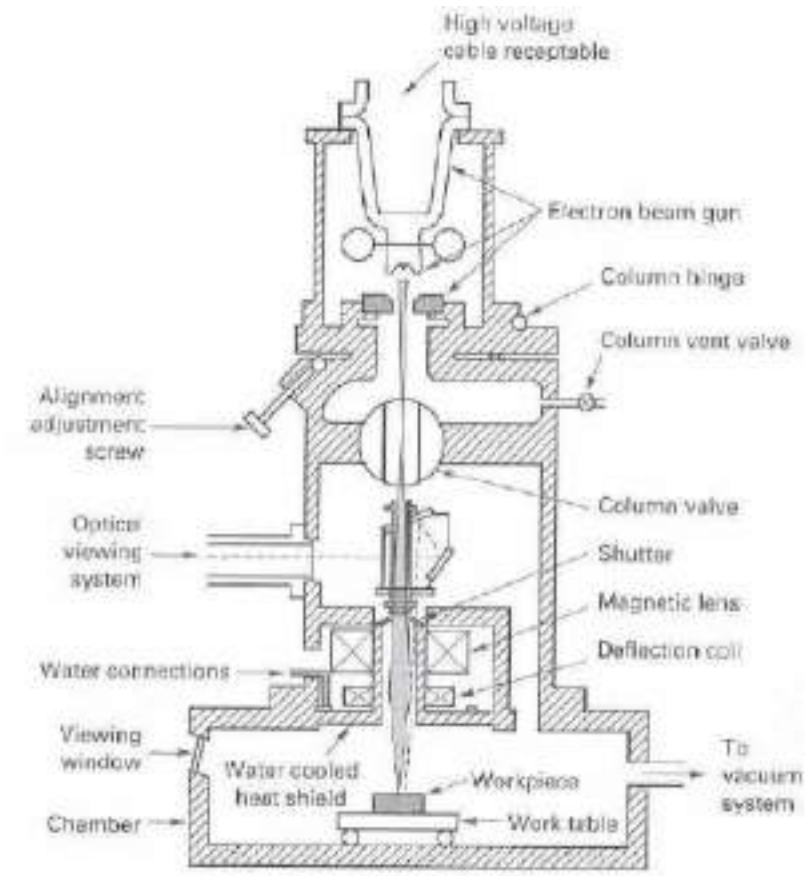


FIGURE 36-10 Schematic diagram of the electron beam welding process. (Courtesy of American Machinist.)

2. Laser Beam Welding (LBW)

- Focused laser beam is used for metal vaporisation
- Vaporised metal heats the surrounded metal
- Depth to width ratio > 4:1
- Laser beam welding has some advantages over e beam
    - vacuum is not required
    - can weld inside the transparent containers (eye surgery)

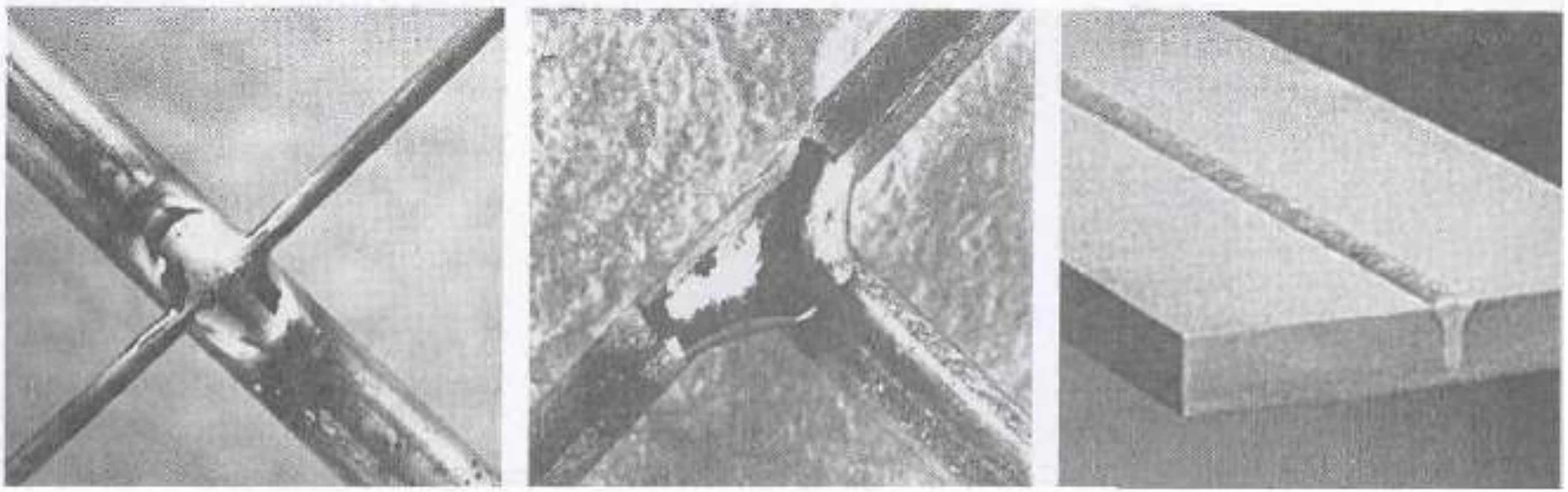


FIGURE 36-12 (*Left*) Small electronic welds made by laser welding. *(Courtesy of Linde Division, Union Carbide Corporation.)*, (*Right*) Laser butt weld of 0.125-in. (3-mm) stainless steel, made at 60 in./min (1.5 m/min) with a 1250-W laser. *(Courtesy of Coherent, Inc.)*

3. Ultrasonic Welding (USW)

- Coalescence is obtained by high shear vibration + pressure localised on the welded pieces
- Used in electronic industry for special precision welding without temperature impact
- Frequency → 10 – 200kHz mechanical vibrations
- Welding depends on right combination of time, pressure and energy output

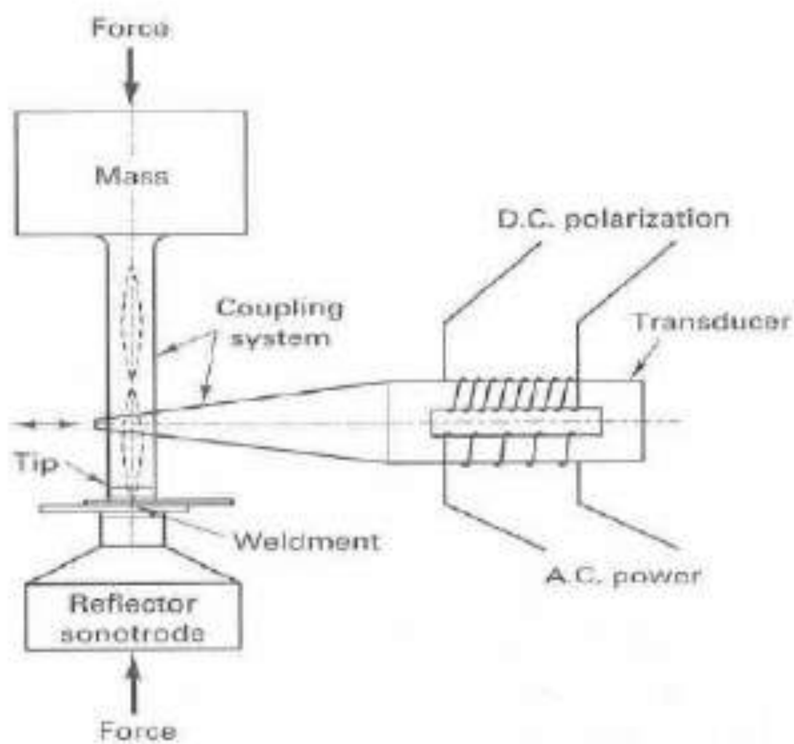


FIGURE 36-7 Schematic diagram of the equipment used in ultrasonic welding.

METALLIZING – metal spraying

- By gas flame, electric arc, plasma
- plasma spray process → highest temperatures (up to 16000^0 C)
- can spray materials with melting point temperature up to 3300^0 C
- For ceramics: conductive or protective surface coating → to protect against built – up surfaces

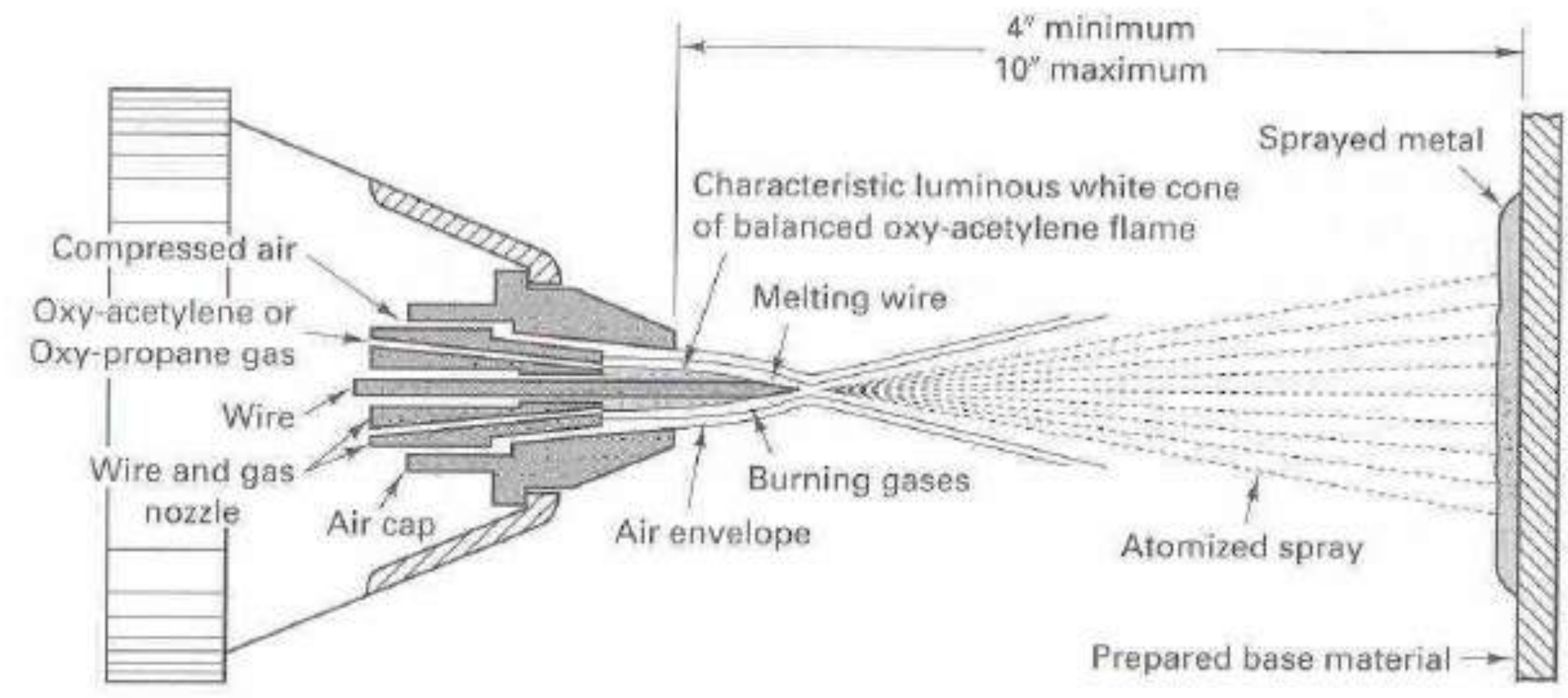


FIGURE 36-17 Schematic diagram of an oxyacetylene metal-spraying gun. (*Courtesy of METCO, Inc.*)

WELDING OF PLASTICS

- Thermoplastic materials only → torch flame temp ~ 300^0 C
- vibration or friction welding (low frequency – 100-240 Hz)

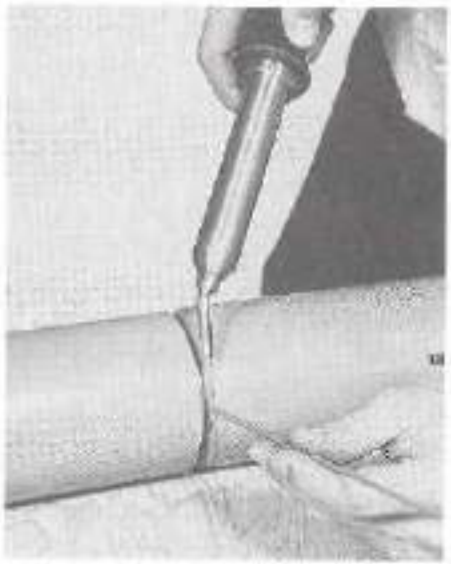


FIGURE 36-16 Using a hot-gas torch to make a weld in plastic pipe.

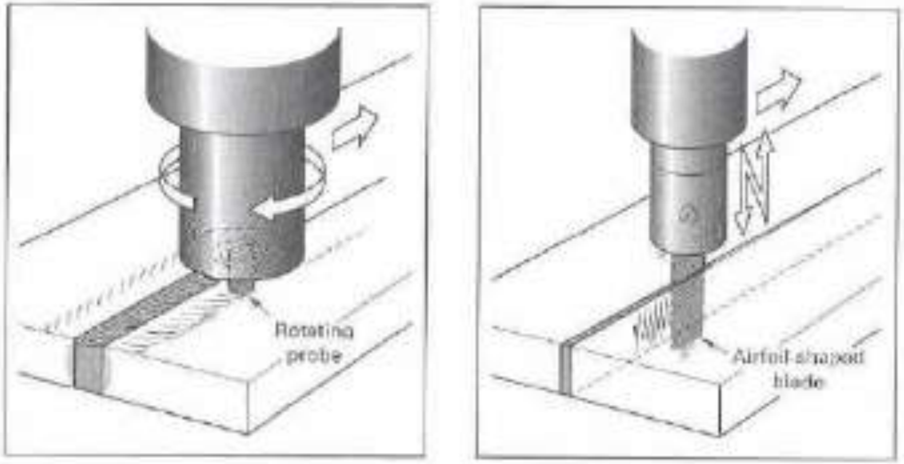


FIGURE 36-15 Friction stir welding using rotary and reciprocal motions to produce welds in plastics. The shoulder on the rotating probe provides additional friction heating to the top surface and prevents expulsion of the softened material from the joint. (Courtesy of ASM International.)

GAS & ELECTRIC ARC CUTTING

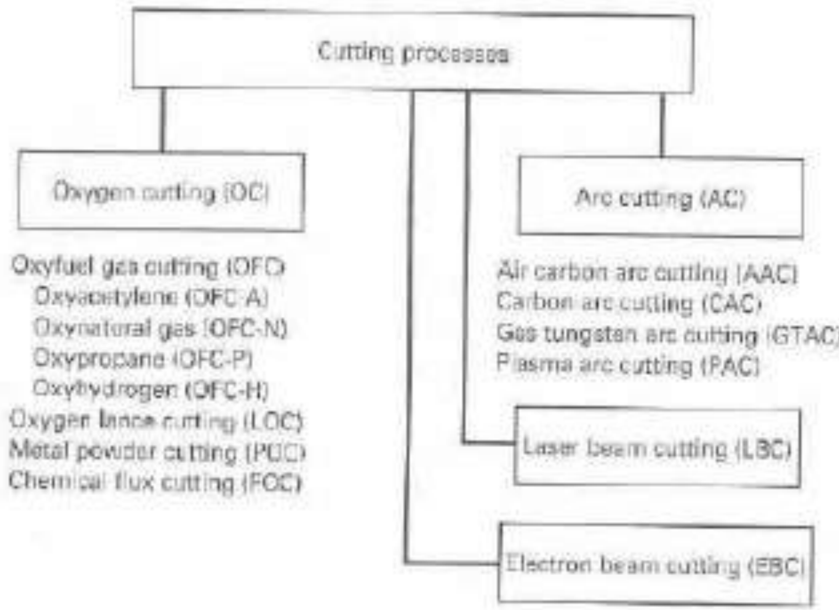


FIGURE 33-5 Classification of common cutting processes with their AWS (American Welding Society) designations.

Oxyacetylene torch cutting: important production processes

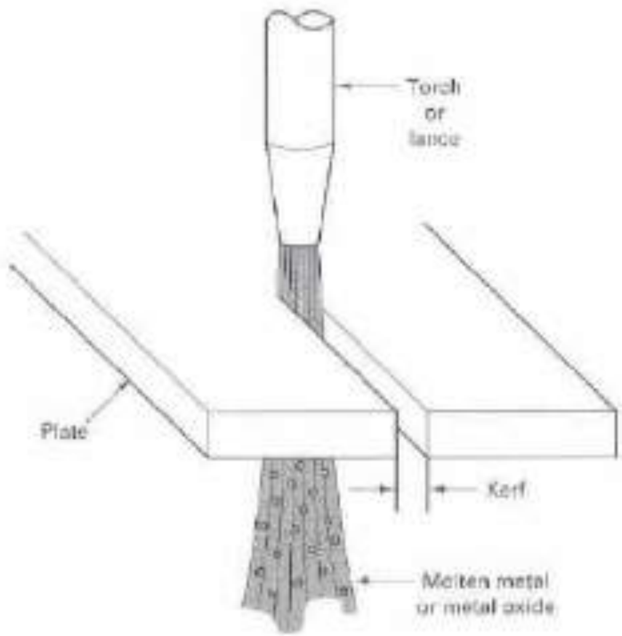


FIGURE 33-6 Flame cutting of a metal plate.

Torch made for cutting is different: It has several small holes surrounding a central hole through which pure oxygen passes → no premixing

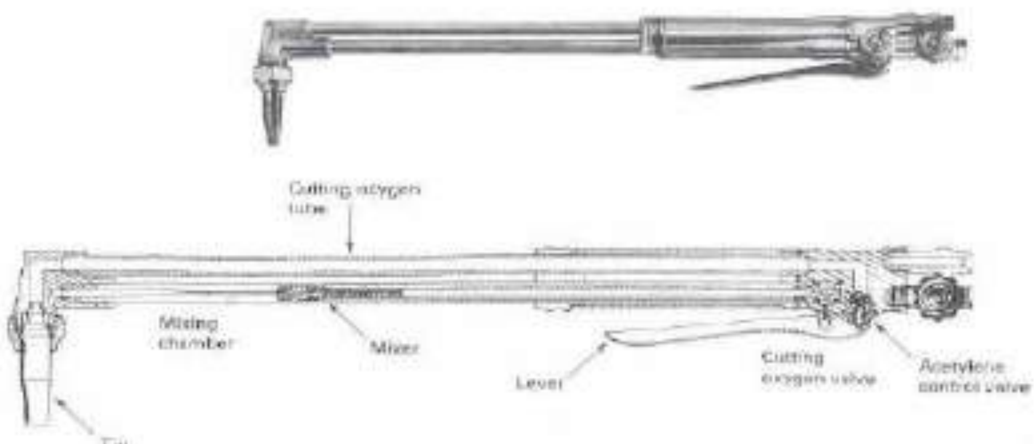


FIGURE 33-7 Typical oxyacetylene cutting torch and cross-sectional schematic (Courtesy of Victor Equipment Company.)

Principle of cutting → oxygen has affinity for ferrous materials (and for Al)

- If steel is heated to the red temperature and a jet of pure O is blown on the surface, the steel is burned instantaneously → iron oxide
  $3Fe + 2O_2 = Fe_3O_4 + heat$
  Metal plates up to 30 in thick can be cut by this method

UNDERWATER CUTTING: Torches are provided with connections for three gases:

- Preheating gas (H_2)
- Oxygen
- Compressed air: Air bubbles around the tip of the torch to stabilise the flame and to displace the water from the tip area

- H2 – for preheating (C_2H_2 – not safe to operate under high pressure created by the water → it can explode)
- Cutting machine → with automatic control of the torch movement
- Usually → a copying system, numerically controlled torch cutting designed with control of speed, preheating, torch light, path, etc.
- Non ferrous metals, cost iron and high manganese alloys are difficult to cut with this method (except Al)

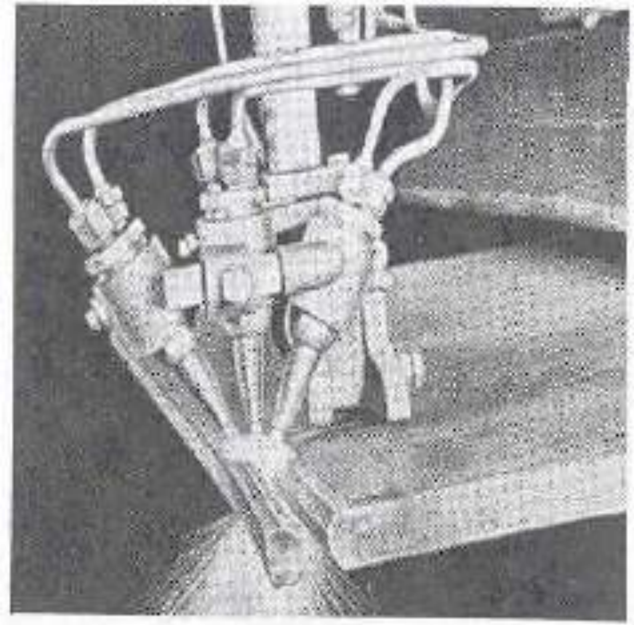


FIGURE 33-9 Plate edge being prepared for welding. The beveled shape is produced by three simultaneous oxyacetylene cuts. *(Courtesy of Linde Division, Union Carbide Corporation.)*

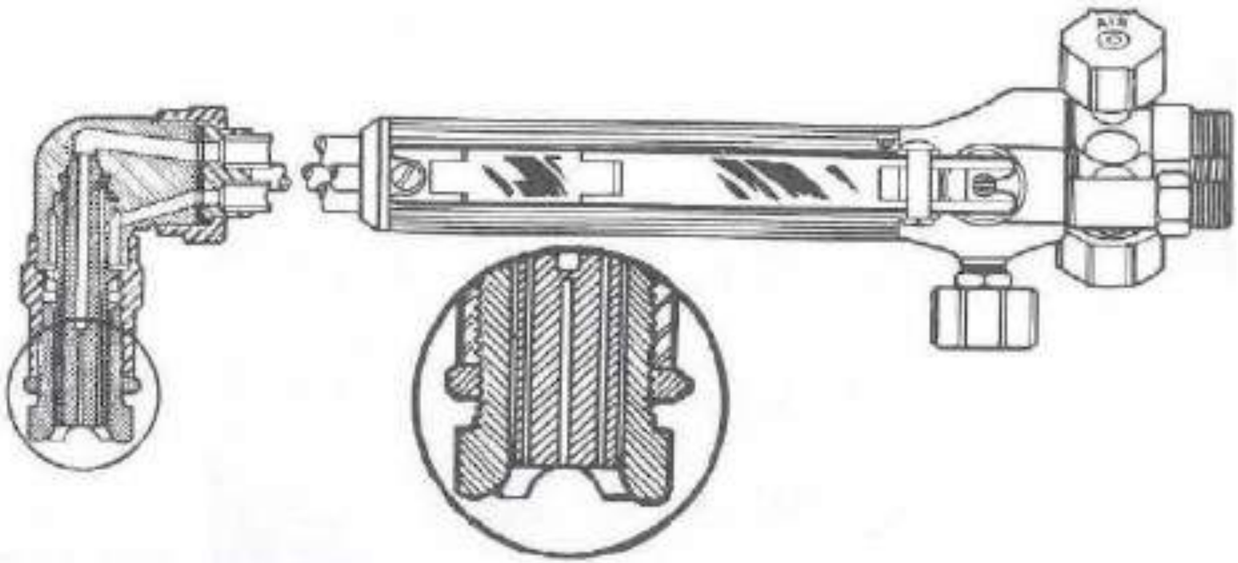


FIGURE 33-10 Underwater cutting torch. Note the extra set of gas openings in the nozzle to permit the flow of compressed air and the extra control valve. *(Courtesy of Bastian-Blessing Company.)*

ARC CUTTING PROCESS

- Melting metal to produce a kerf
- Carbon Arc Cutting (CAC)
- Carbon electrode produces arc
- Air is blowing the metal out from the cut – not oxidising (good for cast iron, which is difficult to cut with oxygen flame)

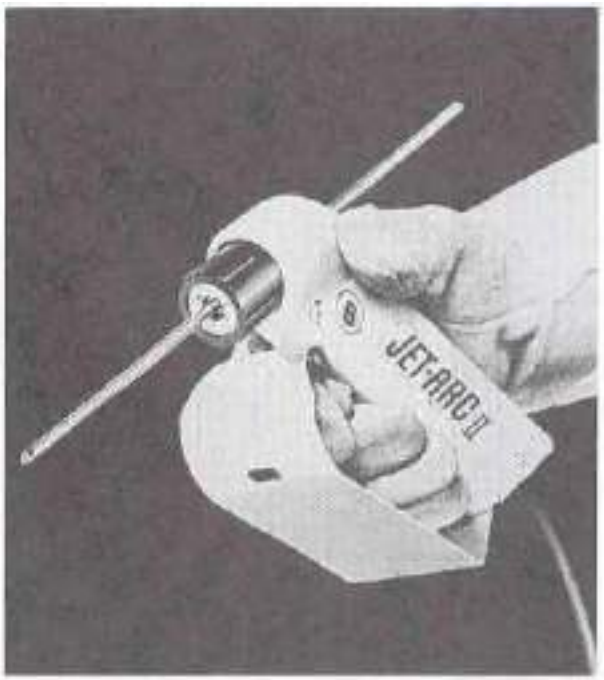


FIGURE 34-18 Gun used in the arc-air cutting process. Note the air holes surrounding the electrode in the holder. *(Courtesy of Jackson Products.)*

PLASMA ARC CUTTING

- Very high temperature – used for Stainless steel and non ferrous materials (carbon electrode cathode)
- inert gas flowing through the arc is forming plasm
- Two types of torch;
  non-transferred arc: ~ 16,000^0 C
  transferred arc (~ 30000^0 C) for non metals
- cutting speeds:
  2.5 m/min (steel)
  7.5 m/min Al – in thick plates

FIGURE 34-20 Cutting sheet metal with a plasma torch. *(Courtesy of GTE Sylvania.)*

LASER BEAM CUTTING (CO_2 lasers)

- Uses the heat of laser cutting to melt and evaporate metal
- any known material can be cut, T>11000^0 C, very accurate, poor surface finishing.

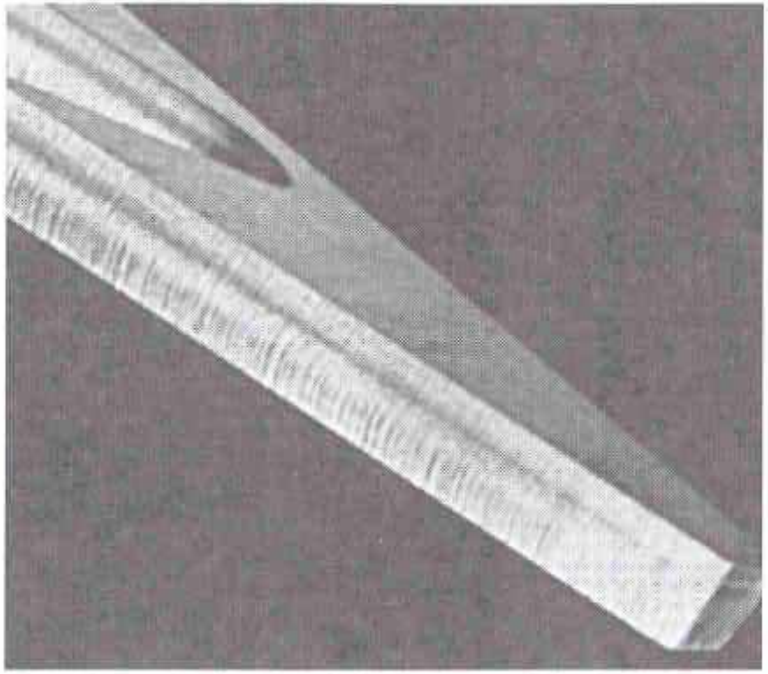


FIGURE 36-13 Surface of $\frac{1}{4}$-in. (6-mm)-thick carbon steel cut with a 1250-W laser at 70 in./min (1.8 m/min). *(Courtesy of Coherent, Inc.)*

Manufacturing Processes: Theory Of Metal Cutting & Machine Tool

Dr. Dwi Rahdiyanta

Jurusan Pendidikan Teknik Mesin

FT-UNY

Introduction to Manufacturing Processes

- **Definition of Manufacturing**
- The word manufacturing is derived from Latin:

  manus = hand,   factus = made

- Manufacturing is the economic term for making goods and services available to satisfy human wants.
- ***Manufacturing implies creating value to a raw material by applying useful mental and physical labour.***
- Whether from nature or industry materials cannot be used in their raw forms for any useful purpose.
- The materials are then shaped and formed into different useful components through different manufacturing processes to fulfil the needs of day-to-day work.
- ***Manufacturing converts the raw materials to finished products to be used for some purpose.***

Manufacturing Processes

- Manufacturing processes is a very fundamental subject since it is of interest not only to mechanical engineers but also to engineers from other discipline of engineering.
- There are various manufacturing processes by which a product can be made.
- Each process however has its own limitation and restriction and due to this reason a particular process is adopted to certain specific applications.
- Thus while a product can be manufactured by two or more processes, the real problem is to select the most economical out of them.
- A detailed understanding of various manufacturing processes is thus very essential for every engineer. This helps in designing the proper product required for him.
- He would be able to assess the feasibility of manufacturing from his designs.
- He may find that there are more than one process is available for manufacturing a particular product and he can make a proper choice of the process which would require lowest manufacturing cost.

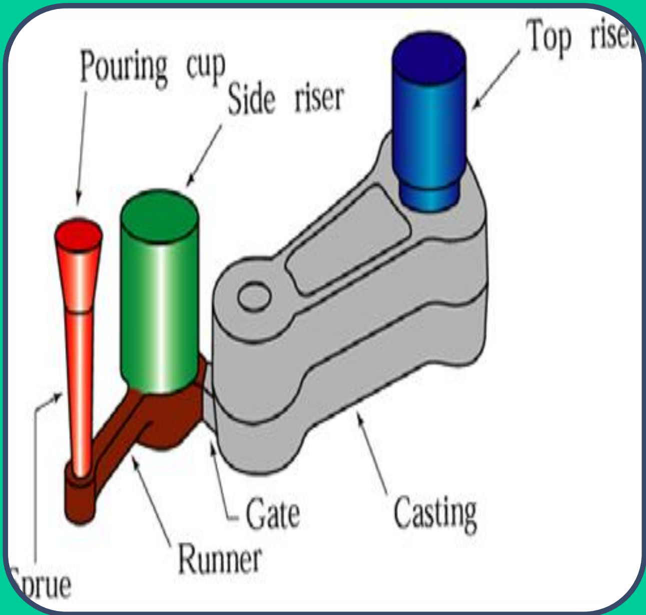
CLASSIFICATION OF MANUFACTURING PROCESSES

Manufacturing processes can be grouped as:

- Casting, foundry or moulding processes.
- Forming or metal working processes.
- Machining (metal removal) processes.
- Joining and assembly
- Surface treatments (finishing).
- Heat treating

These groups are not mutually exclusive. For example, some finishing processes involve a small amount of metal removal or metal forming. A laser can be used for joining/metal removal/heat treating.

CLASSIFICATION OF MANUFACTURING PROCESSES



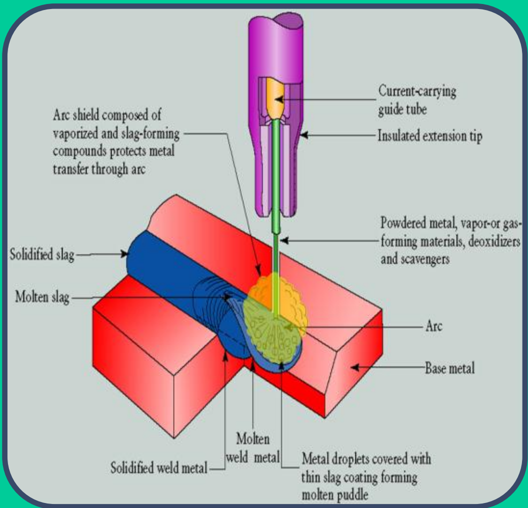
Casting, foundry or moulding processes

- **Sand casting**
- **Investment casting**
- **Die casting**
- **Centrifugal Casting**
- **Continuous Casting**

CLASSIFICATION OF MANUFACTURING PROCESSES

Forming or metal working processes

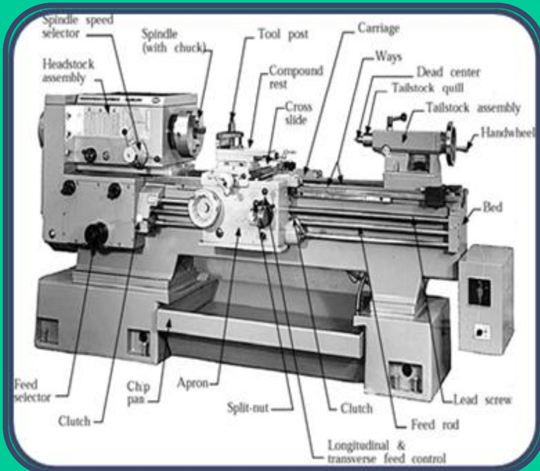
- **Rolling**
- **Forging**
- **Extrusion**
- **Drawing**
- **Sheet metal works**



Joining processes

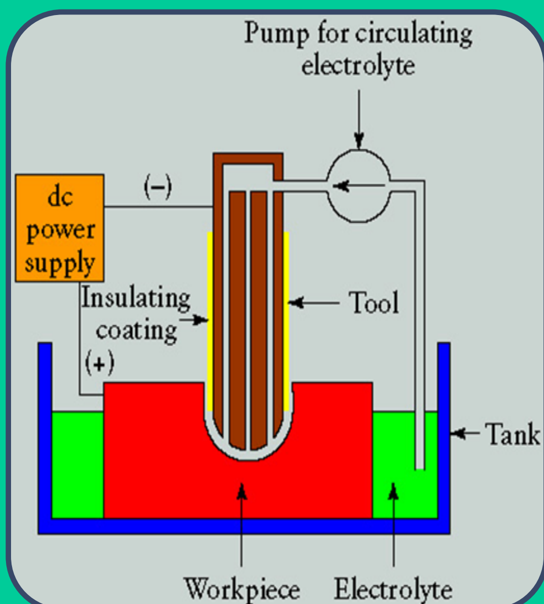
- **Welding (SMAW, TIG, MIG, PLASMA, LBW, EBW etc.)**
- **Soldering**
- **Brazing**
- **Adhesive bonding**
- **Riveting**

CLASSIFICATION OF MANUFACTURING PROCESSES



Conventional Machining processes

- **Turning**
- **Milling**
- **Drilling**
- **Shaping**
- **Grinding**
- **Broaching**



Nonconventional Machining processes

- **Electro chemical Machining (ECM)**
- **Electro Discharge Machining (EDM)**
- **Wire Electro Discharge Machining(WEDM)**
- **Abrasive Jet Machining (AJM)**
- **Ultrasonic Machining (USM)**
- **Liquid Jet Machining (LJM)**
- **Electron Beam Machining (EBM)**
- **Laser Beam Machining (LBM)**
- **Ion Beam Machining (IBM)**
- **Plasma Arc Machining (PAM)**

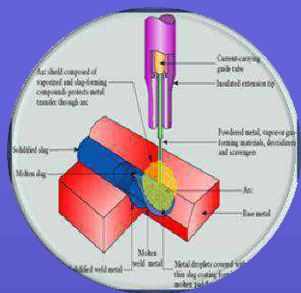
- **Manufacturing system:**
- A collection of operations and processes used to obtain a desired product(s) or component(s) is called a manufacturing system.
- ***The manufacturing system is therefore the design or arrangement of the manufacturing processes..***

- **Production system:**
- ***A production system includes people, money, equipment, materials and supplies, markets, management and the manufacturing system.***

Production System - The Big Picture

Raw materials

Manufacturing Process



Manufacturing Process

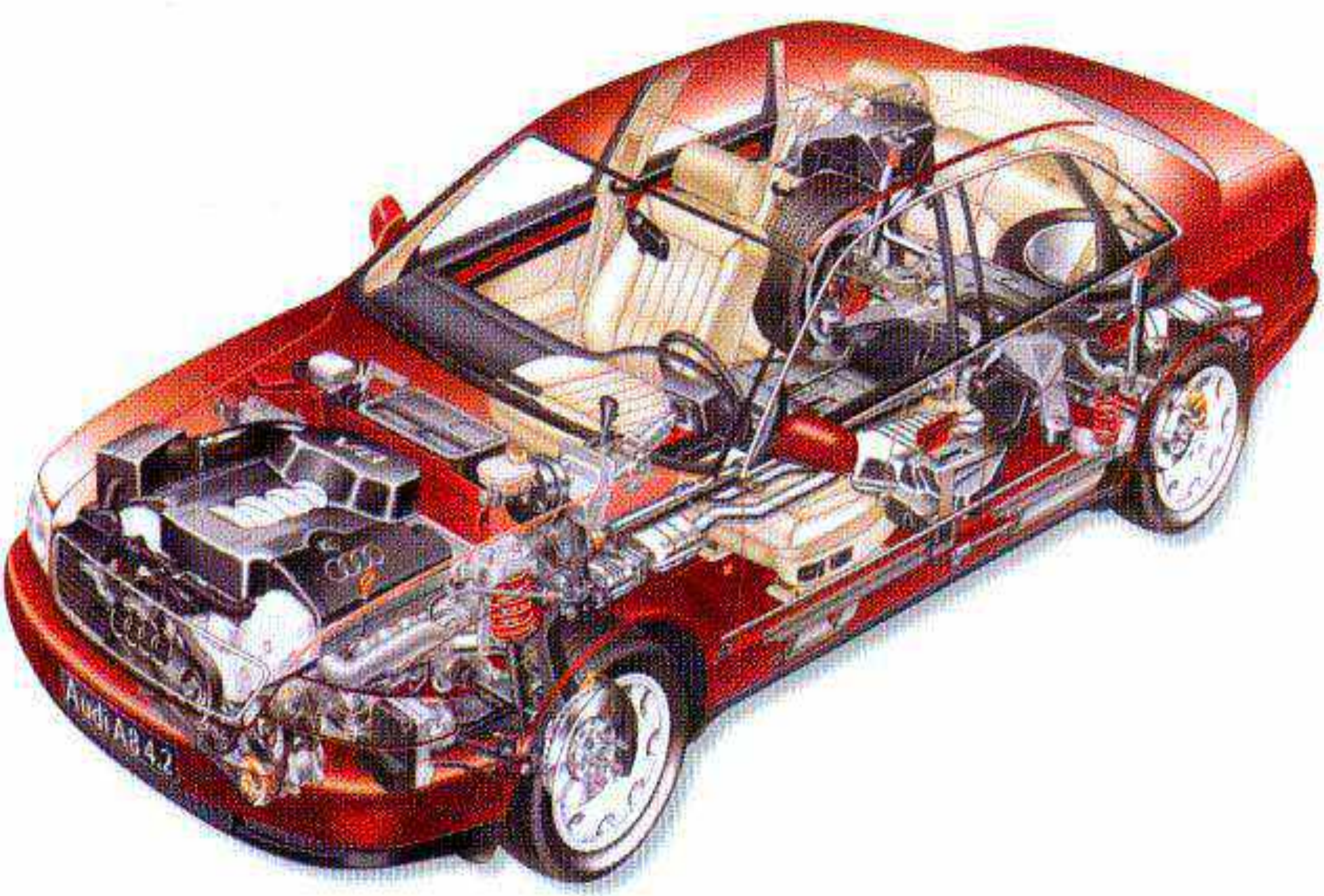
Finished product

Manufacturing System

People, Money, Equipment, Materials and Supplies, Markets, Management

Application of Manufacturing Processes

Application of Manufacturing Processes

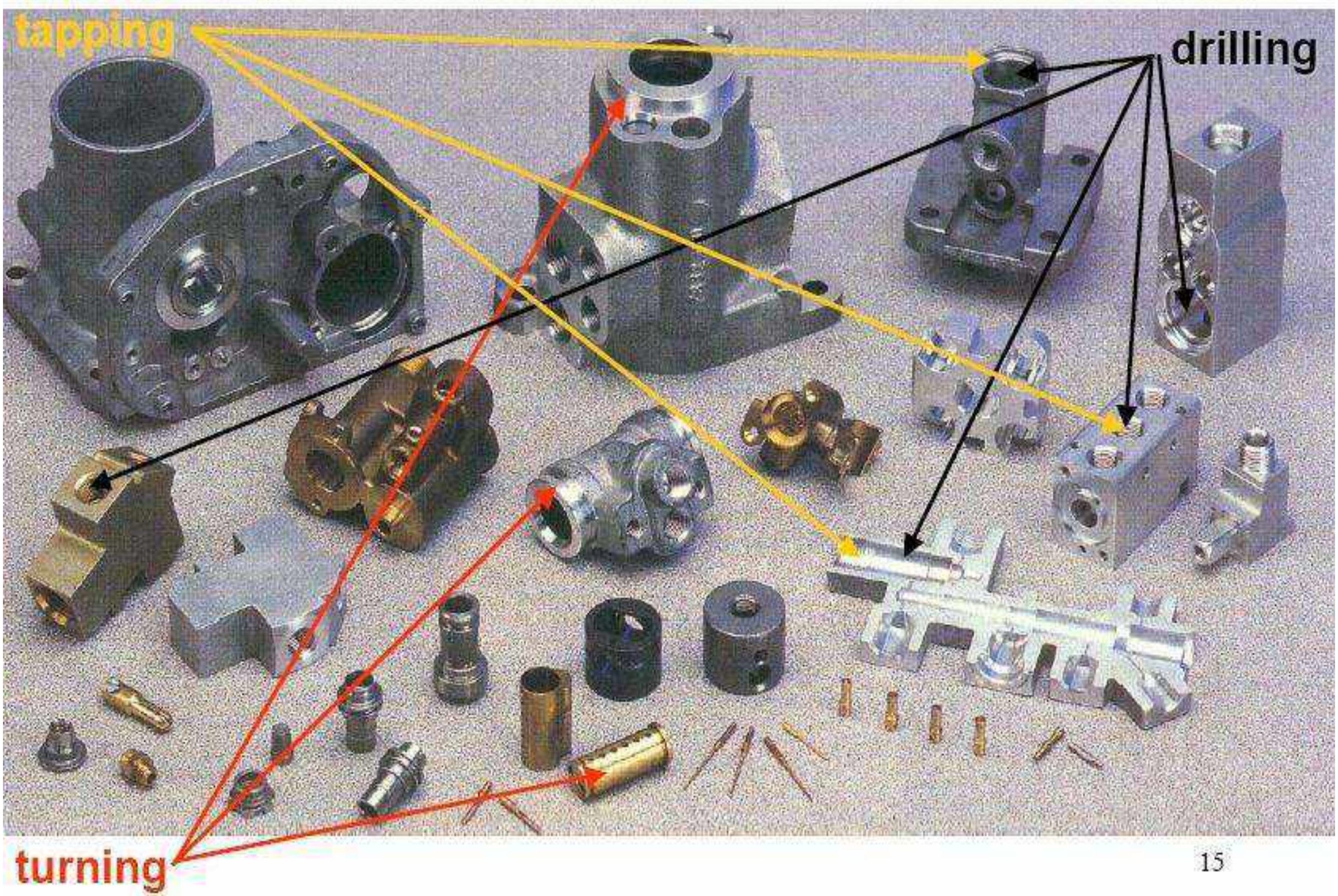


Application of Manufacturing Processes

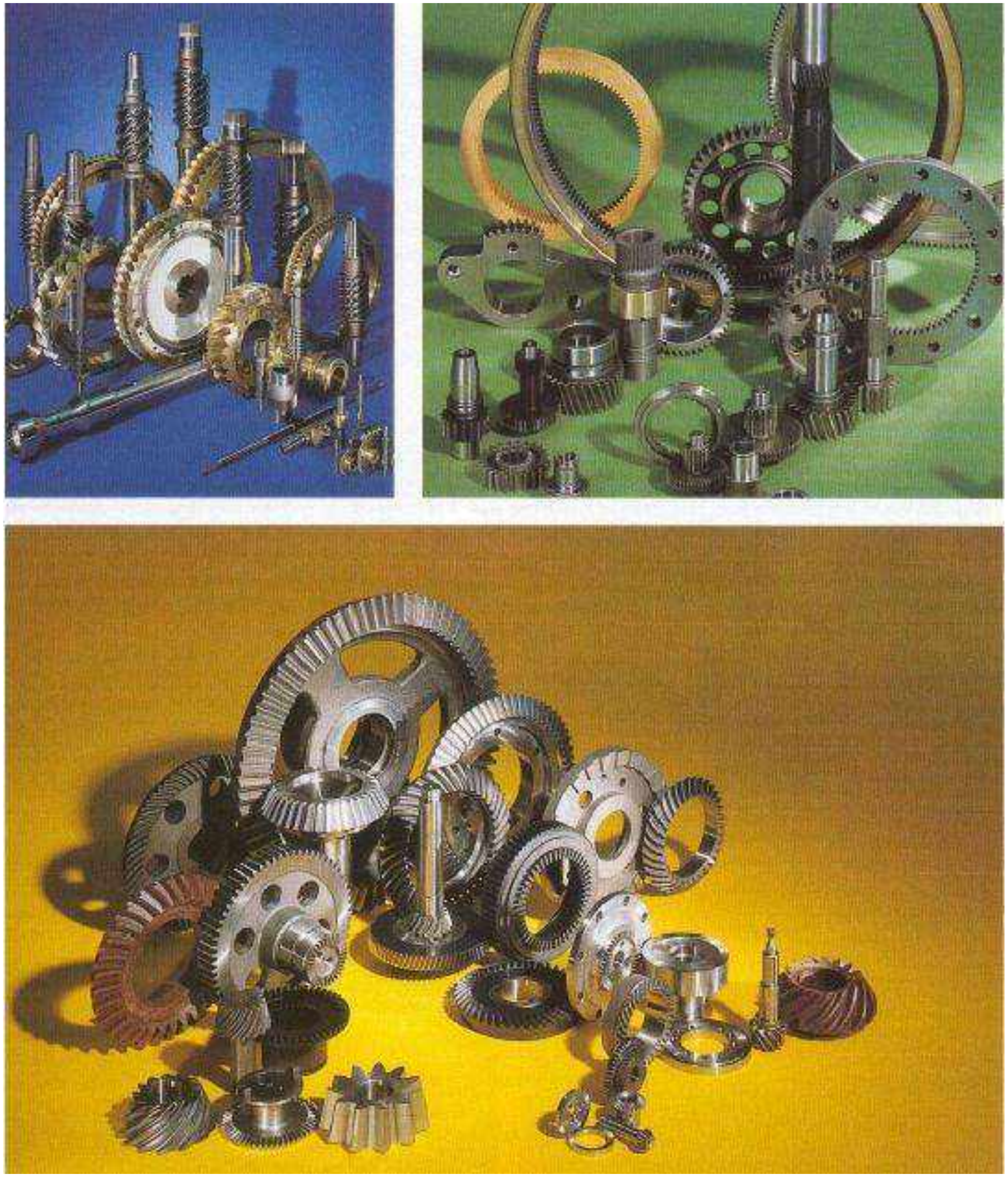
Application of Manufacturing Processes

The "Columbus" carrying the Enterprise space shuttle

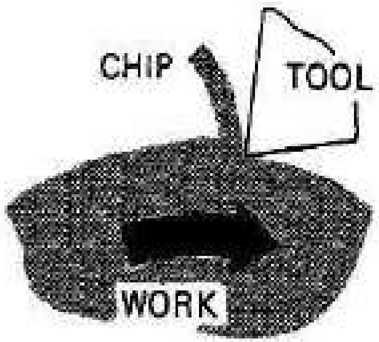
Application of Manufacturing Processes



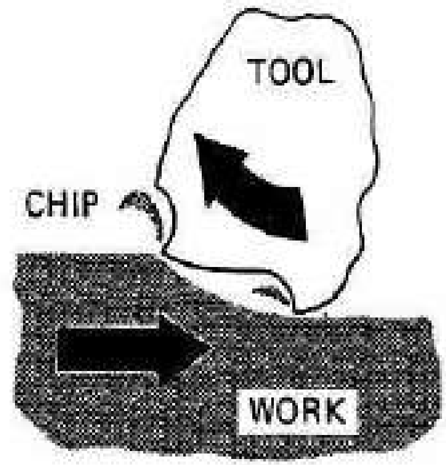
Application of Manufacturing Processes (Gears)



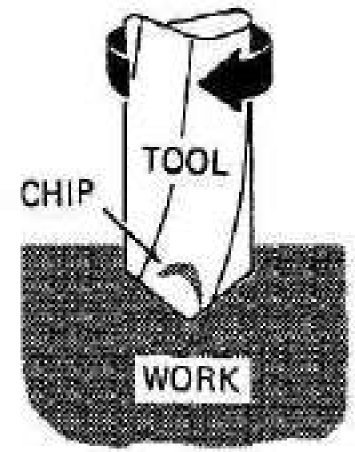
Diagrammatic Representation of Material Removal Operations



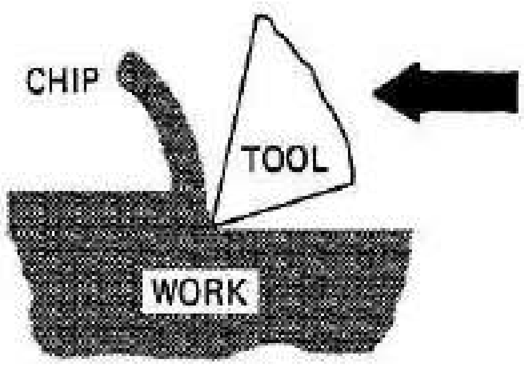
LATHE TURNING



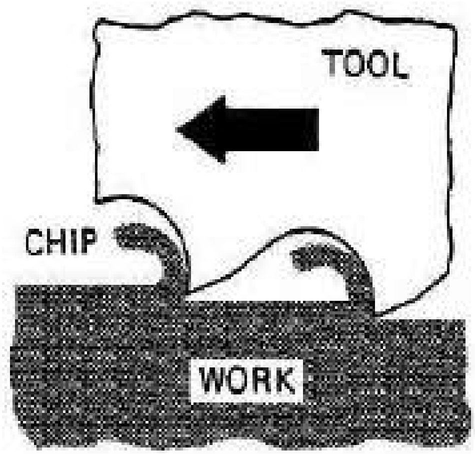
MILLING



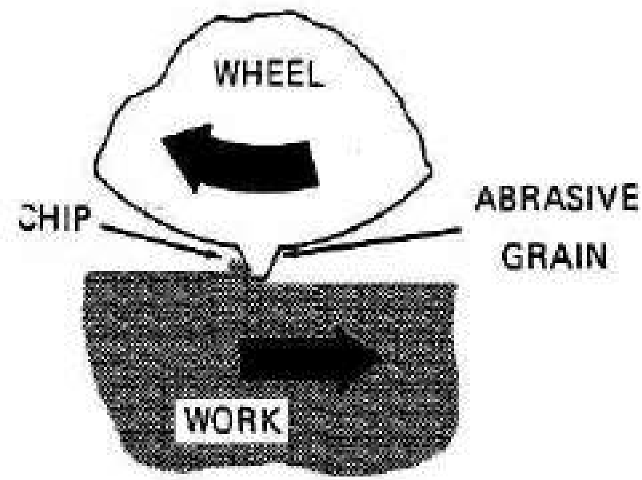
DRILLING



SHAPER

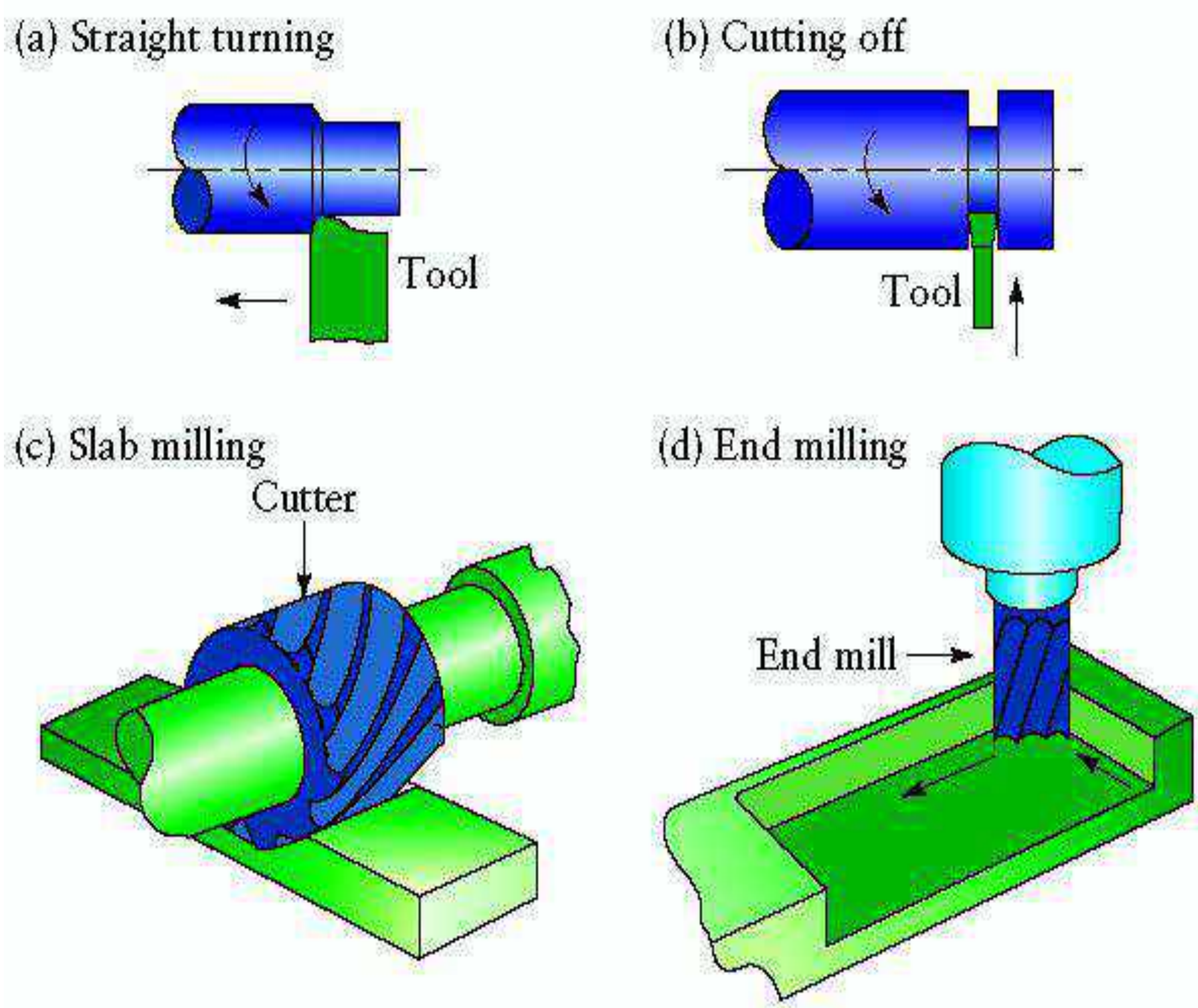


BROACHING



GRINDING

Examples of cutting processes



Source: “ Manufacturing Processes for Engineering Materials”, 4th edition, Kalpakjian, Schmid, Prentice Hall 2003

An Introductory video on Manufacturing Processes

Machine Tools

Machine tools are kind of machines on which metal cutting or metal forming processes are carried out.

Material removal is essentially done on machine tools, which may be Lathe, Milling, Drilling, Shaping, Planing, Broaching and Grinding machines.

The functions of machine tools are:

- holding the workpiece
- holding the tool
- moving the tool or the work piece or both relative to each other,
- supply energy required to cause metal cutting.

Every machine tool has a primary cutting tool for metal removal.

Machining Parameters

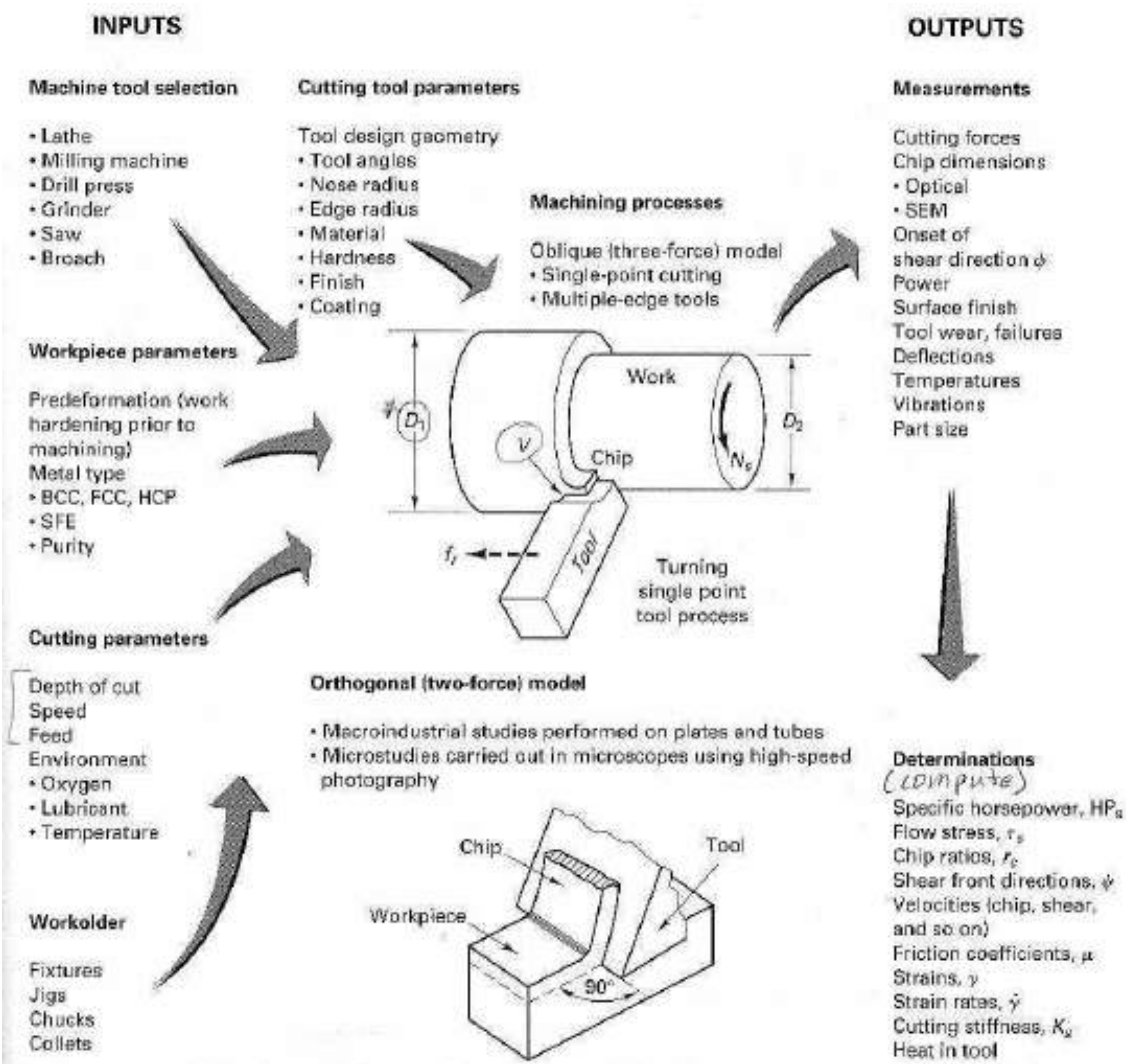


FIGURE 21-1 The fundamental inputs and outputs to machining processes.

Cutting Parameter Relationships

Cutting Parameters

Cutting Speed: Cutting speed is the distance traveled by the work surface in unit time with reference to the cutting edge of the tool.

The cutting speed, ***v*** is simply referred to as speed and usually expressed in m/min.

Feed: The feed is the distance advanced by the tool into or along the workpiece each time the tool point passes a certain position in its travel over the surface.

In case of turning, feed is the distance that the tool advances in one revolution of the workpiece.

Feed ***f*** is usually expressed in mm/rev. Sometimes it is also expressed in mm/min and is called feed rate.

Depth of cut : It is the distance through which the cutting tool is plunged into the workpiece surface.

Thus it is the distance measured perpendicularly between the machined surface and the unmachined (uncut) surface or the previously machined surface of the workpiece.

The depth of cut ***d*** is expressed in mm.

Selection of cutting speed and feed

- **The selection of cutting speed and feed is based on the following parameters:**
  - **Workpiece material**
  - **Tool Material**
  - **Tool geometry and dimensions**
  - **Size of chip cross-section**
  - **Types of finish desired**
  - **Rigidity of the machine**
  - **Types of coolant used**

Selection of cutting speed and feed

Approximate Ranges of Recommended Cutting Speed[s]
Turning Operations

	CUTTING SPE[ED]
WORKPIECE MATERIAL	m/min
Aluminum alloys	200–1000
Cast iron, gray	60–900
Copper alloys	50–700
High-temperature alloys	20–400
Steels	50–500
Stainless steels	50–300
Thermoplastics and thermosets	90–240
Titanium alloys	10–100
Tungsten alloys	60–150

Note: (a) The speeds given in this table are for carbides and ceramic cutting tool

Cutting tools & its characteristics

Cutting tool is a device, used to remove the unwanted material from given workpiece. For carrying out the machining process, cutting tool is fundamental and essential requirement. A cutting tool must have the following characteristics:

- **Hardness:** The tool material must be harder than the work piece material. Higher the hardness, easier it is for the tool to penetrate the work material.
- **Hot hardness:** Hot Hardness is the ability of the cutting tool must to maintain its Hardness and strength at elevated temperatures. This property is more important when the tool is used at higher cutting speeds, for increased productivity.
- **Toughness:** Inspite of the tool being tough, it should have enough toughness to withstand the impact loads that come in the start of the cut to force fluctuations due to imperfections in the work material. Toughness of cutting tools is needed so that tools don't chip or fracture, especially during interrupted cutting operations like milling.

Cutting tools & its characteristics

- **Wear Resistance: T**he tool-chip and chip-work interface are exposed to severe conditions that adhesive and abrasion wear is very common. Wear resistance means the attainment of acceptable tool life before tools need to be replaced.
- **Low friction:** The coefficient of friction between the tool and chip should be low. This would lower wear rates and allow better chip flow.
- **Thermal characteristics:** Since a lot of heat is generated at the cutting zone, the tool material should have higher thermal conductivity to dissipate the heat in shortest possible time, otherwise the tool temperature would become high, reducing its life.

Cutting Tool Materials

- **Carbon and Medium alloy steels :** These are the oldest of the tool materials dating back hundreds of years. In simple terms it is a high carbon steel (steel which contains about 0.9 to 1.3% carbon). Inexpensive, easily shaped, sharpened. No sufficient hardness and wear resistance. Limited to low cutting speed operation
- **High Speed Steel (1900):** The major difference between high speed tool steel and plain high carbon steel is the addition of alloying elements (manganese, chromium, tungsten, vanadium, molybdenum, cobalt, and niobium) to harden and strengthen the steel and make it more resistant to heat (hot hardness). They are of two types: Tungsten HSS (denoted by T), Molybdenum HSS (denoted by M).
- **Cemented Carbides or Sintered Carbides (1926-30):** These tools are produced by powder metallurgy. Carbide tools are basically of three types: tungsten carbide (WC), tantalum carbide (TaC), and titanium carbide (TiC). The carbides or combined carbides are mixed with a binder of cobalt. They are able to retain hardness to a temperature of about 1000^0C. So they can be used at high speeds. Carbide tool are available as brazed tip tools (carbide tip is brazed to steel tool) and inserts (inserts are of various shapes- triangular, square diamond and round).

Typical carbide inserts

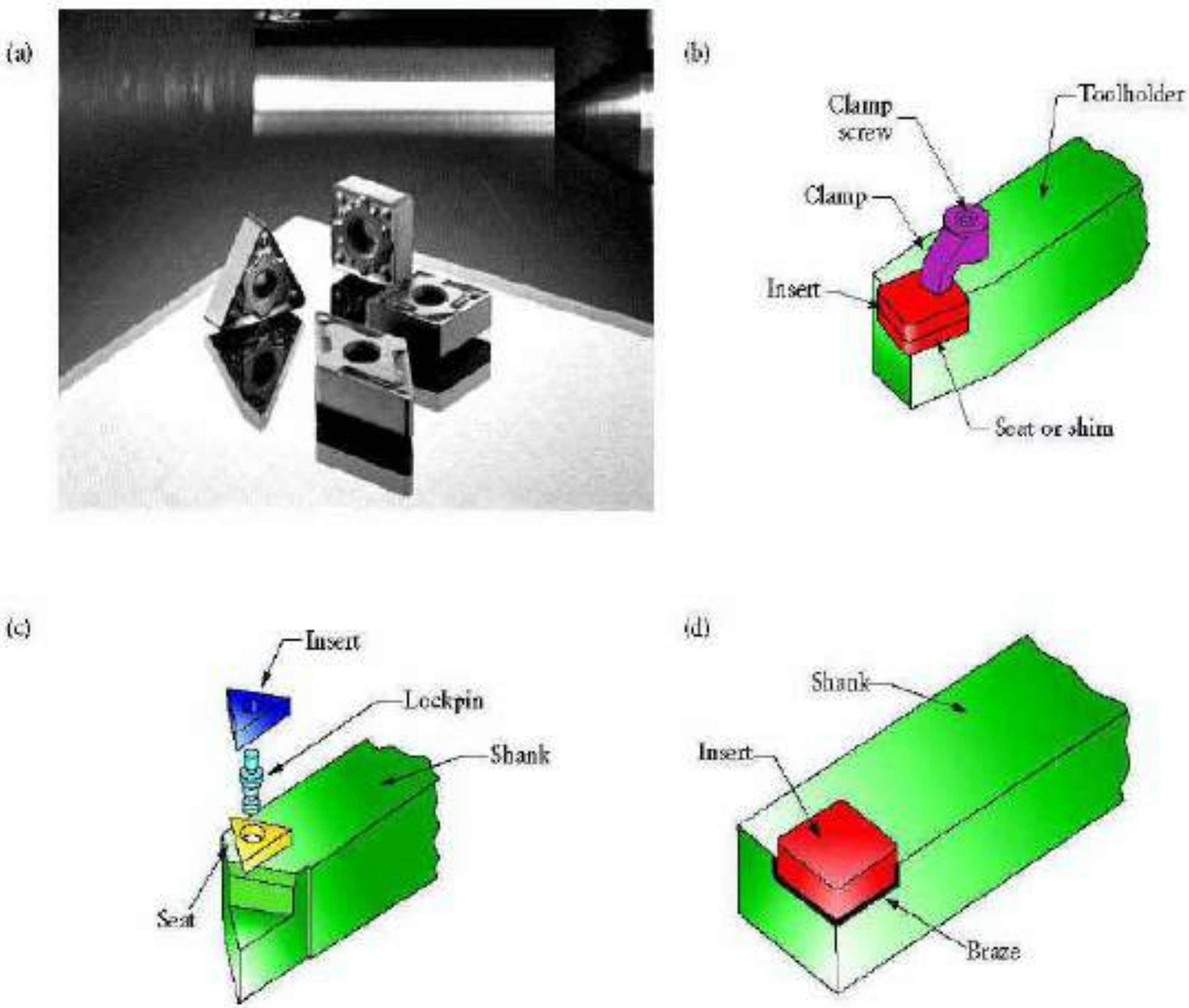


FIGURE: (a) Typical carbide inserts with various shapes and chip-breaker features. Round inserts are also available. The holes in the inserts are standardized for interchangeability. *Source*: Courtesy of Kyocera Engineered Ceramics, Inc., and *Manufacturing Engineering*, Society of Manufacturing Engineers. (b) Methods of attaching inserts to a tool shank by clamping, (c) with wing lockpins, and (d) with a brazed insert on a shank

Cutting Tool Materials

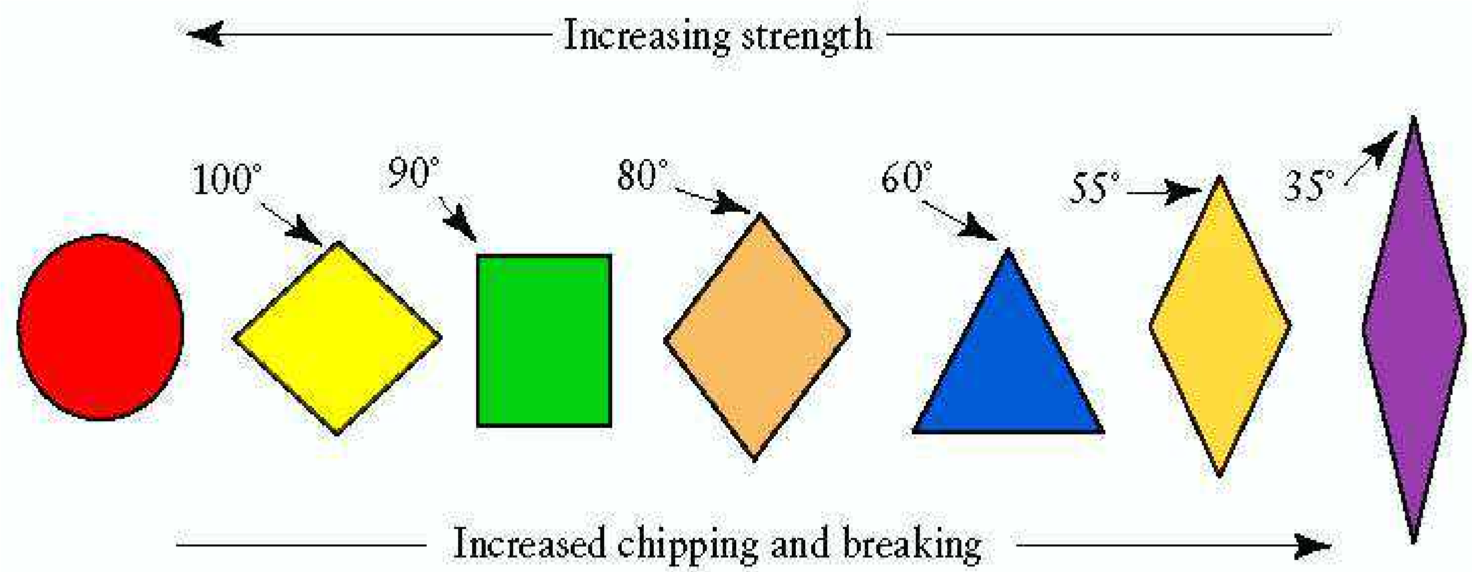
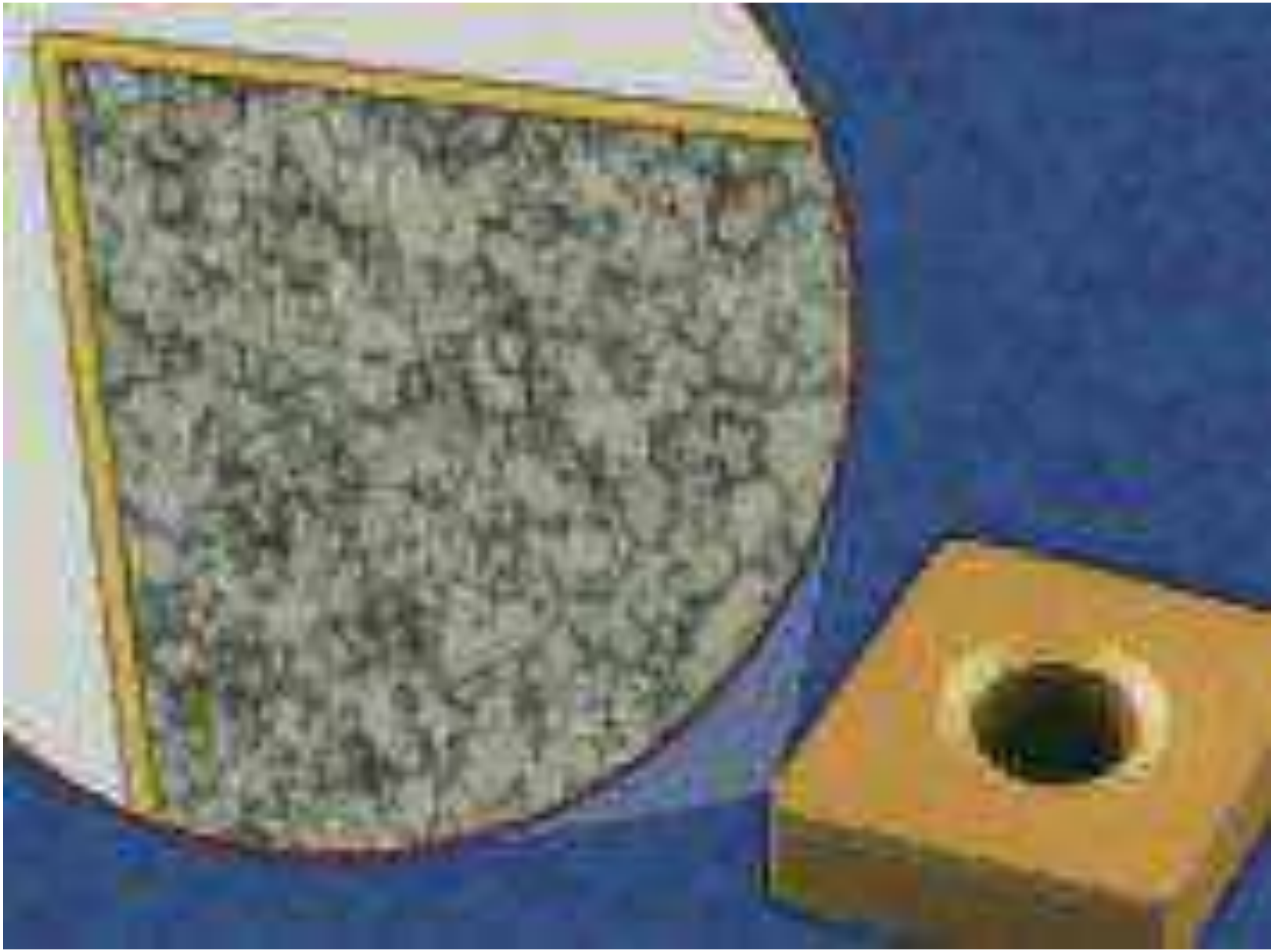


FIGURE: Relative edge strength and tendency for chipping and breaking of inserts with various shapes. Strength refers to that of the cutting edge shown by the included angles. *Source*: Kennametal, Inc.

Cutting Tool Materials



Cutting Tool Materials

Factors affecting choice of insert shape	R	90	80	80	60	55	35
Roughing (strength)	●	●	●	○	○		
Light roughing/Semi-finishing (No. of edges)		○	●	●	●	●	
Finishing (No. of edges)			○	○	●	●	●
Turning and Facing (feed directions)			●	○	○	●	●
Profiling (Accessability)			○	○	○	●	●
Operational versatility	○		●	○	○	●	○
Limited machine power			○	○	●	●	●
Vibration tendencies (reduction)				○	●	●	●
Hard material	●	●					
Intermittent Machining	●	●	○	○	○		
Large entering angle			●	●	●	●	●
Small entering angle	●	●		●	●		

● Most suitable ○ Suitable

Cutting Tool Materials

Carbides are now so popular that ISO has developed an application chart.

The chart is divided into three main areas: ISO - P, M and K.

ISO P: is for the machining of long chip formation materials.

ISO M: is for the machining of difficult to machine materials such as austenitic stainless steel.

ISO K: is for the machining of short chip formation materials such as cast iron, hardened steel.

Range of materials		Typical Machining Operations	Demands on the grade
P Steel, cast steel, stainless steel, long chipping malleable iron.	01	Extreme finishing to high surface finish.	High wear resistance. ↑
	05		
	10	Finishing at high cutting speed.	
	15		
	20	Copy turning operations.	
	25		
	30	Rough turning and turning with low cutting speeds.	
	35		
	40		
	45		
	50	Heavy roughing and intermittent machining.	↓ Good toughness and edge strength.
M Steel, cast steel, manganese steel, alloy cast iron, austenic stainless steel castings, malleable iron, free-cutting steel.	10	Finishing at high cutting data	High wear resistance. ↑
	20	Finishing at low cutting data	
	30		
	40	Heavy roughing and intermittent machining.	↓ Good toughness and edge strength.
K Cast iron, chilled cast iron, short chipping malleable iron, hardened steel, non-ferrous metals, plastics, wood.	01	Finishing to high surface finish.	High wear resistance. ↑
	05		
	10	Semi-finishing to light roughing	
	15		
	20	Heavy roughing and intermittent machining.	
	25		
	30	Machining at low cutting data.	↓ Good toughness and edge strength.

Cutting Tool Materials

- **Coated cemented carbide (1960): T**ool life to about 200 to 300 % or more. A thin, chemically stable, hard refractory coating of TiC, TiN or Al_2O_3 is used. The bulk of the tool is tough, shock resistant carbide that can withstand high temperatures. Because of its wear resistance, coated tool can be used at still higher speeds.

- **Cast cobalt alloys or Stellites (1915):** It is a non-ferrous alloy consisting mainly of cobalt, tungsten and chromium (38% to 53% Cobalt, 30% to 33% Chromium, and 4% to 20% Tungsten). Other elements added in varying proportions are molybdenum, manganese, silicon and carbon. It has good shock and wear resistance properties and retains its harness up to 900^0C. Stellite tools can operate at speed about 25% higher than that of HSS tools .

- **Cemented oxides or Ceramic Cutting Tools (1950s): N**on-metallic materials made of pure Aluminum oxide by powder metallurgy. The application ceramic cutting tools are limited because of their extreme brittleness. The transverse rupture strength (TRS) is very low. This means that they will fracture more easily when making heavy interrupted cuts. However, the strength of ceramics under compression is much higher than HSS and carbide tools. It has high hot hardness (up to 1200 degree C), so capable of running at high speeds.

Cutting Tool Materials

- **Cermets:** Cermets are ceramic material in metal binders. TiC, nickel, TiN, and other carbides are used as binders. Cermets have higher hot hardness and oxidation resistance than cemented carbides but less toughness. They are used for finishing operation. The main problem with cermets is that due to thermal shock the inserts crack.
- **Diamond:** They are of two types - industrial grade natural diamonds, and synthetic polycrystalline diamonds. Because diamonds are pure carbon, they have an affinity for the carbon of ferrous metals. Therefore, they can only be used on non-ferrous metals. Feeds should be very light and high speeds Rigidity in the machine tool and the setup is very critical because of the extreme hardness and brittleness of diamond.
- **Cubic Boron Nitride (1962):** Cubic boron nitride (CBN) is similar to diamond in its polycrystalline structure and is also bonded to a carbide base. With the exception of titanium, or titanium-alloyed materials, CBN will work effectively as a cutting tool on most common work materials. However, the use of CBN should be reserved for very hard and difficult-to-machine materials.

Properties of Cutting Tool Materials

PROPERTY	CARBIDES						
	HIGH-SPEED STEEL	CAST ALLOYS	WC	TiC	CERAMICS	CUBIC BORON NITRIDE	SINGLE-CRYSTAL DIAMOND*
Hardness	83-86 HRA	82-84 HRA 46-62 HRC	90-95 HRA 1800-2400 HK	91-93 HRA 1800-3200 HK	91-95 HRA 2000-3000 HK	4000-5000 HK	7000-8000 HK
Compressive strength MPa psi x 10^3	4100-4500 600-650	1500-2300 220-335	4100-5850 600-850	3100-3850 450-560	2750-4500 400-650	6900 1000	6900 1000
Transverse rupture strength MPa psi x 10^3	2400-4800 350-700	1380-2050 200-300	1050-2600 150-375	1380-1900 200-275	345-950 50-135	700 105	1350 200
Impact strength J in.-lb	1.35-8 12-70	0.34-1.25 3-11	0.34-1.35 3-12	0.79-1.24 7-11	< 0.1 < 1	< 0.5 < 5	< 0.2 < 2
Modulus of elasticity GPa psi x 10^5	200 30	- -	520-690 75-100	310-450 45-65	310-410 45-60	850 125	820-1050 120-150
Density kg/m^3 lb/in^3	8600 0.31	8000-8700 0.29-0.31	10,000-15,000 0.36-0.54	5500-5800 0.2-0.22	4000-4500 0.14-0.16	3500 0.13	3500 0.13
Volume of hard phase (%)	7-15	10-20	70-90	-	100	95	95
Melting or decomposition temperature °C °F	1300 2370	- -	1400 2550	1400 2550	2000 3600	1300 2400	700 1300
Thermal conductivity, W/mK	30-50	-	42-125	17	29	13	500-2000
Coefficient of thermal expansion, x 10^{-6}/°C	12	-	4-6.5	7.5-9	6-8.5	4.8	1.5-4.8

* The values for polycrystalline diamond are generally lower, except impact strength, which is higher

Source " Manufacturing Processes for Engineering Materials", 4th edition, Kalpakjian, Schmid, Prentice Hall 2003

Cutting tool material and recommended speed range:

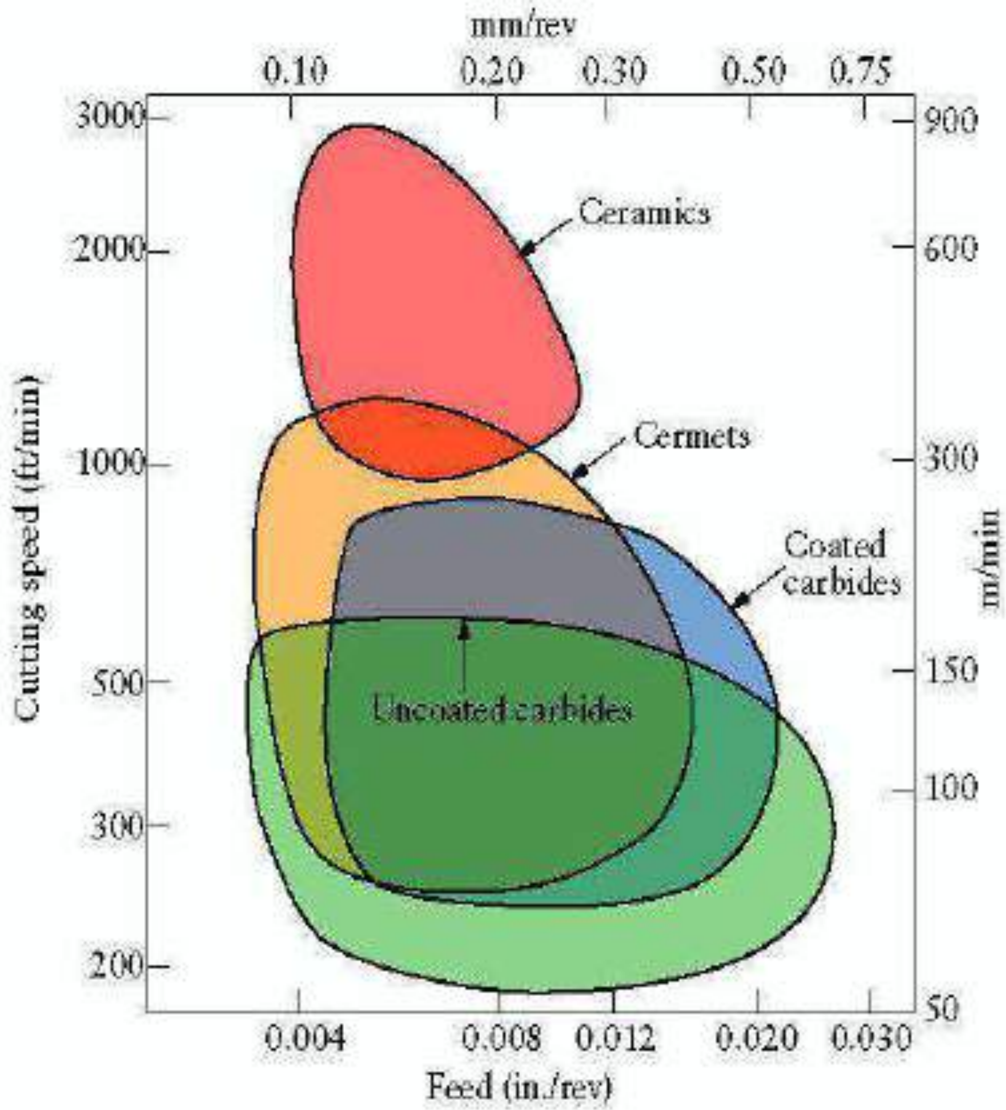
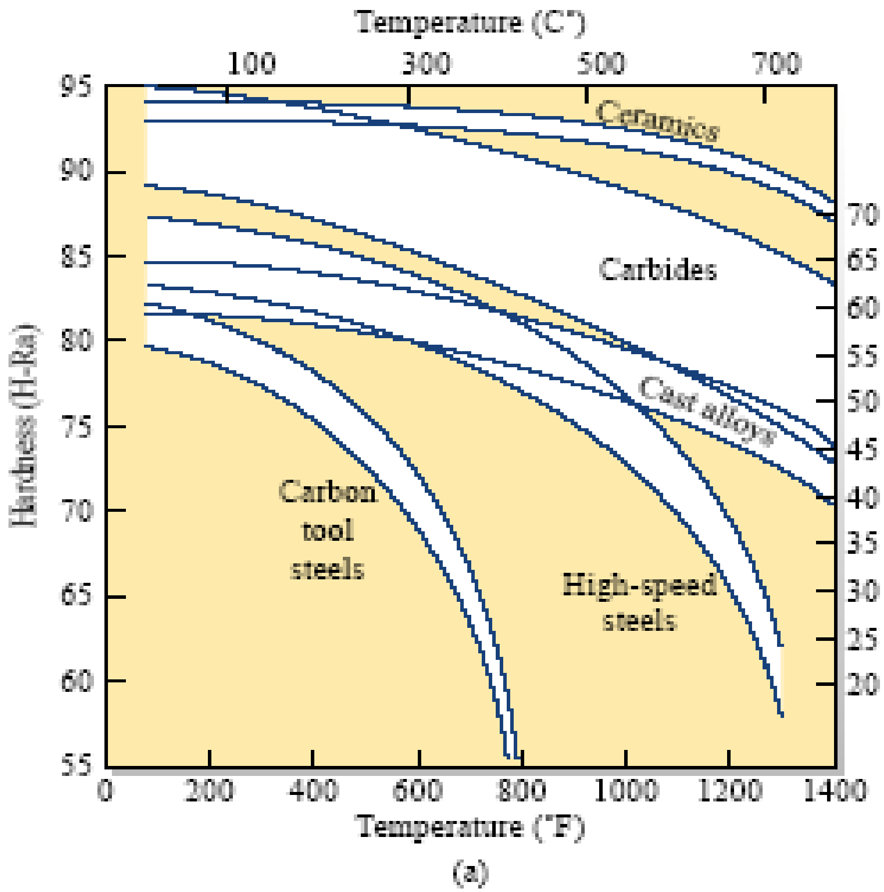
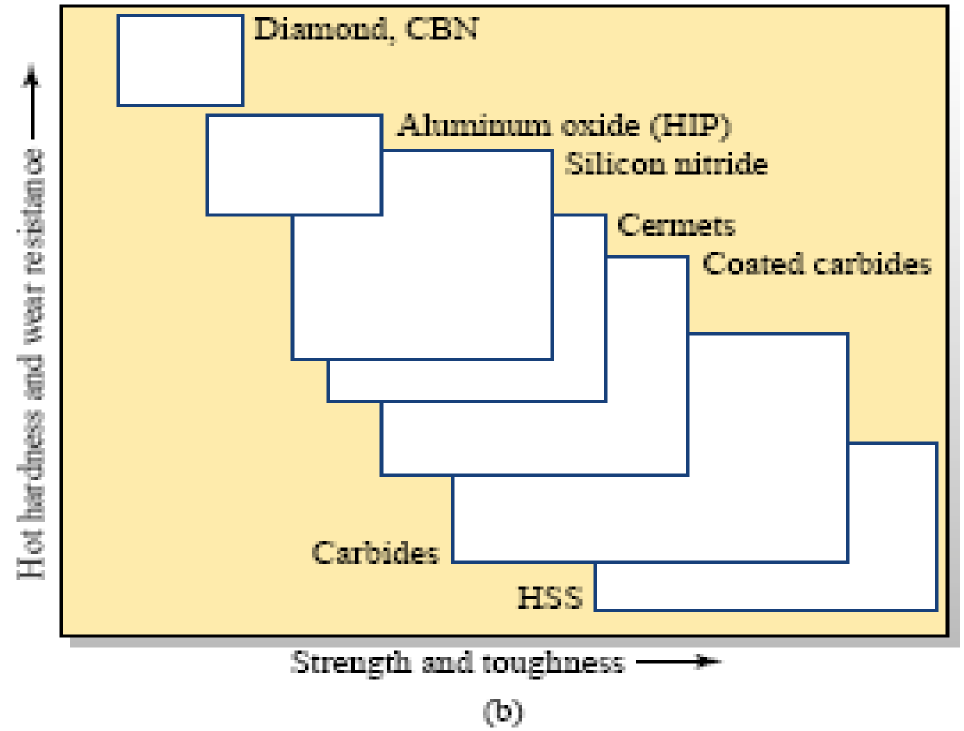


FIGURE : The range of applicable cutting speeds and fees for a variety of tool materials. *Source*: Valenite, Inc.

Figure from: " Manufacturing Processes for Engineering Materials", 4th edition, Kalpakjian, Schmid, Prentice Hall 2003

Cutting tool materials hardness and strength





(a) Hardness of various cutting-tool materials as a function of temperature. (b) Ranges of properties of various groups of materials.

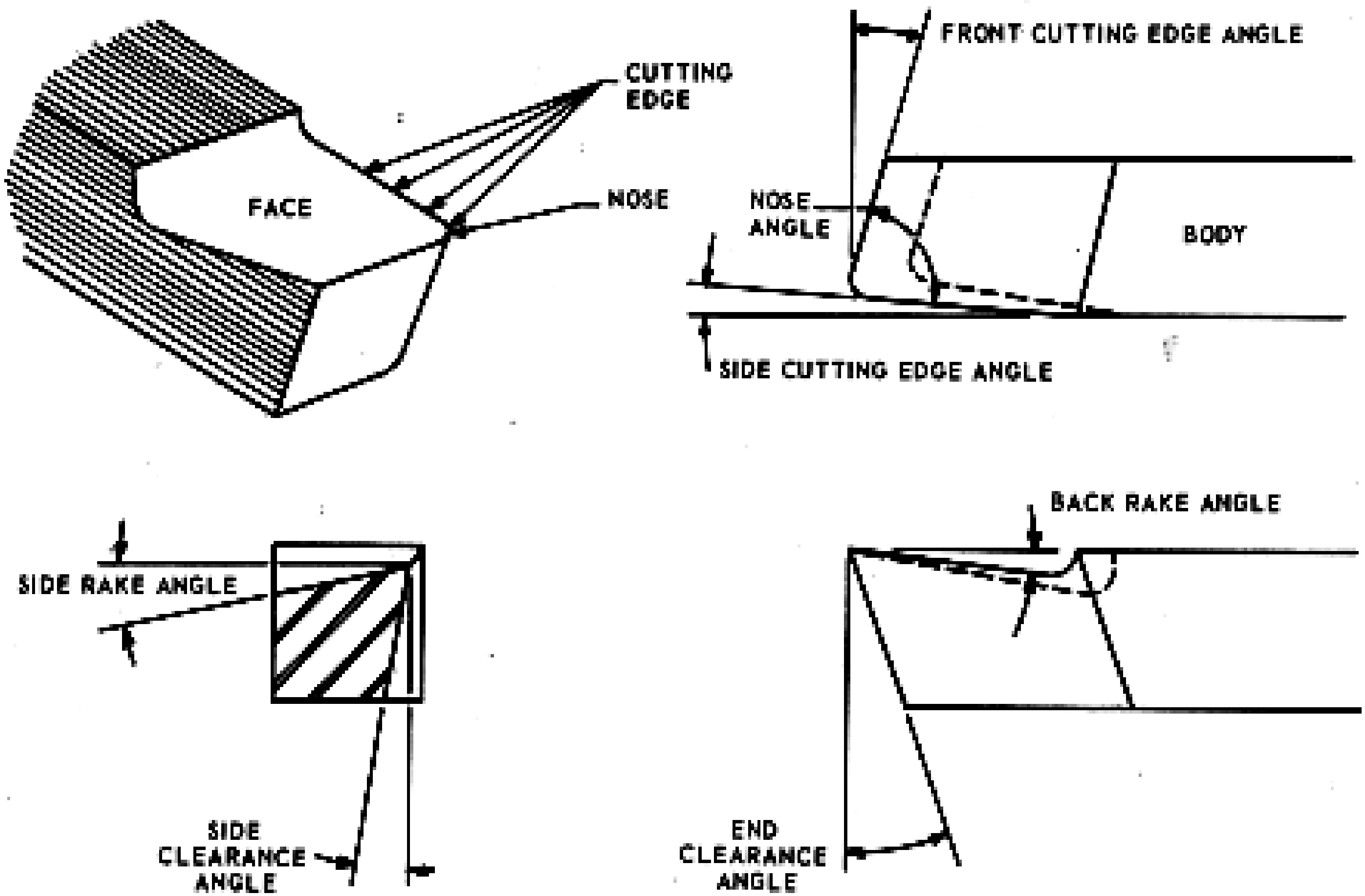
Source: **George Schneider,Jr. CMfgE,** Cutting Tool Applications

Operating Characteristics of Cutting tool materials

Operating Characteristics of Cutting-Tool Materials

Tool materials	General characteristics	Modes of tool wear or failure	Limitations
High-speed steels	High toughness, resistance to fracture, wide range of roughing and finishing cuts, good for interrupted cuts	Flank wear, crater wear	Low hot hardness, limited hardenability, and limited wear resistance
Uncoated carbides	High hardness over a wide range of temperatures, toughness, wear resistance, versatile and wide range of applications	Flank wear, crater wear	Cannot use at low speed because of cold welding of chips and microchipping
Coated carbides	Improved wear resistance over uncoated carbides, better frictional and thermal properties	Flank wear, crater wear	Cannot use at low speed because of cold welding of chips and microchipping
Ceramics	High hardness at elevated temperatures, high abrasive wear resistance	Depth-of-cut line notching, microchipping, gross fracture	Low strength, low thermomechanical fatigue strength
Polycrystalline cubic boron nitride (cBN)	High hot hardness, toughness, cutting-edge strength	Depth-of-cut line notching, chipping, oxidation, graphitization	Low strength, low chemical stability at higher temperature
Polycrystalline diamond	Hardness and toughness, abrasive wear resistance	Chipping, oxidation, graphitization	Low strength, low chemical stability at higher temperature

Single Point Cutting Tool Geometry



Right hand single point cutting tool

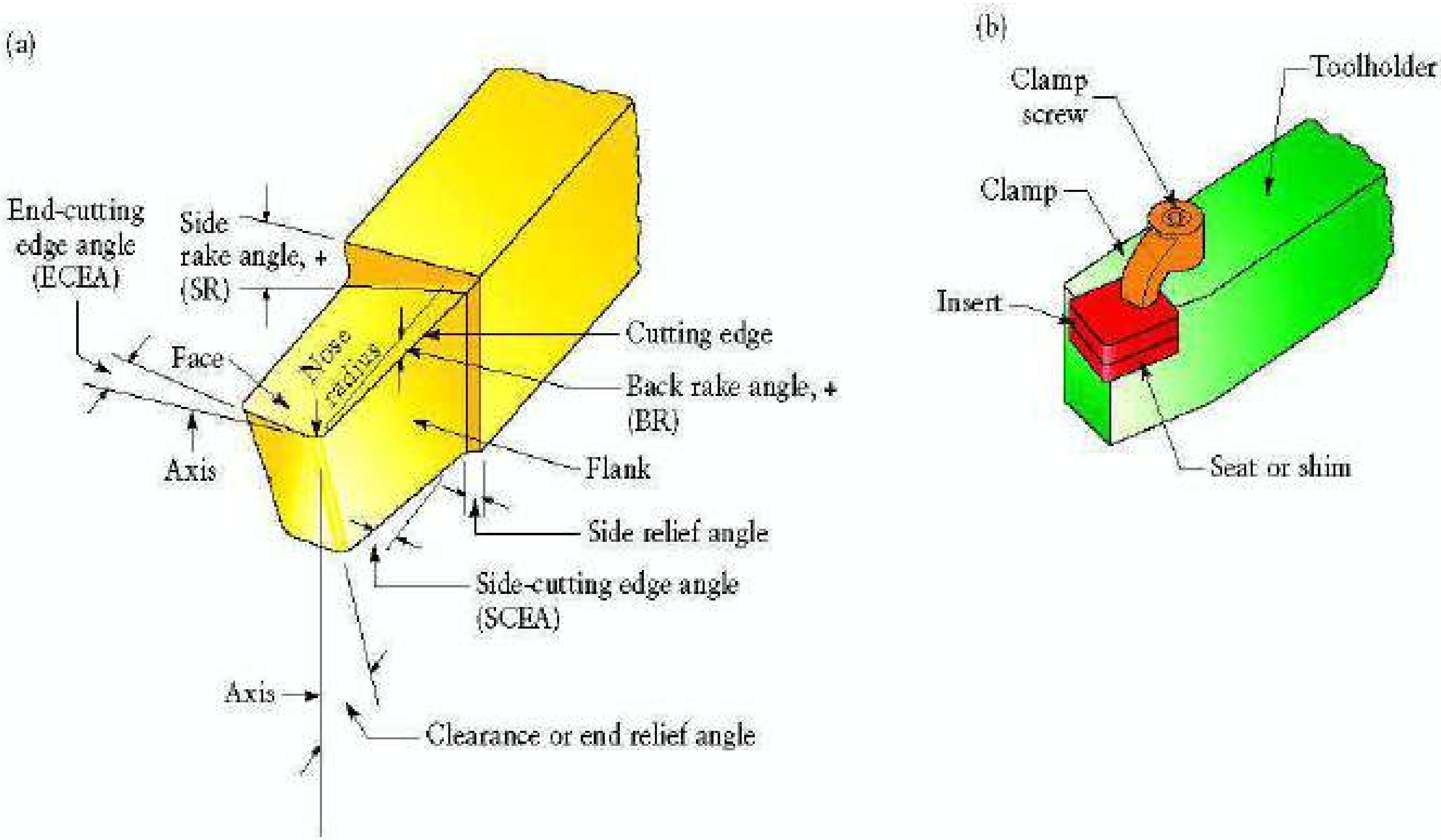
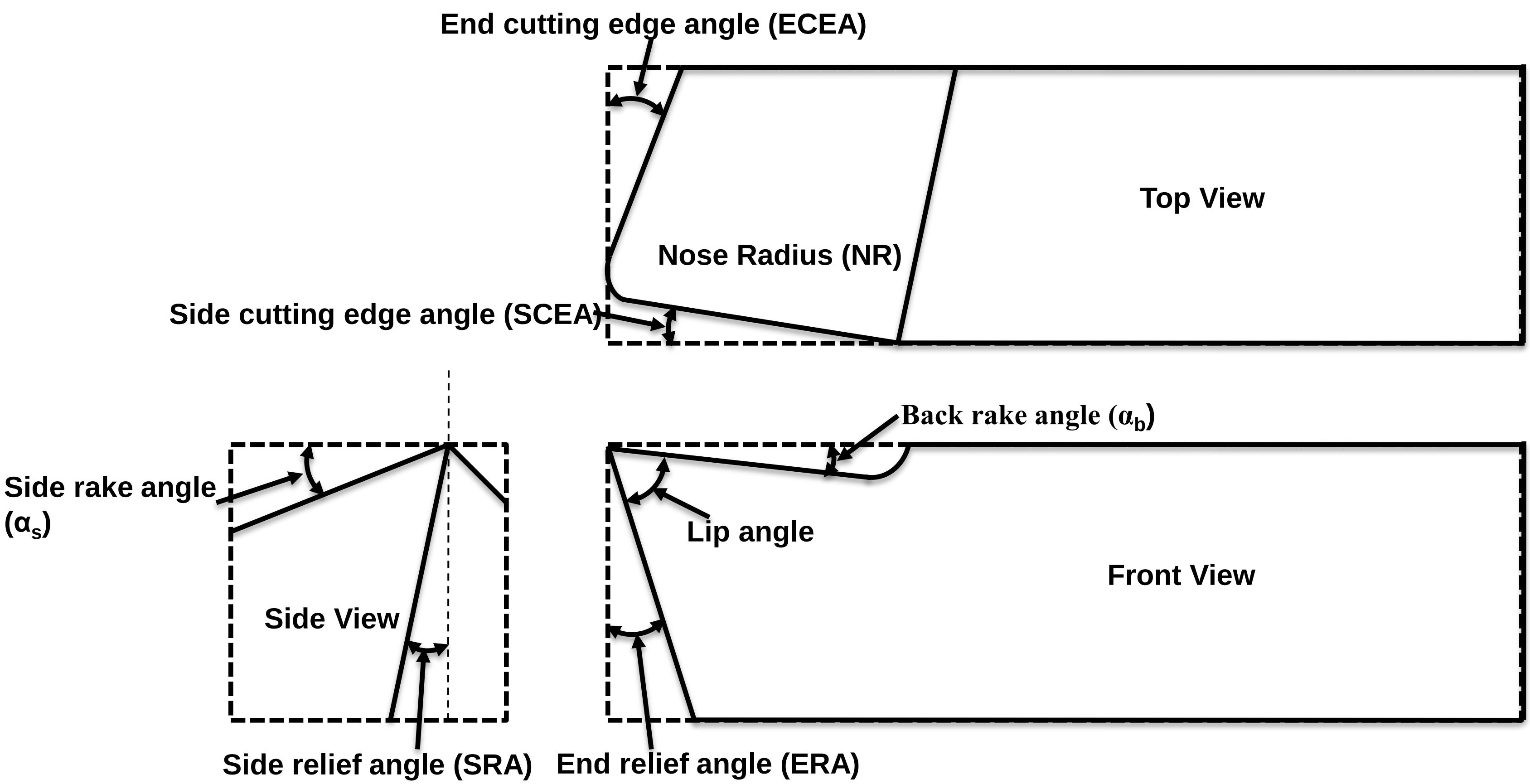


FIGURE : (a) Schematic illustration of a right-hand cutting tool. Although these tools have traditionally been produced from solid tool-steel bars, they have been largely replaced by carbide or other inserts of various shapes and sizes, as shown in (b).

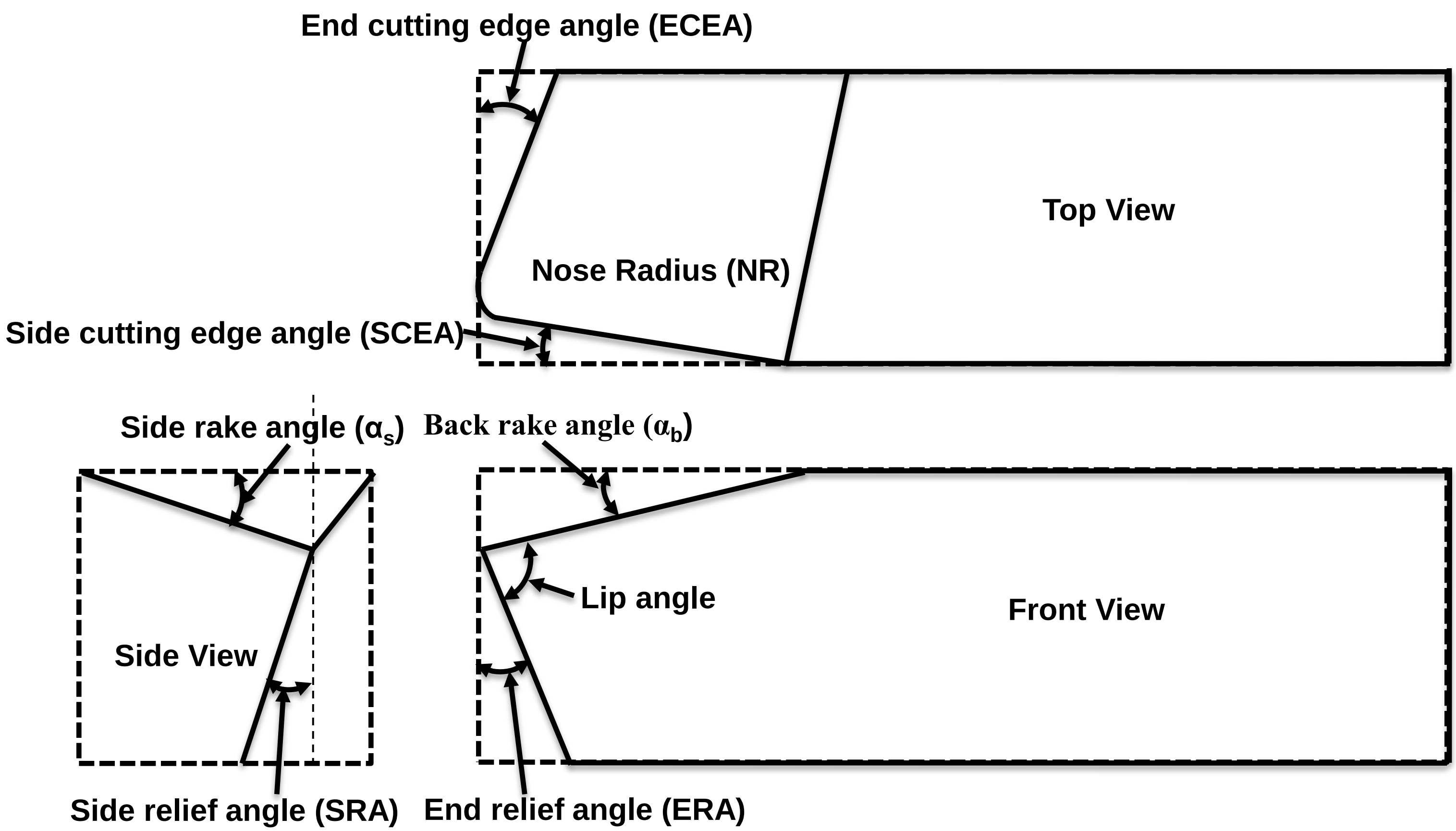
Source: " Manufacturing Processes for Engineering Materials", 4th edition, Kalpakjian, Schmid, Prentice Hall 2003

Single Point Cutting Tool Geometry

Geometry of positive rake single point cutting tool



Geometry of negative rake single point cutting tool



Significance of Rake and Relief Angles

The Rake Angle ***Click for video***

Cutting tool angles and their significance

Back rake angle:

•The back rake angle is the angle between the face of the tool and a line parallel to the base of the shank in a plane parallel to the side cutting edge.

•The back rake angle affects the ability of the tool to shear the work material and form chip.

Side Rake Angles:

•It is the angle by which the face of the tool is inclined side ways.

The Rake Angle:

The rake angle is always at the topside of the tool.

The side rake angle and the back rake angle combine to form the effective rake angle. This is also called true rake angle or resultant rake angle of the tool.

The basic tool geometry is determined by the rake angle of the tool.

Rake angle has two major effects during the metal cutting process.

One major effect of rake angle is its influence on tool strength. A tool with negative rake will withstand far more loading than a tool with positive rake.

The other major effect of rake angle is its influence on cutting pressure. A tool with a positive rake angle reduces cutting forces by allowing the chips to flow more freely across the rake surface.

Cutting tool angles and their significance

Cutting tool angles and their significance

The rake angle has the following function:

- It allows the chip to flow in convenient direction.
- It reduces the cutting force required to shear the metal and consequently helps to increase the tool life and reduce the power consumption. It provides keenness to the cutting edge.
- It improves the surface finish.

Positive Rake:

•Positive rake or increased rake angle reduces compression, the forces, and the friction, yielding a thinner, less deformed and cooler chip.

•But increased rake angle reduces the strength of the tool section, and heat conduction capacity.

•Some areas of cutting where positive rake may prove more effective are, when cutting tough, alloyed materials that tend to work-harden, such as certain stainless steels, when cutting soft or gummy metals, or when low rigidity of workpiece, tooling, machine tool, or fixture allows chatter to occur.

•The shearing action and free cutting of positive rake tools will often eliminate problems in these areas.

Cutting tool angles and their significance

Negative Rake:

- To provide greater strength at the cutting edge and better heat conductivity, zero or negative rake angles are employed on carbide, ceramic, polycrystalline diamond, and polycrystalline cubic boron nitride cutting tools.
- These materials tend to be brittle, but their ability to hold their superior hardness at high temperature results in their selection for high speed and continuous machining operation.
- Negative rakes increases tool forces but this is necessary to provide added support to the cutting edge. This is particularly important in making intermittent cuts and in absorbing the impact during the initial engagement of the tool and work.
- Negative rakes are recommended on tool which does not possess good toughness (low transverse rupture strength).
- Thus negative rake (or small rake) causes high compression, tool force, and friction, resulting in highly deformed, hot chip.

The rake angle for a tool depends on the following factors:

- **Type of material being cut**: A harder material like cast iron may be machined by smaller rake angle than that required by soft material like mid steel or aluminum.
- **Type of tool material**: Tool material like cemented carbide permits turning at very high speed. At high speeds rake angle has little influence on cutting pressure. Under such condition the rake angle can minimum or even negative rake angle is provided to increase the tool strength.
- **Depth of cut**: In rough turning, high depth of cut is given to remove maximum amount of material. This means that the tool has to withstand severe cutting pressure. So the rake angle should be decreased to increase the lip angle that provides the strength to the cutting edge.
- **Rigidity of the tool holder and machine**: An improperly supported tool on old or worn out machine cannot take up high cutting pressure. So while machining under the above condition, the tool used should have larger rake angle.

Relief Angles

- Relief angles are provided to minimize physical interference or rubbing contact with machined surface and the work piece.
- Relief angles are for the purpose of helping to eliminate tool breakage and to increase tool life.
- If the relief angle is too large, the cutting tool may chip or break. If the angle is too small, the tool will rub against the workpiece and generate excessive heat and this will in turn, cause premature dulling of the cutting tool.
- Small relief angles are essential when machining hard and strong materials and they should be increased for the weaker and softer materials.
- A smaller angle should be used for interrupted cuts or heavy feeds, and a larger angle for semi-finish and finish cuts.

Side relief angle: The Side relief angle prevents the side flank of the tool from rubbing against the work when longitudinal feed is given. Larger feed will require greater side relief angle.

End relief angle: The End relief angle prevents the side flank of the tool from rubbing against the work. A minimum relief angle is given to provide maximum support to the tool cutting edge by increasing the lip angle. The front clearance angle should be increased for large diameter works.

Cutting tool angles and their significance

Side cutting edge angle:

The following are the advantages of increasing this angle:

- It increases tool life as, for the same depth of cut; the cutting force is distributed on a wider surface.
- It diminishes the chip thickness for the same amount of feed and permits greater cutting speed.
- It dissipates heat quickly for having wider cutting edge.

•The side cutting edge angle of the tool has practically no effect on the value of the cutting force or power consumed for a given depth of cut and feed.

•Large side cutting edge angles are lightly to cause the tool to chatter.

End cutting edge angle:

The function of end cutting edge angle is to prevent the trailing front cutting edge of the tool from rubbing against the work. A large end cutting edge angle unnecessarily weakens the tool.

It varies from 8 to 15 degrees.

Cutting tool angles and their significance

Nose radius:

The nose of a tool is slightly rounded in all turning tools.

The function of nose radius is as follows:

- Greater nose radius clears up the feed marks caused by the previous shearing action and provides better surface finish.
- All finish turning tool have greater nose radius than rough turning tools.
- It increases the strength of the cutting edge, tends to minimize the wear taking place in a sharp pointed tool with consequent increase in tool life.
- Accumulation heat is less than that in a pointed tool which permits higher cutting speeds.

Tool signature

It is the system of designating the principal angles of a single point cutting tool.

The signature is the sequence of numbers listing the various angles, in degrees, and the size of the nose radius.

There are several systems available like American standard system (ASA), Orthogonal rake system (ORS), Normal rake system (NRS), and Maximum rake system (MRS).

The system most commonly used is American Standard Association (ASA), which is:

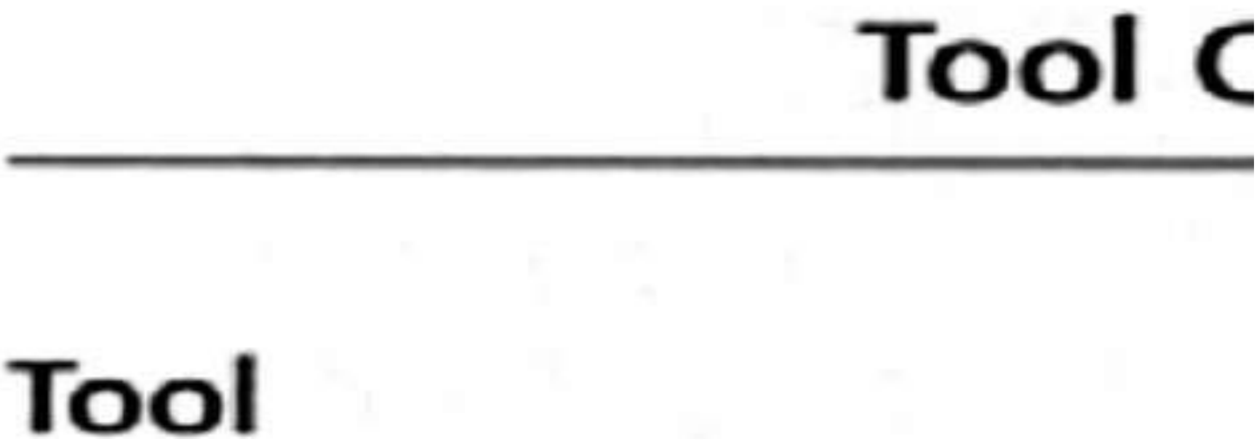
Bake rake angle, Side rake angle, End relief angle, Side relief angle, End cutting Edge angle, Side cutting Edge angle and Nose radius.

Tool signature

For example a tool may designated in the following sequence:

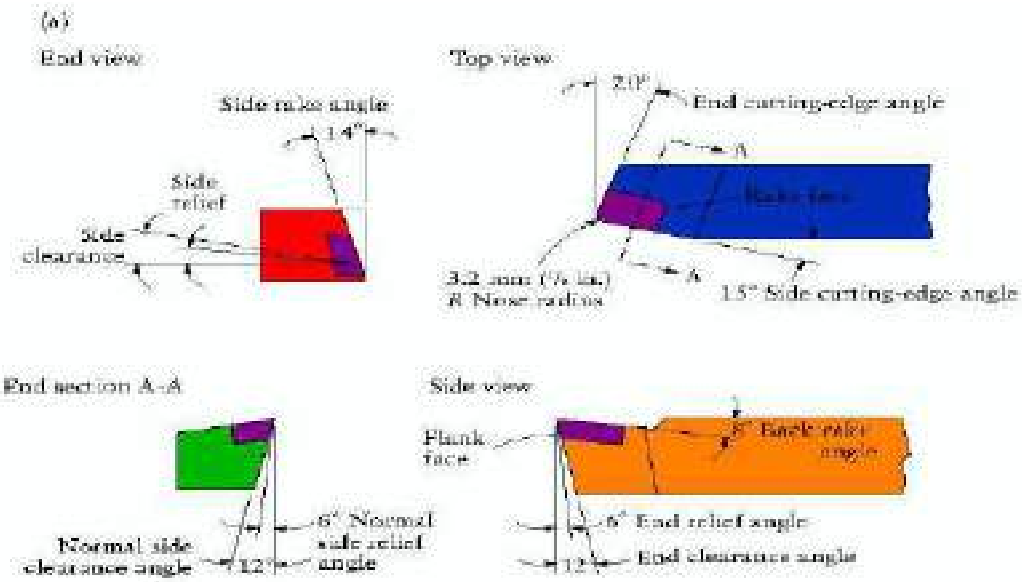
8-14-6-6-6-15-1

1. Bake rake angle is 8
2. Side rake angle is 14
3. End relief angle is 6
4. Side relief angle is 6
5. End cutting Edge angle is 6
6. Side cutting Edge angle is 15
7. Nose radius is 1 mm



Designations for a Right-Handed Cutting Tool

(a)



Tool Signature	Dimensions	Abbreviation
8	Back rake angle	BR
14	Side rake angle	SR
6	End relief angle	ER
12	End clearance angle	. . .
6	Side relief angle	SRF
12	Side clearance angle	. . .
20	End cutting-edge angle	ECEA
15	Side cutting-edge angle	SCEA
1/8	Nose radius	NR

(b)

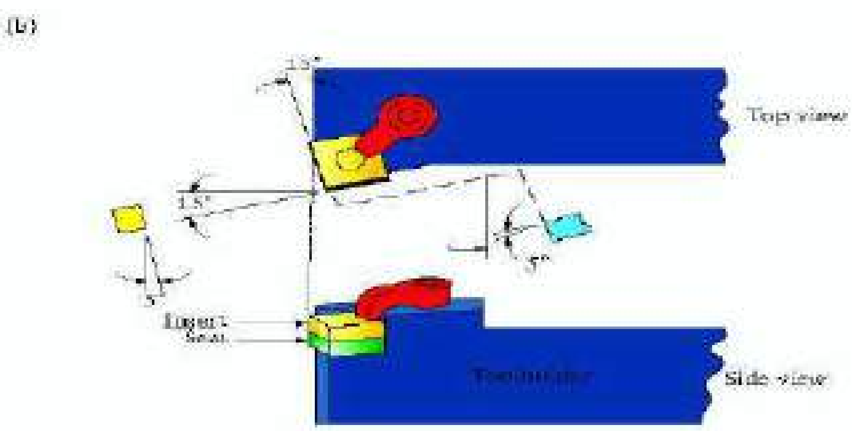


FIGURE: (a) Designations and symbols for a right-hand cutting tool; solid high-speed-steel tools have a similar designation. (b) Square insert in a right-hand toolholder for a turning operation. A wide variety of toolholder is available for holding inserts at various angles. Thus, the angles shown in (a) can be achieved easily by selecting an appropriate insert and toolholder. *Source*: Kennametal, Inc.

THEORY OF METAL CUTTING

- The process of metal removal, a process in which a wedge-shaped tool engages a workpiece to remove a layer of material in the form of a chip, goes back many years.

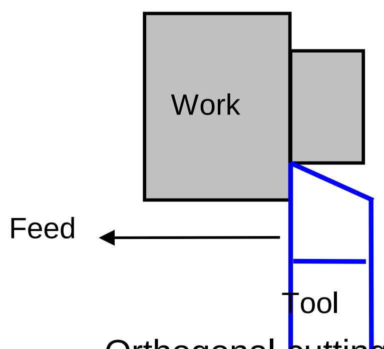
Video showing the wedge-shape of different tools.

- Even with all of the sophisticated equipment and techniques used in today's modern industry, the basic mechanics of forming a chip remain the same.
- As the cutting tool engages the workpiece, the material directly ahead of the tool is sheared and deformed under tremendous pressure. The deformed material then seeks to relieve its stressed condition by fracturing and flowing into the space above the tool in the form of a chip.

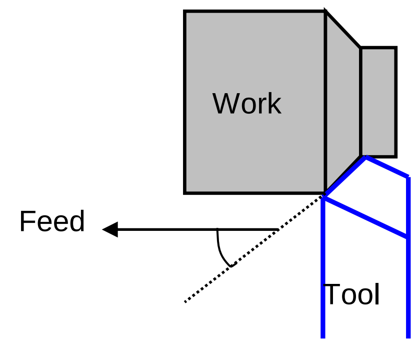
Orthogonal and Oblique Cutting

The two basic methods of metal cutting using a single point tool are the orthogonal (2 D) and oblique (3D). Orthogonal cutting takes place when the cutting face of the tool is 90 degree to the line of action of the tool. If the cutting face is inclined at an angle less than 90 degree to the line of action of the tool, the cutting action is known as oblique.

Orthogonal and Oblique Cutting



Orthogonal cutting



Oblique cutting

Orthogonal Cutting:

- The cutting edge of the tool remains normal to the direction of tool feed or work feed.
- The direction of the chip flow velocity is normal to the cutting edge of the tool.
- Here only two components of forces are acting: Cutting Force and Thrust Force. So the metal cutting may be considered as a two dimensional cutting.

Oblique Cutting:

- The cutting edge of the tool remains inclined at an acute angle to the direction of tool feed or work feed.
- The direction of the chip flow velocity is at an angle with the normal to the cutting edge of the tool. The angle is known as chip flow angle.
- Here three components of forces are acting: Cutting Force, Radial force and Thrust Force or feed force. So the metal cutting may be considered as a three dimensional cutting.
- The cutting edge being oblique, the shear force acts on a larger area and thus tool life is increased.

Oblique Cutting

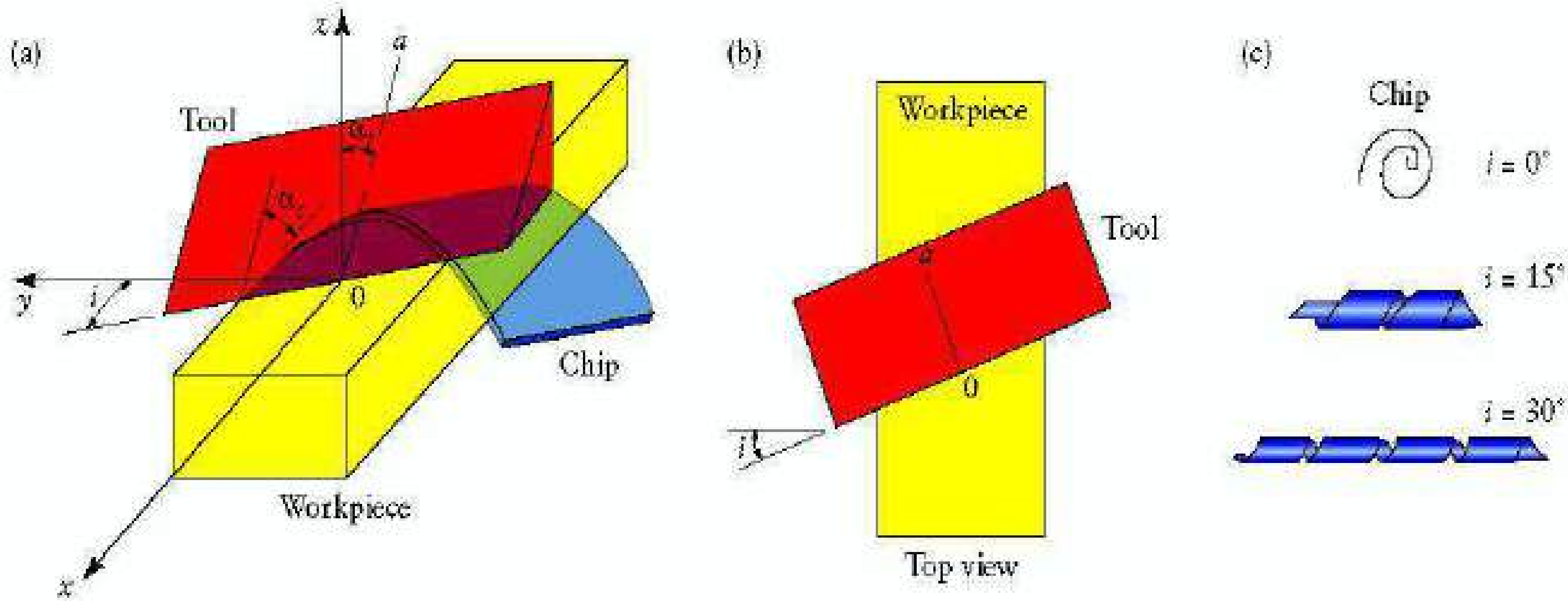


FIGURE (a) Schematic illustration of cutting with an oblique tool. (b) Top view, showing the inclination angle *i*. (c) Types of chips produced with different inclination angles

Source: " Manufacturing Processes for Engineering Materials", 4^{th} edition, Kalpakjian, Schmid, Prentice Hall 2003

Mechanics of orthogonal metal cutting

During metal cutting, the metal is severely compressed in the area in front of the cutting tool.

This causes high temperature shear, and plastic flow if the metal is ductile.

When the stress in the workpiece just ahead of the cutting tool reaches a value exceeding the ultimate strength of the metal, particles will shear to form a chip element, which moves up along the face of the work.

The outward or shearing movement of each successive element is arrested by work hardening and the movement transferred to the next element.

The process is repetitive and a continuous chip is formed.

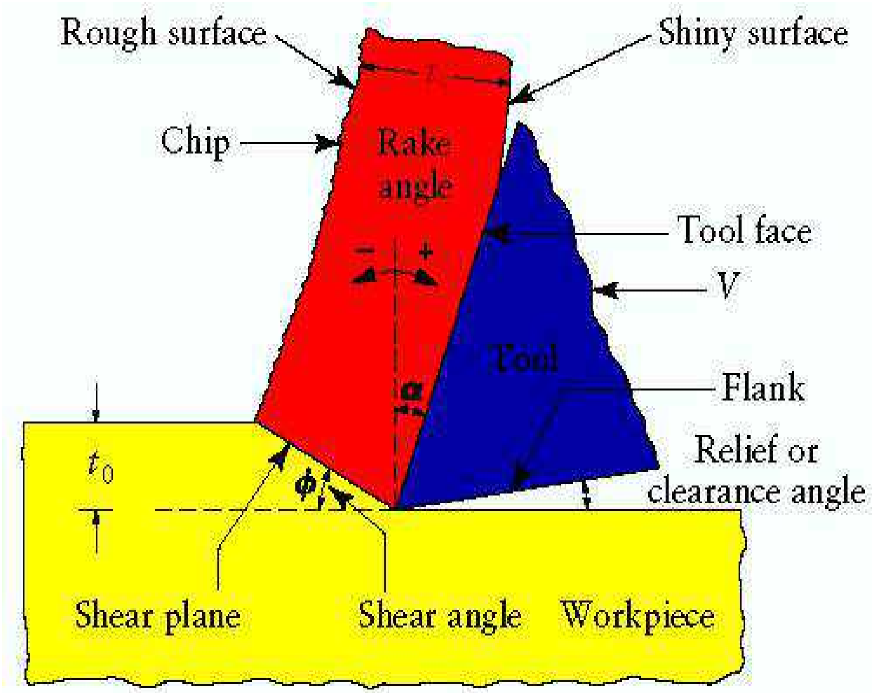
The plane along which the element shears, is called shear plane.

Click for video

Assumptions in orthogonal metal cutting

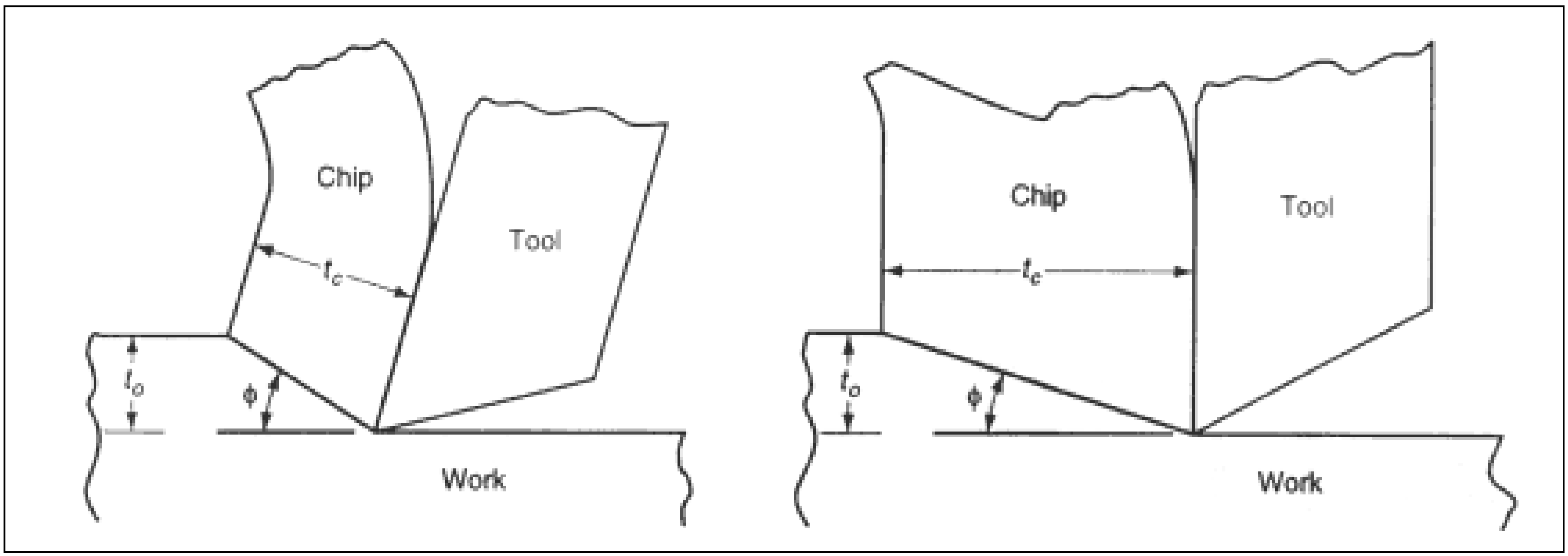
- No contact at the flank i.e. the tool is perfectly sharp.
- No side flow of chips i.e. width of the chips remains constant.
- Uniform cutting velocity.
- A continuous chip is produced with no built up edge.
- The chip is considered to be held in equilibrium by the action of the two equal and opposite resultant forces R and R/ and assume that the resultant is collinear.

Metal cutting Terminologies



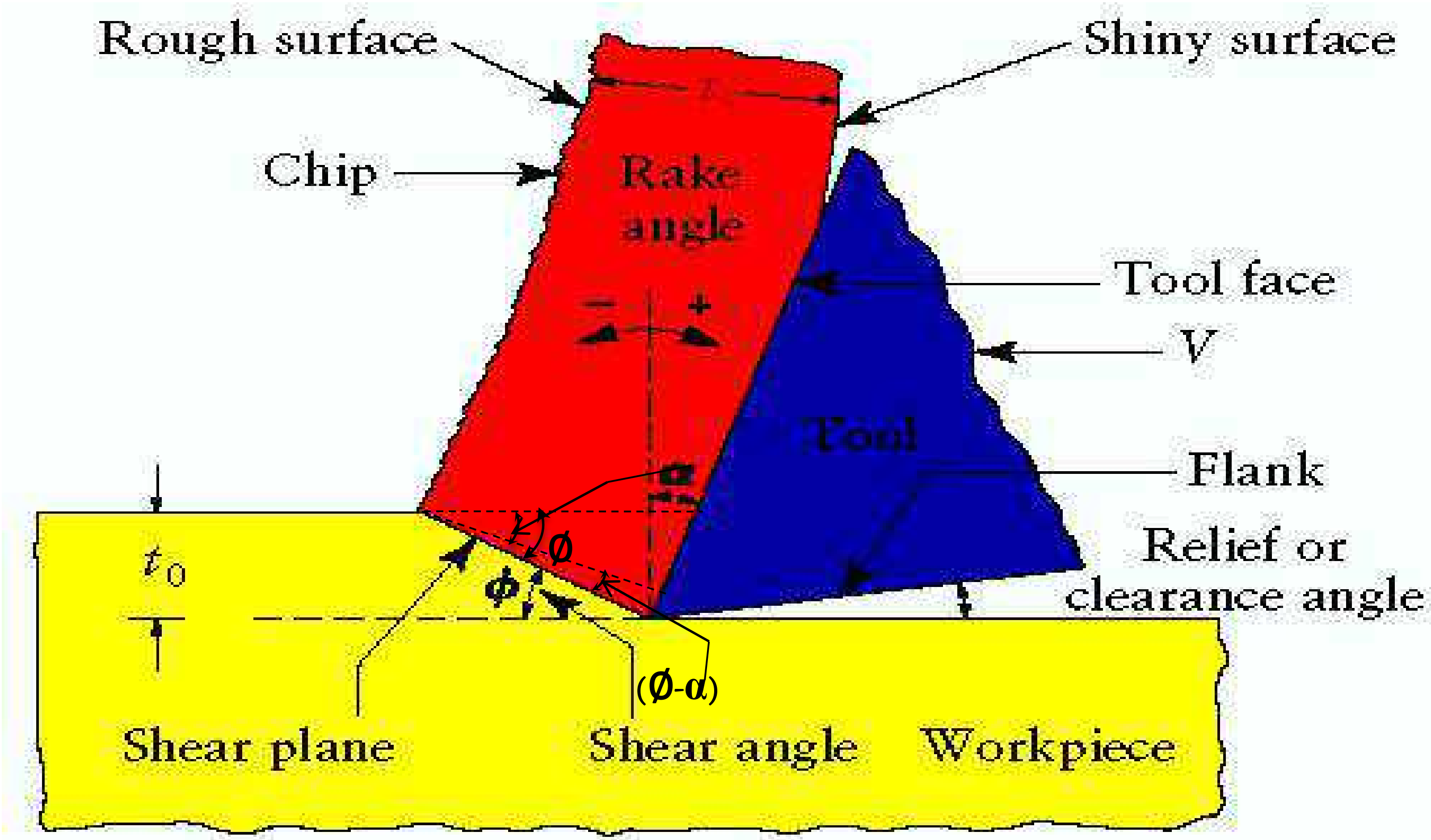
Schematic illustration of a two-dimensional cutting process (also called *orthogonal cutting*).

Source: " Manufacturing Processes for Engineering Materials", 4th edition, Kalpakjian, Schmid, Prentice Hall 2003



Chip thickness ratios

The outward flow of the metal causes the chip to be thicker after the separation from the parent metal. That is the chip produced is thicker than the depth of cut.

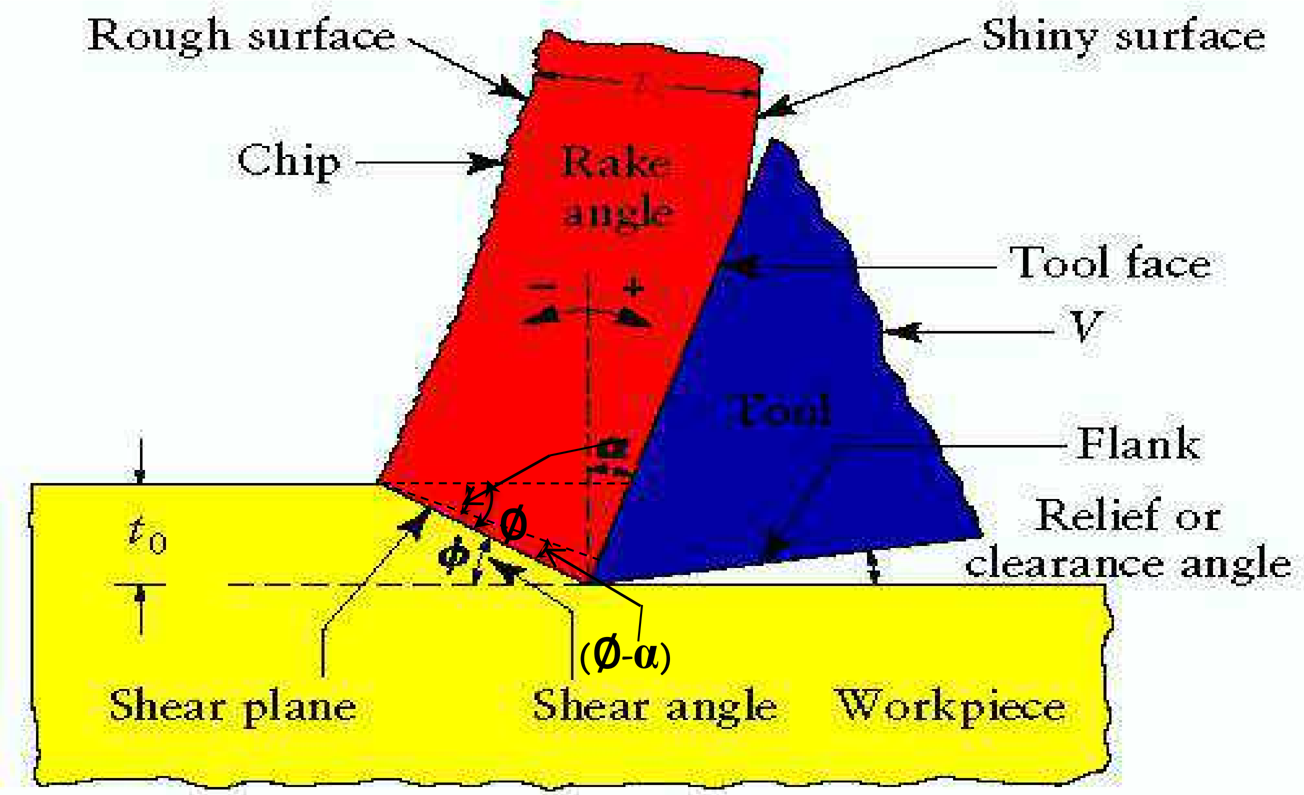


Chip thickness ratio

Chip thickness ratio

$$r = \frac{t_o}{t_c} = \frac{l_s \sin\phi}{l_s \cos(\phi-\alpha)}$$

$$r = \frac{\sin\phi}{\cos(\phi-\alpha)}$$



$$r = \frac{1}{r_c} = \frac{t_o}{t_c} = \frac{\sin\phi}{\cos(\phi-\alpha)}$$

Rearranging:

$$\tan\phi = \frac{r\cos\alpha}{1-r\sin\alpha}$$

Velocity Relationship

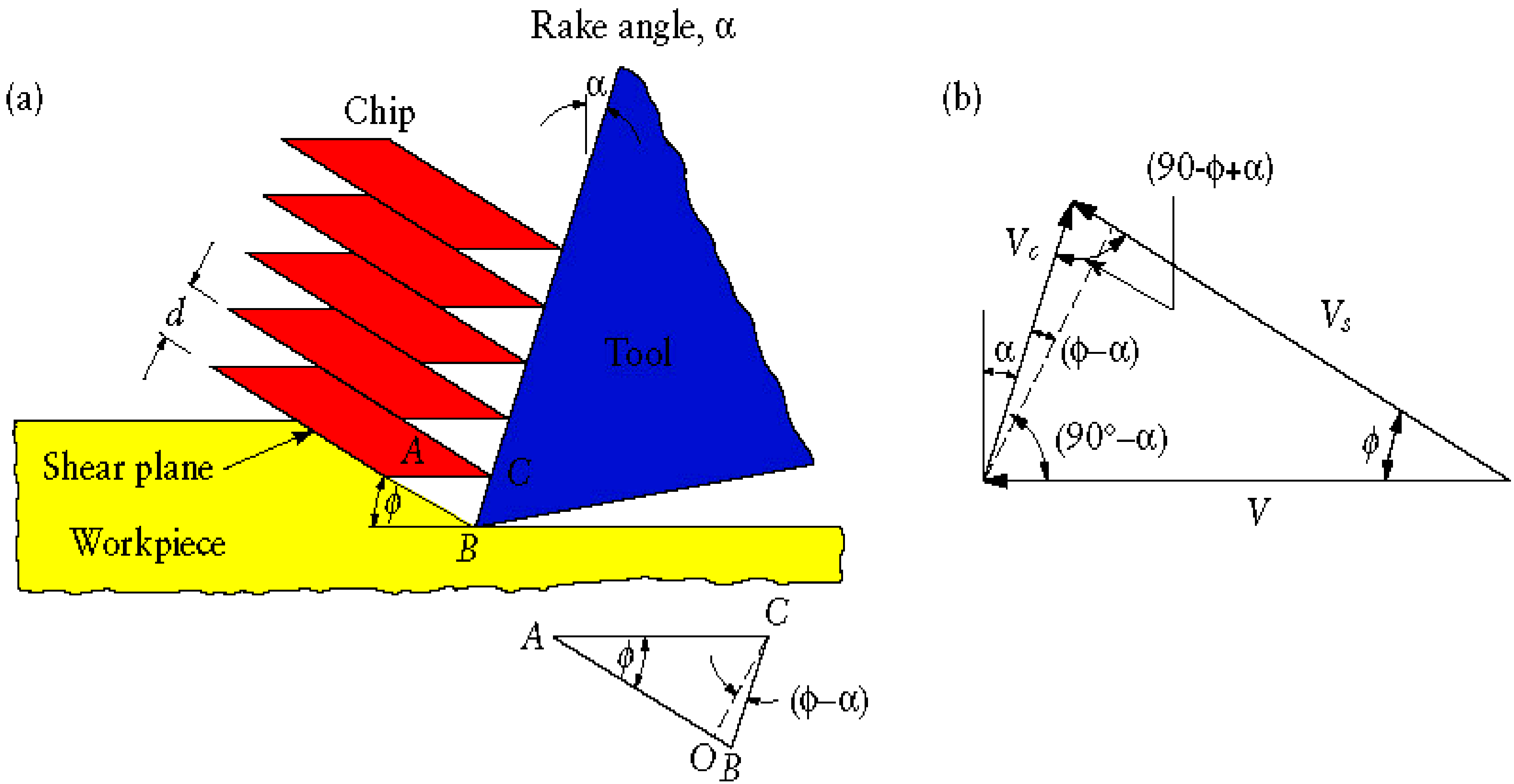
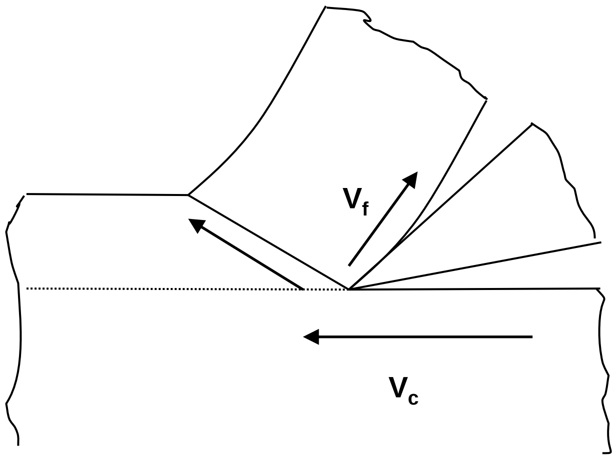
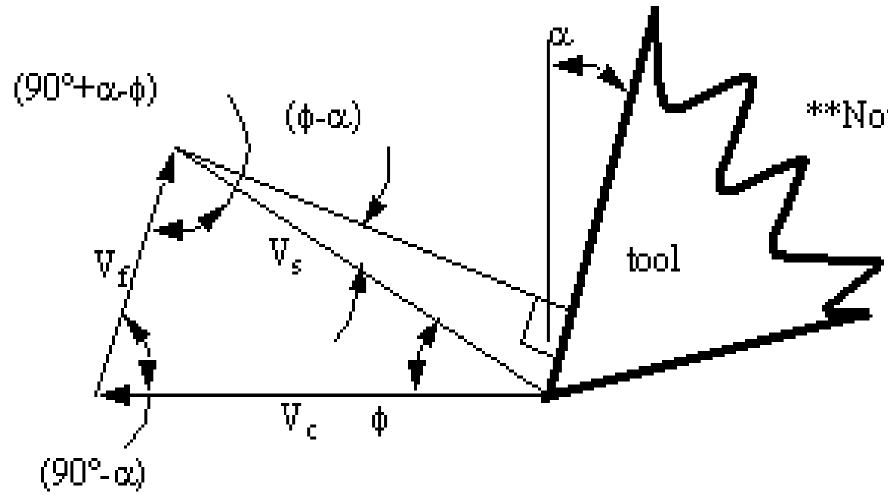


FIGURE (a) Schematic illustration of the basic mechanism of chip formation in cutting. (b) Velocity diagram in the cutting zone

Source " Manufacturing Processes for Engineering Materials", 4th edition, Kalpakjian, Schmid, Prentice Hall 2003

Velocity Relationship





where,

V_c = cutting velocity (ft./min.) - as set or measured on
V_s = shearing velocity
V_f = frictional velocity

Analytically,

$$\frac{v_c}{\sin(90-(\phi-\alpha))} = \frac{v_f}{\sin\phi} = \frac{v_s}{\sin(90-\alpha)}$$

$$\frac{v_c}{\cos(\phi-\alpha)} = \frac{v_f}{\sin\phi} = \frac{v_s}{\cos\alpha}$$

$$\boxed{v_f = \frac{v_c \sin\phi}{\cos(\phi-\alpha)}}$$

$$\left[r = \frac{\sin\phi}{\cos(\phi-\alpha)}\right]$$

$$v_f = v_c \times r$$

$$\boxed{v_s = \frac{v_c \cos\alpha}{\cos(\phi-\alpha)}}$$

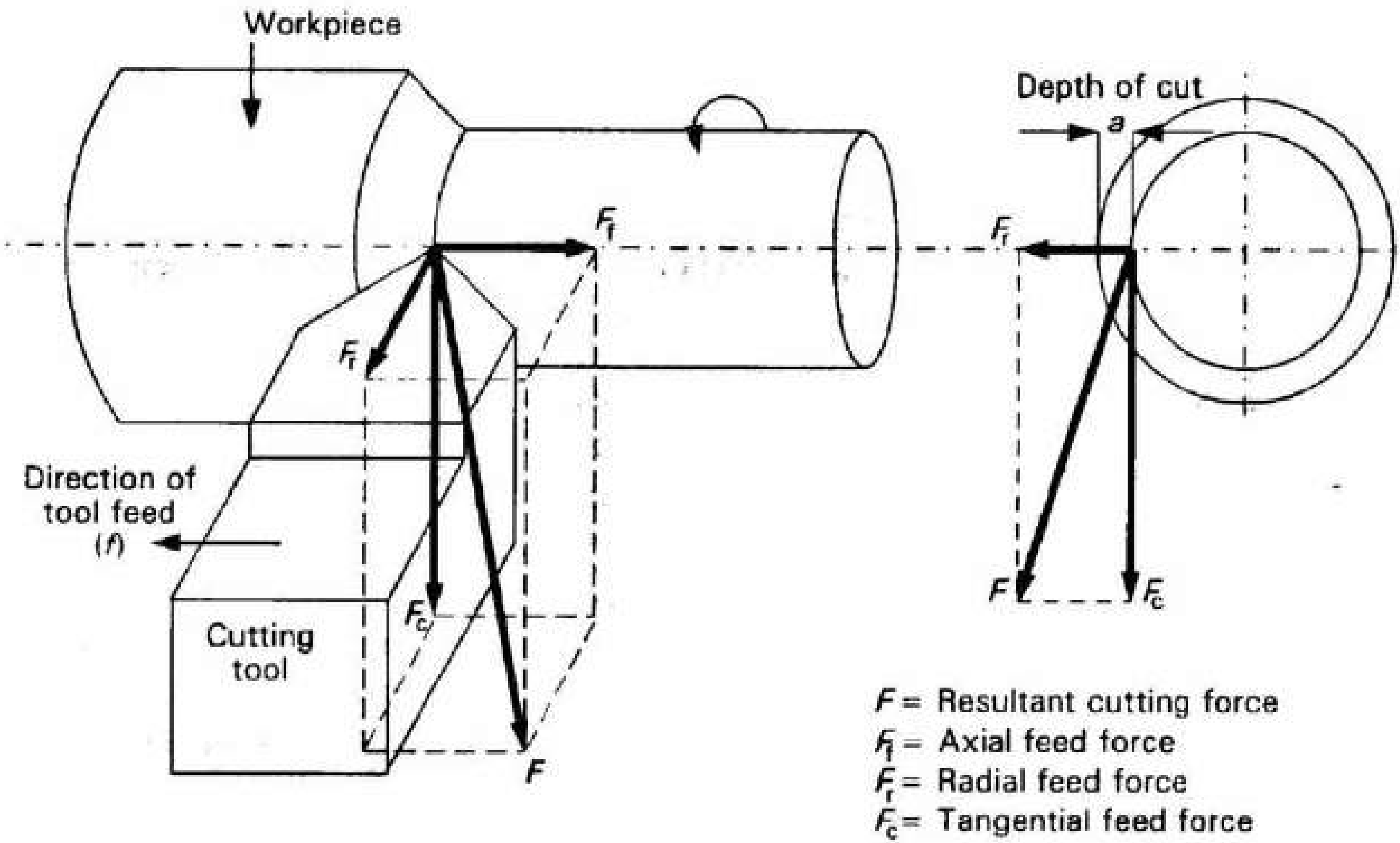
$$\text{Volume of material per unit time} = \text{Volume of material flowing up the chip}$$

$$\Rightarrow v_c \times t_0 \times w = v_f \times t_c \times w$$

$$\Rightarrow v_f = v_c \times r \quad \text{As, } r = \frac{t_0}{t_c}$$

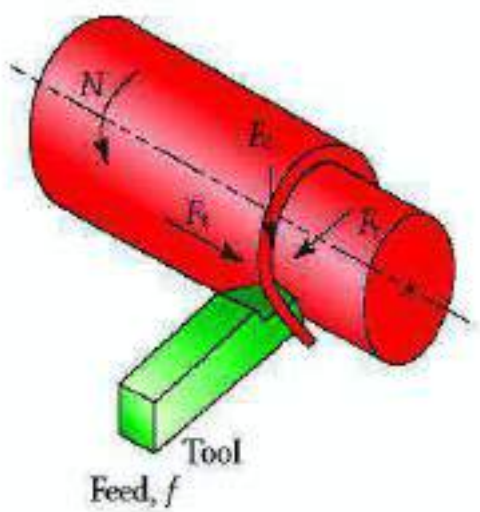
Cutting forces

The force system in general case of conventional turning process



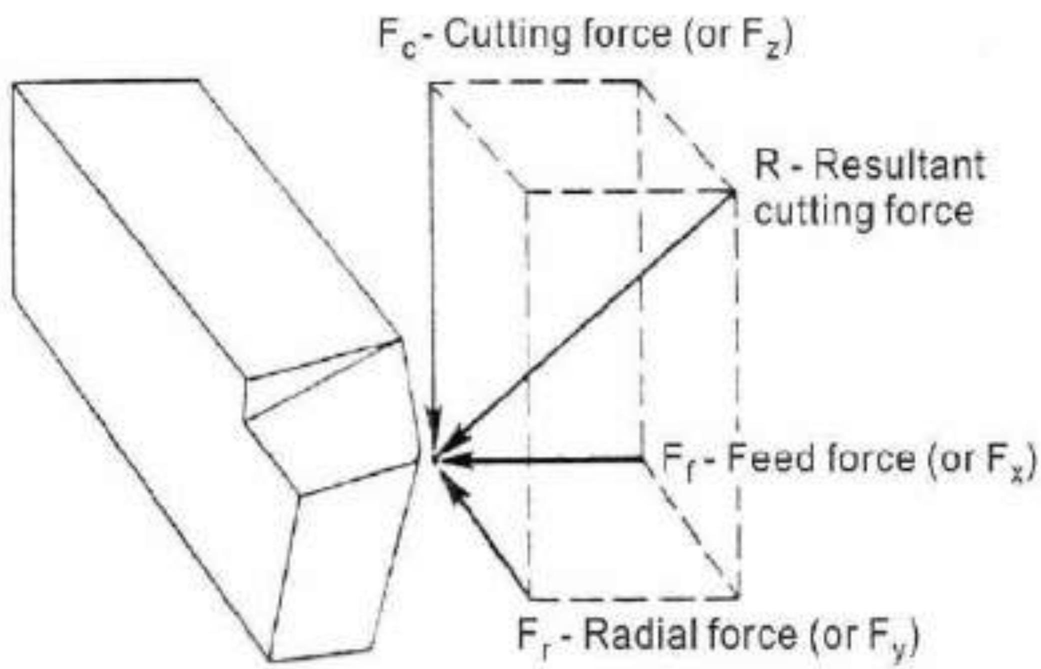
Primary forces involved in single-edge cutting. (Courtesy of Sandvik Coromant, Halesowen.)

Cutting forces



The largest magnitude is the vertical force F_c which in turning is larger than feed force F_f, and F_f is larger than radial force F_r.

For orthogonal cutting system F_r is made zero by placing the face of cutting tool at 90 degree to the line of action of the tool.



$$\overline{R} = \overline{F}_x + \overline{F}_y + \overline{F}_z$$
$$= \overline{F}_c + \overline{F}_f + \overline{F}_r$$

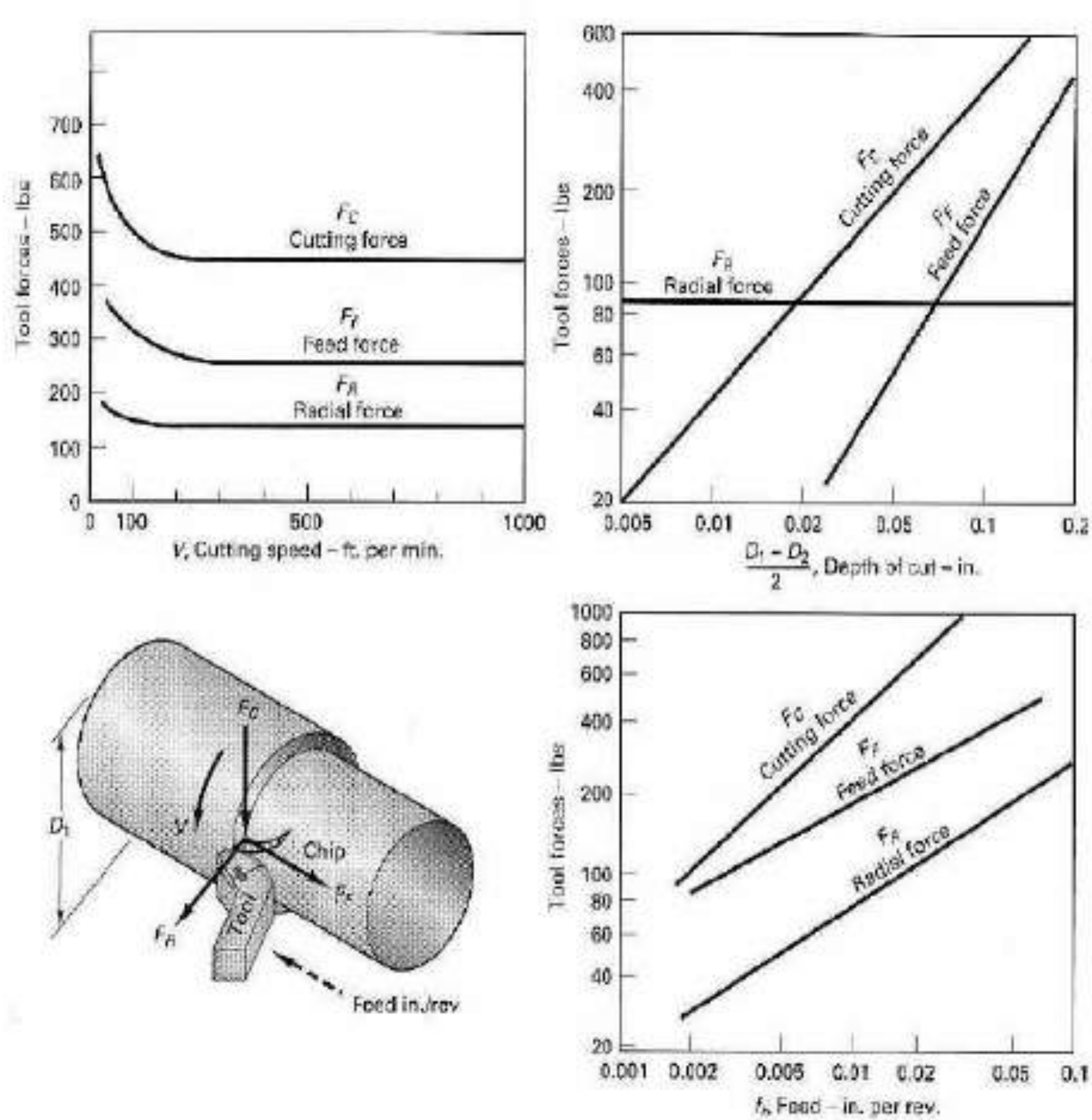
Tangential Force (Cutting Force)
Feed Force
Radial Force

In orthogonal cutting

$$\overline{R} = \overline{F}_c + \overline{F}_t$$

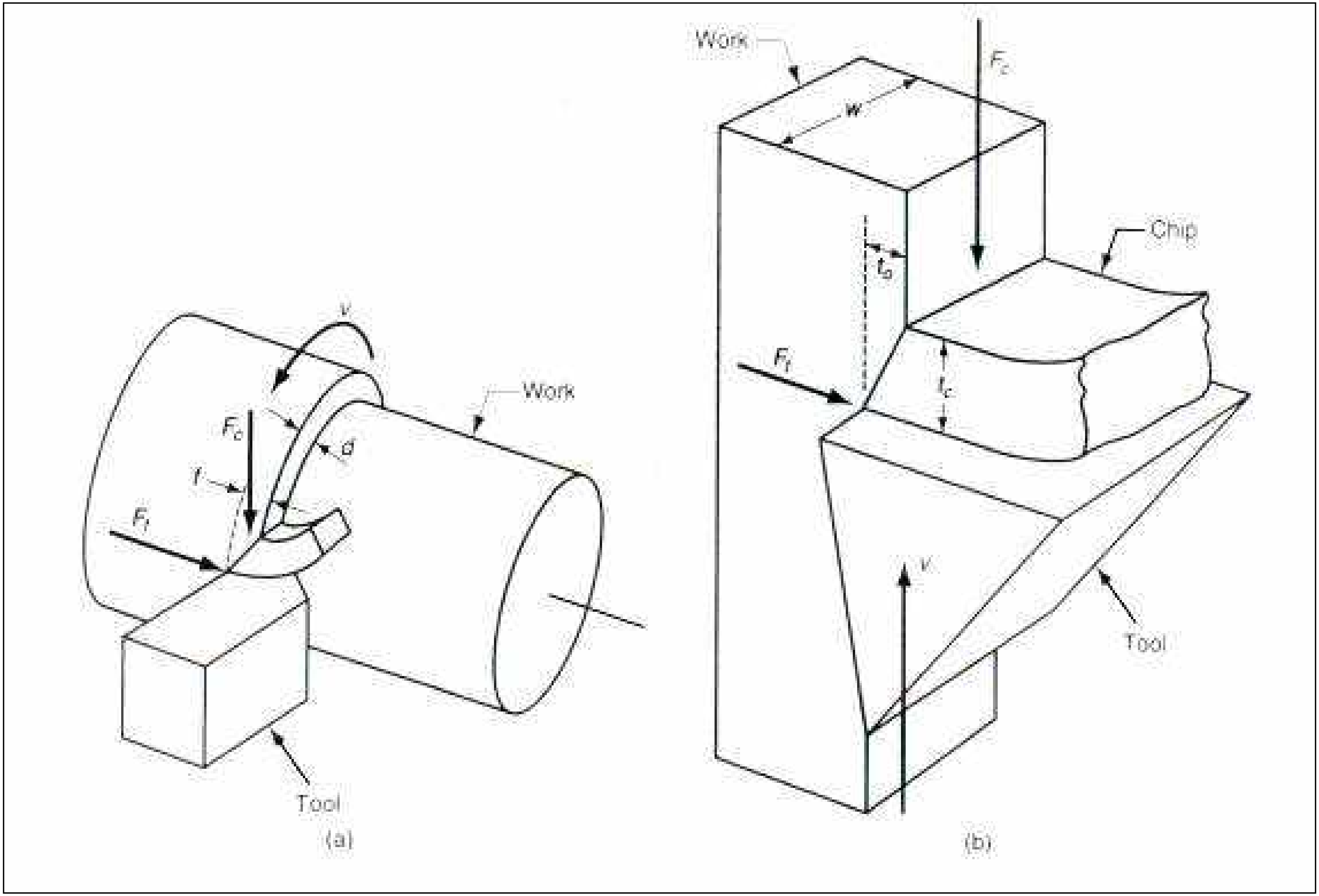
Thrust Force

Cutting forces in oblique cutting

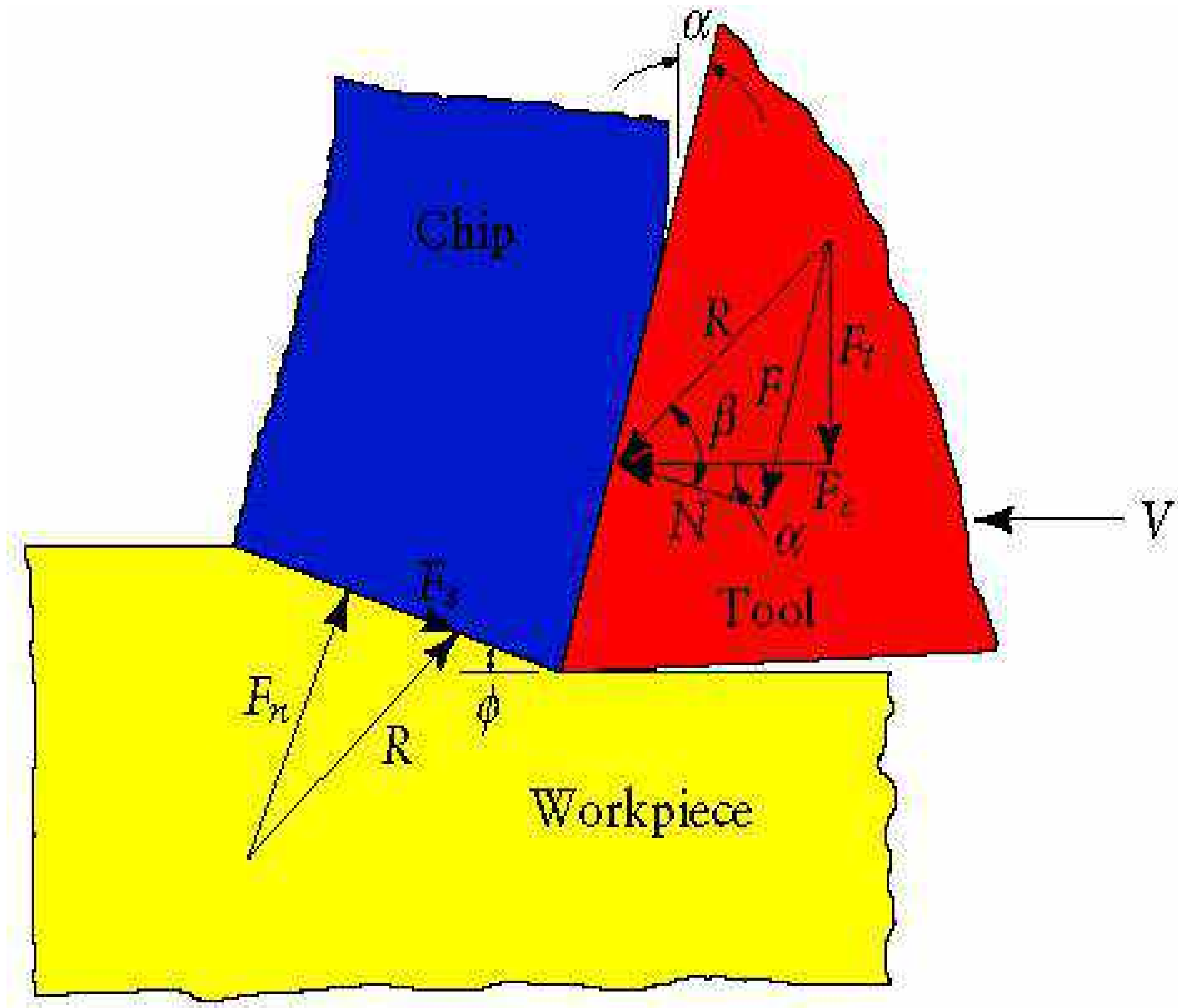


From **DeGarmo, E. P., J. T. Black, and R. A. Kohser**, Materials and processes in Manufacturing, *PHI*.

The forces in orthogonal cutting (turning)



Forces acting on Chip in two-dimensional cutting



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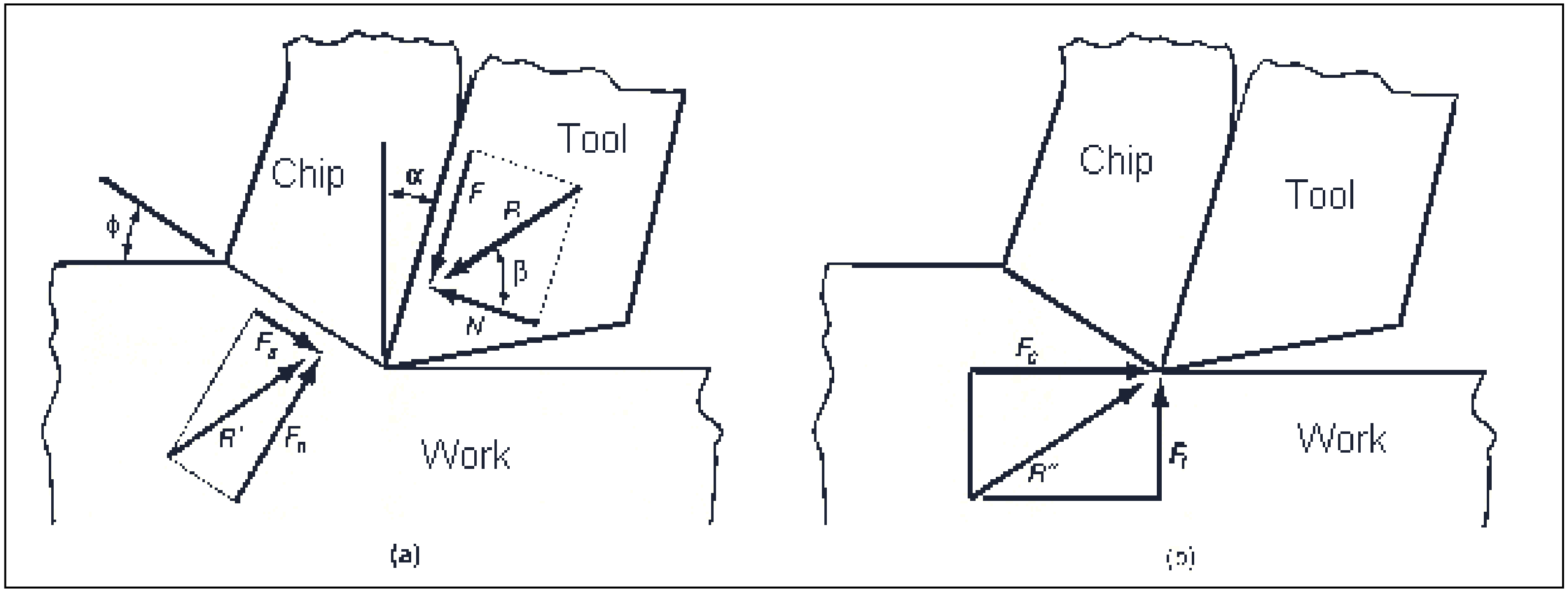
The forces acting on the chip in orthogonal cutting



$$\vec{R}' = \vec{N} + \vec{F}$$

$$\vec{R} = \vec{F}_S + \vec{F}_N$$

F_s = Shear Force, which acts along the shear plane, is the resistance to shear of the metal in forming the chip.

F_n = Force acting normal to the shear plane, is the backing up force on the chip provided by the workpiece.

F = Frictional resistance of the tool acting against the motion of the chip as it moves upward along the tool.

N = Normal to the chip force, is provided by the tool.

It is assumed that the resultant forces R & R/ are equal and opposite in magnitude and direction. Also they are Collinear. Therefore for the purpose of analysis the chip is regarded as an independent body held in mechanical equilibrium by the action of two equal and opposite forces R, which the workpiece exerts upon the chip and R/ which the tool exerts upon the chip.

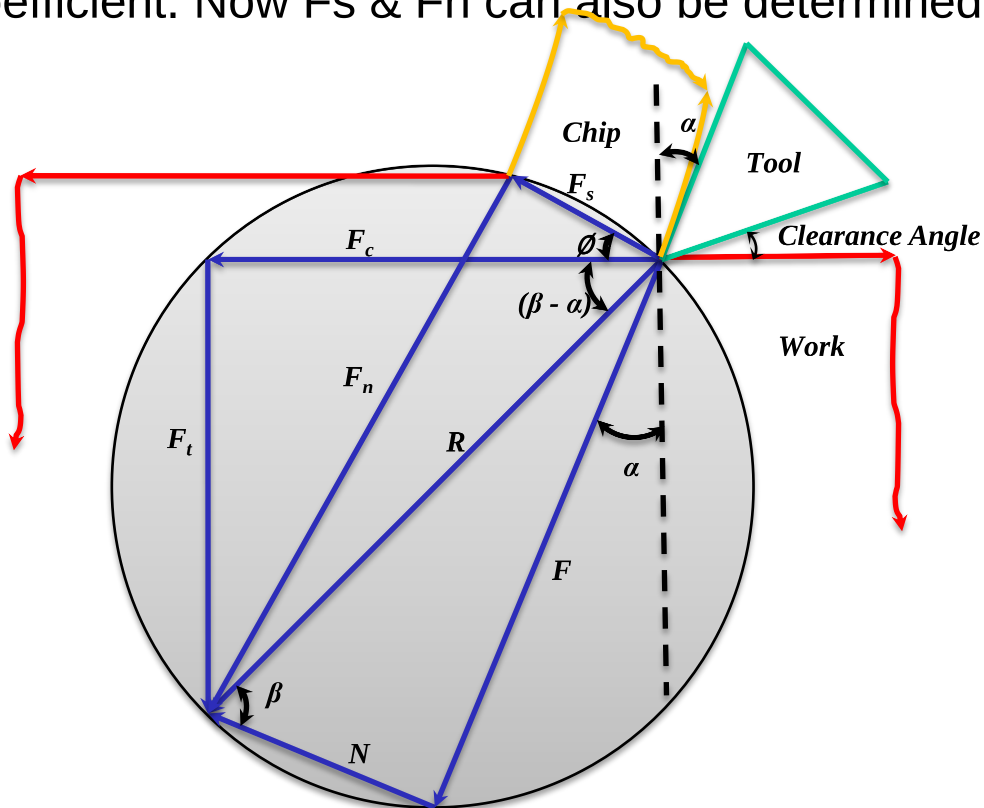
Merchant's Circle Diagram

The following is a circle diagram. Known as Merchant's circle diagram, which is convenient to determine the relation between the various forces and angles. In the diagram two force triangles have been combined and R and R/ together have been replaced by R. the force R can be resolved into two components F_c and F_t.

Fc and Ft can be determined by force dynamometers.

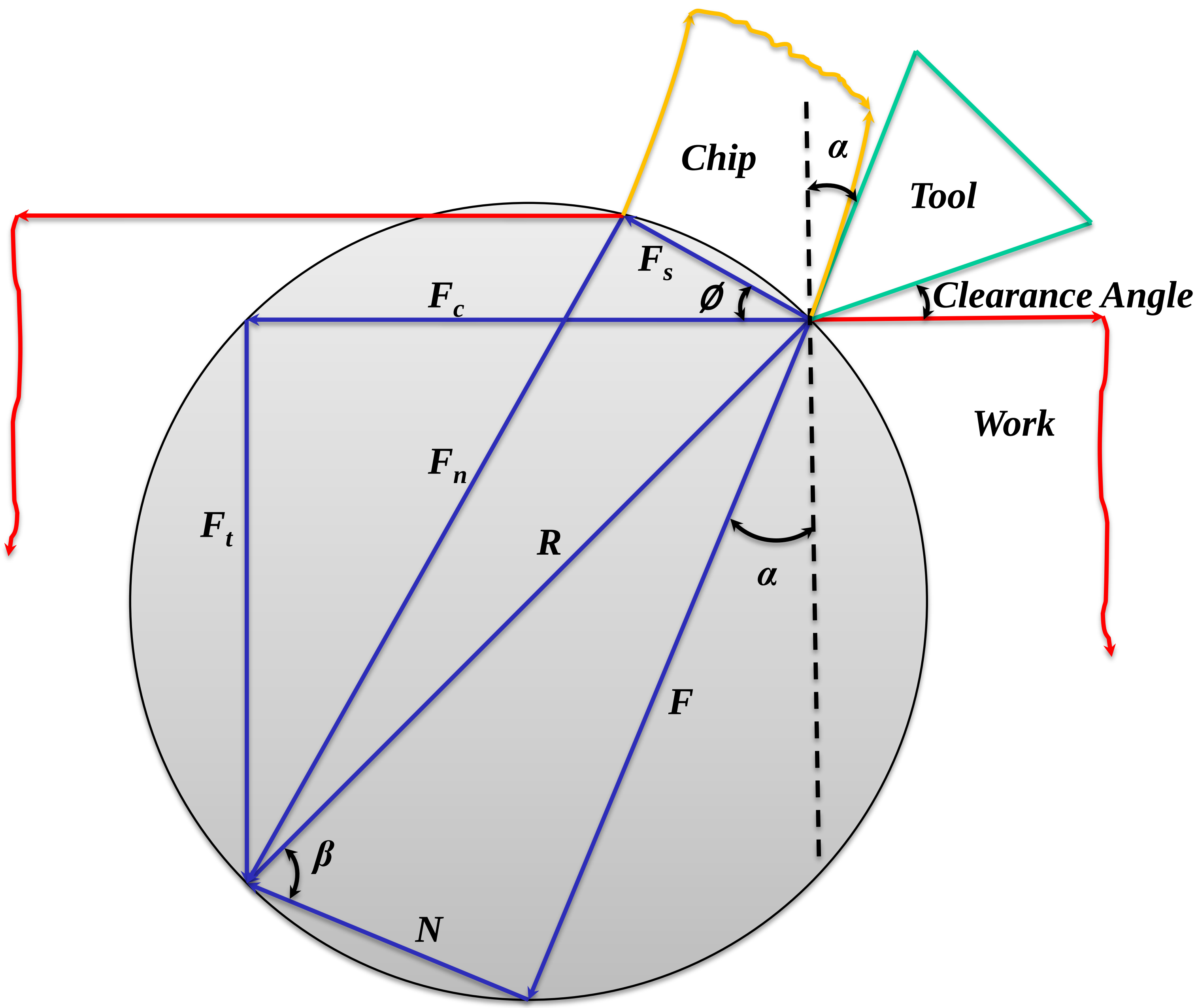
$$\vec{R} = \vec{F}_c + \vec{F}_t$$

The rake angle (α) can be measured from the tool, and forces F and N can then be determined. The shear angle (ϕ) can be obtained from it's relation with chip reduction coefficient. Now Fs & Fn can also be determined.



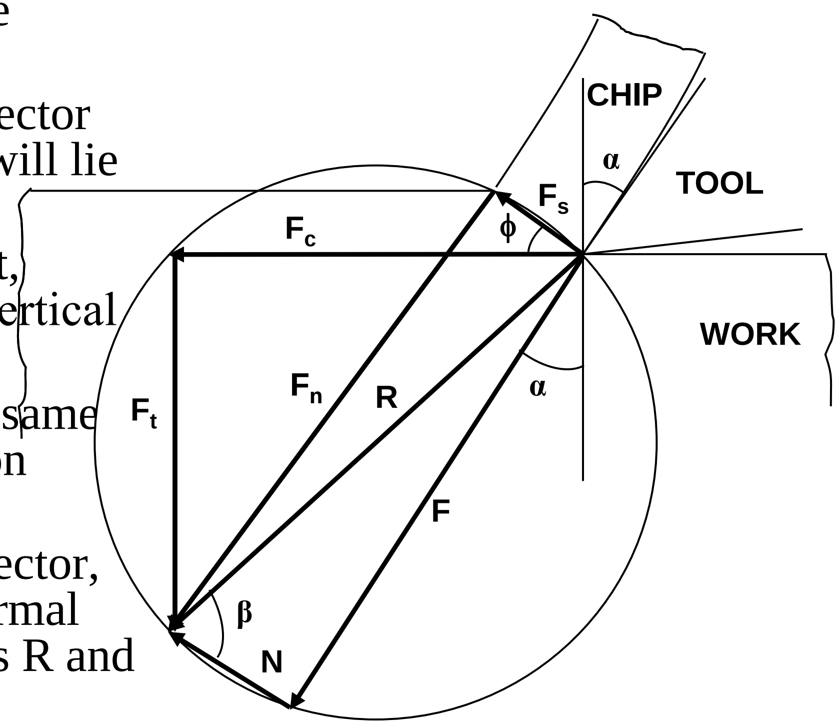
M. Eugene Merchant

The procedure to construct a merchants circle diagram

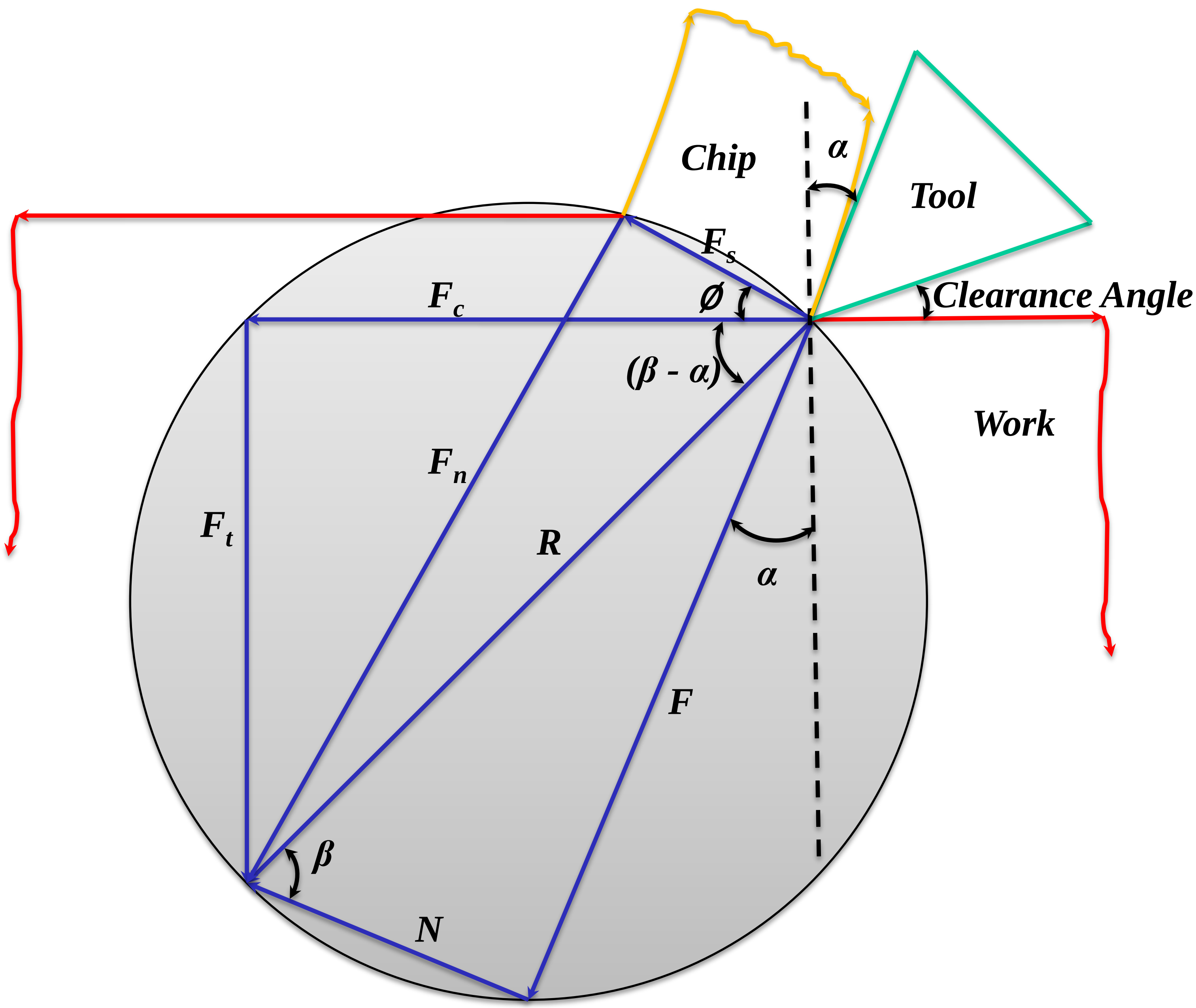


The procedure to construct a merchants circle diagram

- Set up x-y axis labeled with forces, and the origin in the centre of the page. The cutting force (Fc) is drawn horizontally, and the tangential force (Ft) is drawn vertically. (Draw in the resultant (R) of Fc and Ft.
- Locate the centre of R, and draw a circle that encloses vector R. If done correctly, the heads and tails of all 3 vectors will lie on this circle.
- Draw in the cutting tool in the upper right hand quadrant, taking care to draw the correct rake angle (α) from the vertical axis.
- Extend the line that is the cutting face of the tool (at the same rake angle) through the circle. This now gives the friction vector (F).
- A line can now be drawn from the head of the friction vector, to the head of the resultant vector (R). This gives the normal vector (N). Also add a friction angle (**β**) between vectors R and N. Therefore, mathematically, R = Fc + Ft = F + N.
- Draw a feed thickness line parallel to the horizontal axis. Next draw a chip thickness line parallel to the tool cutting face.
- Draw a vector from the origin (tool point) towards the intersection of the two chip lines, stopping at the circle. The result will be a shear force vector (Fs). Also measure the shear force angle between Fs and Fc.
- Finally add the shear force normal (Fn) from the head of Fs to the head of R.
- Use a scale and protractor to measure off all distances (forces) and angles.

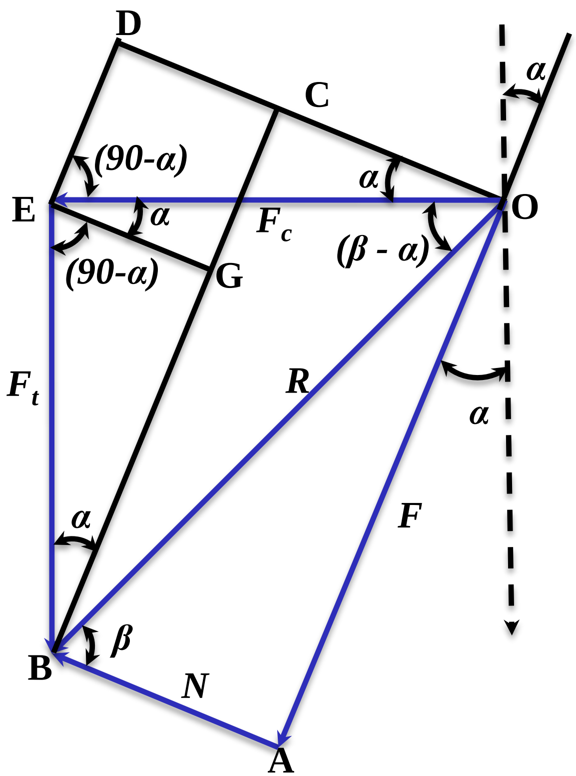


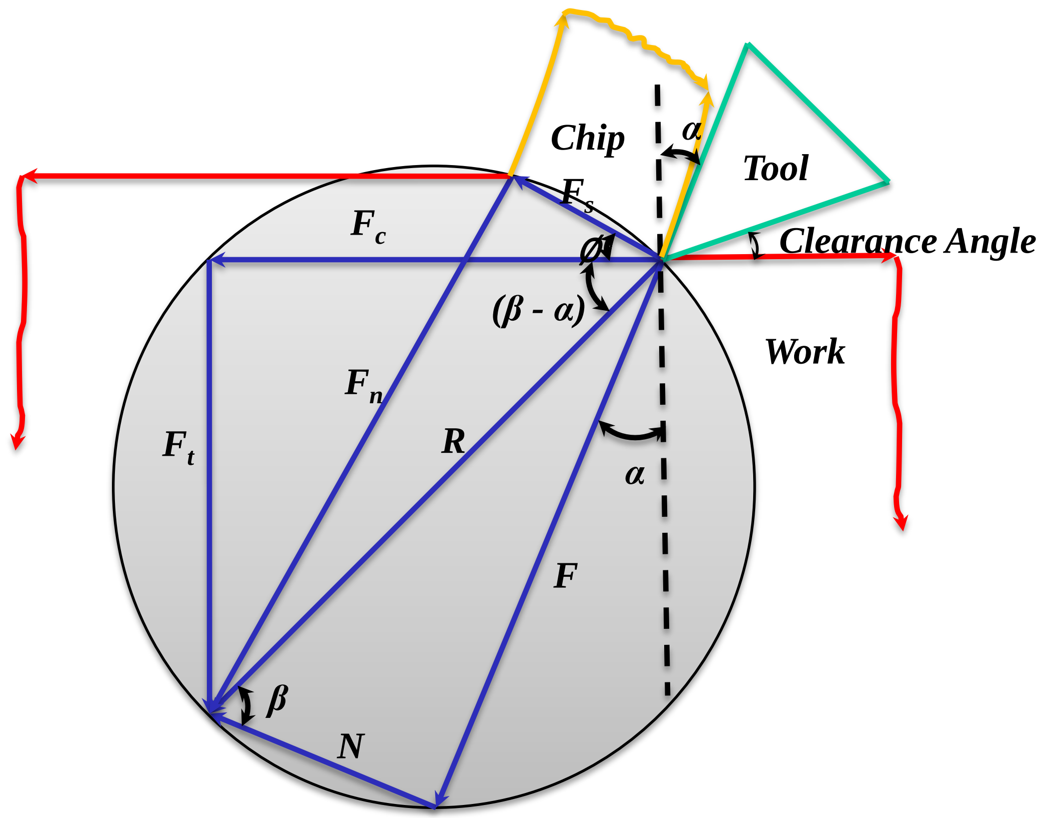
Merchant's Circle Diagram



Relationship of various forces acting on the chip with the horizontal and vertical cutting force from Merchant circle diagram

Frictional Force System





$$F = OA = CB = CG + GB = ED + GB$$

$$\Rightarrow F = F_C \sin\alpha + F_t \cos\alpha$$

$$N = AB = OD - CD = OD - GE$$

$$\Rightarrow N = F_C \cos\alpha - F_t \sin\alpha$$

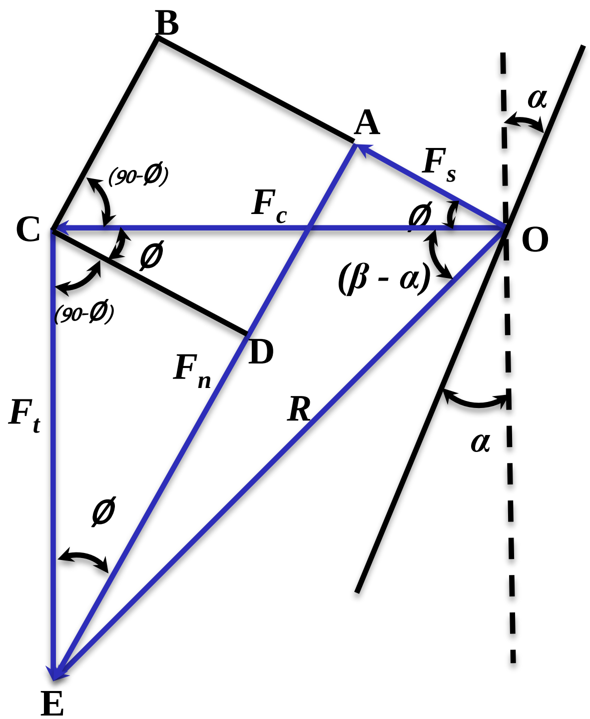
The coefficient of friction

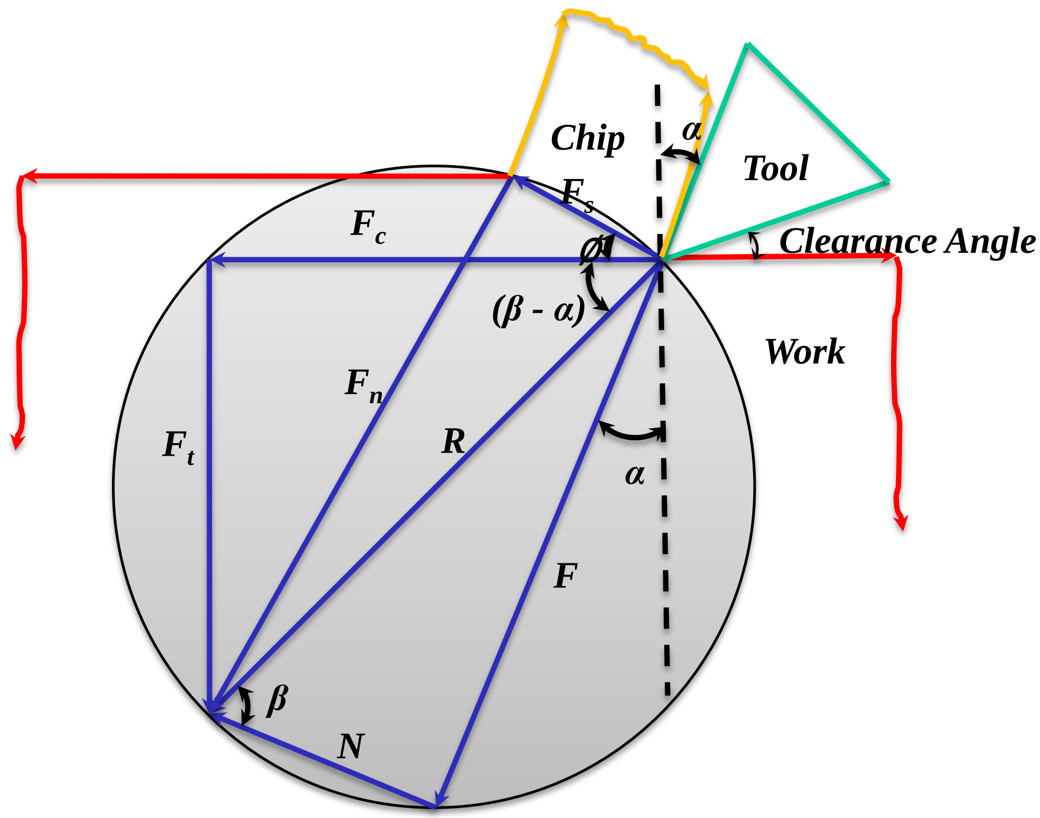
$$\mu = \tan\beta = \frac{F}{N}$$

Where β = *Friction angle*

Relationship of various forces acting on the chip with the horizontal and vertical cutting force from Merchant circle diagram

Shear Force System





$$F_S = OA = OB - AB = OB - CD$$

$$\Rightarrow F_S = F_C \cos\phi - F_t \sin\phi$$

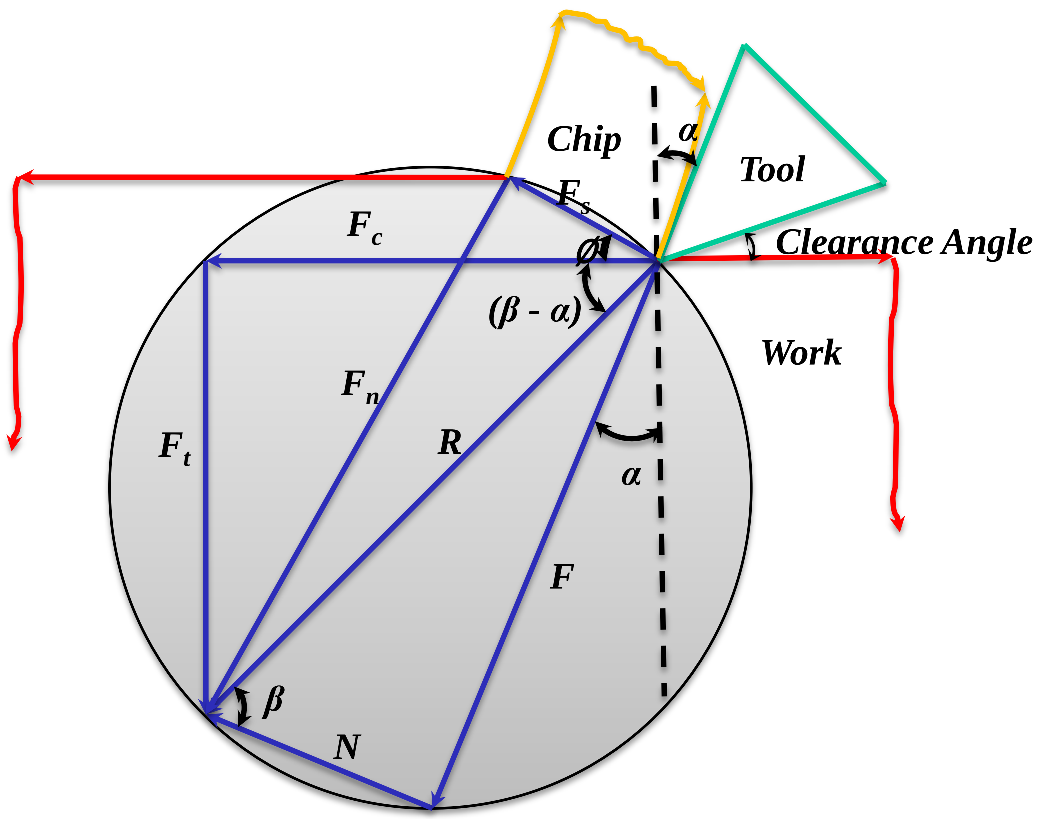
$$F_N = AE = AD + DE = BC + DE$$

$$\Rightarrow F_N = F_C \sin\phi + F_t \cos\phi$$

Also:

$$F_N = F_S \tan(\phi + \beta - \alpha)$$

Relationship of various forces acting on the chip with the horizontal and vertical cutting force from Merchant circle diagram



$$F = F_C \sin\alpha + F_t \cos\alpha$$

$$N = F_C \cos\alpha - F_t \sin\alpha$$

$$F_S = F_C \cos\phi - F_t \sin\phi$$

$$F_N = F_C \sin\phi + F_t \cos\phi$$

$$F_N = F_S \tan(\phi + \beta - \alpha)$$

Power required in Metal cutting

The Power consumed/ work done per sec *in cutting*: $P_C = F_C \times v_C$

The Power consumed/ work done per sec *in shear*: $P_s = F_s \times v_s$

The Power consumed/ work done per sec *in friction*: $P_F = F \times v_f$

The total Power required*:*

$$\text{P} = \text{Power supplied by the motor}$$

$$\Rightarrow \text{P} = \text{Work consumed in cutting per sec} + \text{work spent in feeding per sec}$$

$$\Rightarrow \text{P} = \text{F}_\text{c} \times v_c + F_t \times \textit{feed velocity}$$

In comparison to the cutting velocity the feed velocity is very nominal. Similarly Fc is very small compared to Fc. So the work spent in feeding can be considered negligible.

Therefore, total power required in cutting $P = P_c = P_s + P_f$

Specific Energy

Specific Energy, u_t ,is defined as the total energy per unit volume of material removed.

$$u_t = \frac{F_C v_c}{w t_0 v_c} = \frac{F_C}{w t_0}$$

Therefore is simply the cutting force to the projected area of cut.

If u_f and u_s be specific energy for friction and specific energy for shearing , then

$$u_t = u_f + u_s = \frac{F v_f}{w t_0 v_c} + \frac{F_s v_s}{w t_0 v_c} = \frac{F r}{w t_0} + \frac{F_s v_s}{w t_0 v_c}$$

As the rake angle increases, the frictional specific energy remains more or less constant, where as the shear specific energy rapidly reduced.

Approximate specific-energy requirements in cutting operations.

MATERIAL	SPECIFIC ENERGY*	
	W-s/mm^3	hp-min/in^3
Aluminum alloys	0.4-1.1	0.15-0.4
Cast irons	1.6-5.5	0.6-2.0
Copper alloys	1.4-3.3	0.5-1.2
High-temperature alloys	3.3-8.5	1.2-3.1
Magnesium alloys	0.4-0.6	0.15-0.2
Nickel alloys	4.9-6.8	1.8-2.5
Refractory alloys	3.8-9.6	1.1-3.5
Stainless steels	3.0-5.2	1.1-1.9
Steels	2.7-9.3	1.0-3.4
Titanium alloys	3.0-4.1	1.1-1.5

* At drive motor, corrected for 80% efficiency; multiply the energy by 1.25 for dull tools.

Source " Manufacturing Processes for Engineering Materials", 4th edition, Kalpakjian, Schmid, Prentice Hall 2003

Theory of Ernst and Merchant (1944)

Ernest and Merchant gave the relation

$$\phi = \frac{\pi}{4} - \frac{1}{2}(\beta - \alpha)$$

M. Eugene Merchant

Assumptions of the theory:

- Tool edge is sharp.
- The work material undergoes deformation across a thin shear plane.
- There is uniform distribution of normal and shear stress on the shear plane.
- The work material is rigid and perfectly plastic.
- The shear angle Ø adjusts itself to give minimum work.
- The friction angle β remains constant and is independent of Ø.
- The chip width remains constant.

Theory of Ernst and Merchant (1944)

$$F_s = R\cos(\phi+\beta-\alpha)$$

$$R = F_c \sec(\beta-\alpha)$$

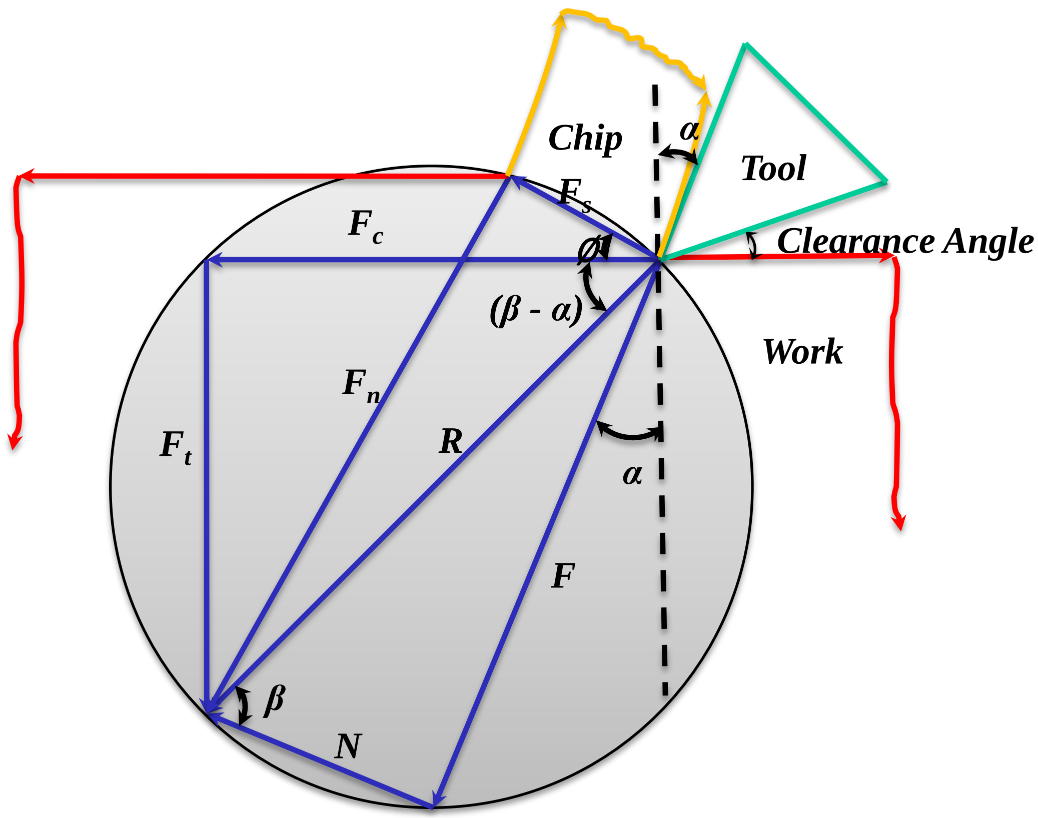
$$\Rightarrow F_s = F_c \sec(\beta-\alpha)\cos(\phi+\beta-\alpha)$$

$$\tau_s = \frac{F_s}{A_s}$$

$$where,\ A_s = \frac{wt_0}{\sin\phi}$$

$$\Rightarrow \tau_s = \frac{F_c \sec(\beta-\alpha)\cos(\phi+\beta-\alpha)}{\dfrac{wt_0}{\sin\phi}}$$

$$\Rightarrow \tau_s = \frac{F_c \sec(\beta-\alpha)\cos(\phi+\beta-\alpha)\sin\phi}{wt_0}$$



They have assumed that ϕ adjusts itself to give minimum work. And for a given set of cutting condition, to, w and α are all constants. They also assumed that β is independent of ϕ.

Theory of Ernst and Merchant (1944)

We can either maximize τ_s or minimize F_c

Therefore in the above equation the term $\cos(\phi+\beta-\alpha)\sin\phi$ contains only one variable ϕ.

$$let\ y = \cos(\phi+\beta-\alpha)\sin\phi$$

$$\frac{dy}{d\phi} = -\sin(\phi+\beta-\alpha)\sin\phi + \cos(\phi+\beta-\alpha)\cos\phi$$

for maximum value of y

$$\Rightarrow \frac{dy}{d\phi} = 0$$

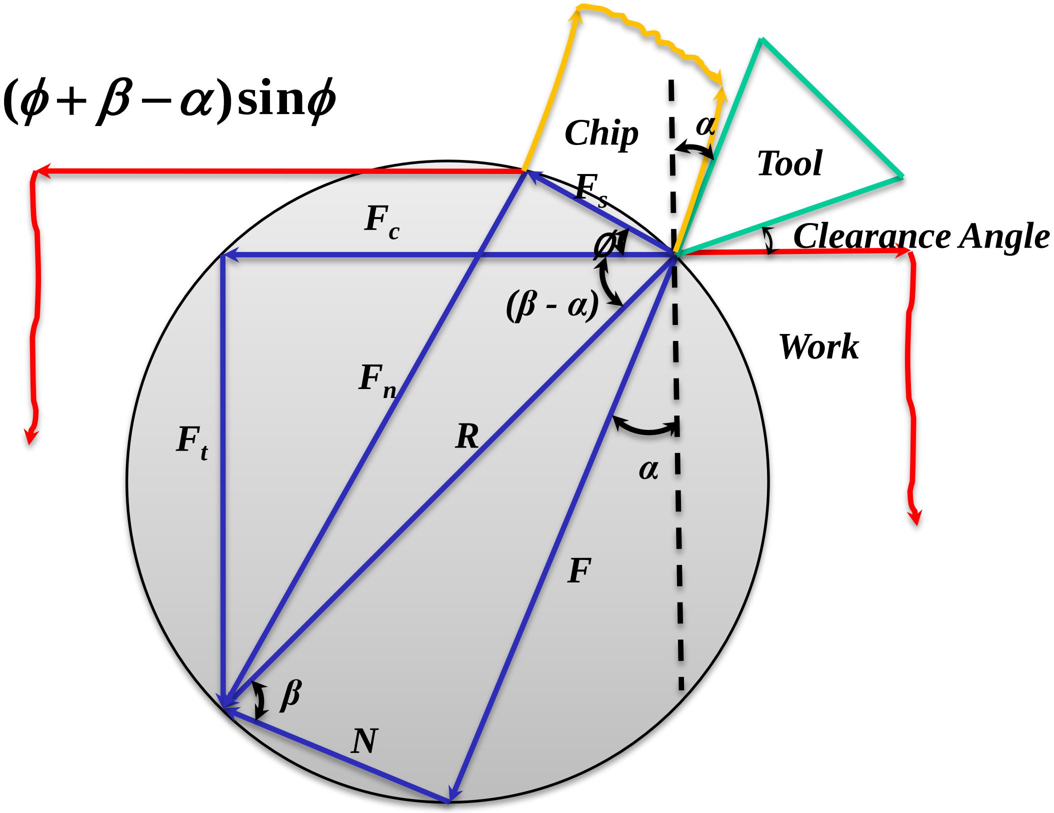
$$\Rightarrow \sin(\phi+\beta-\alpha)\sin\phi = \cos(\phi+\beta-\alpha)\cos\phi$$

$$\Rightarrow \tan(\phi+\beta-\alpha) = \cot\phi$$

$$\Rightarrow \tan(\phi+\beta-\alpha) = \tan(\pi/2 - \phi)$$

$$\Rightarrow \phi+\beta-\alpha = \pi/2 - \phi$$

$$\Rightarrow \phi = \frac{\pi}{4} - \frac{1}{2}(\beta-\alpha)$$



Experimental verification revealed that the above equation is an over estimate.

Merchant later modified this equation and gave another equation $2\phi+\beta-\alpha = C$

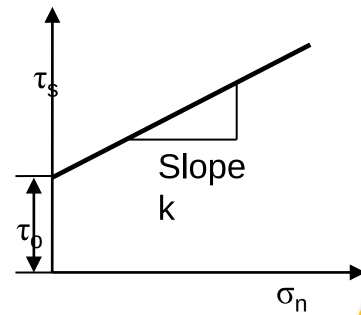
Where C is the machining constant. Usually $C \le \frac{\pi}{2}$ depends upon the work materials.

According to Merchant, C is a property of work material unaffected by cutting conditions, but grain size and micro structure have an affect on C.

Merchant's second solution (Modified Merchant's Theory)

Merchant attempted an alternative solution assuming that the effect of deformation and friction are reflected through a change of normal force F_n, acting in a direction perpendicular to the plane of shear. In turn the normal stress, σ_n, of the shear plane affects the shear stress, τ_s, in the direction of shear.

It was assumed that $\boldsymbol{\tau_s = \tau_0 + k\sigma_n}$ this is commonly known as Bridgeman's relation and k is the slope of τ_s- σ_n characteristic



$$\tau_s = \tau_0 + k\sigma_n \ldots (1)$$

From the Merchant Circle diagram Relation

$$\text{We Know } F_n = F_s \tan(\phi + \beta - \alpha)$$

Dividing by the area of the shear plane, we get

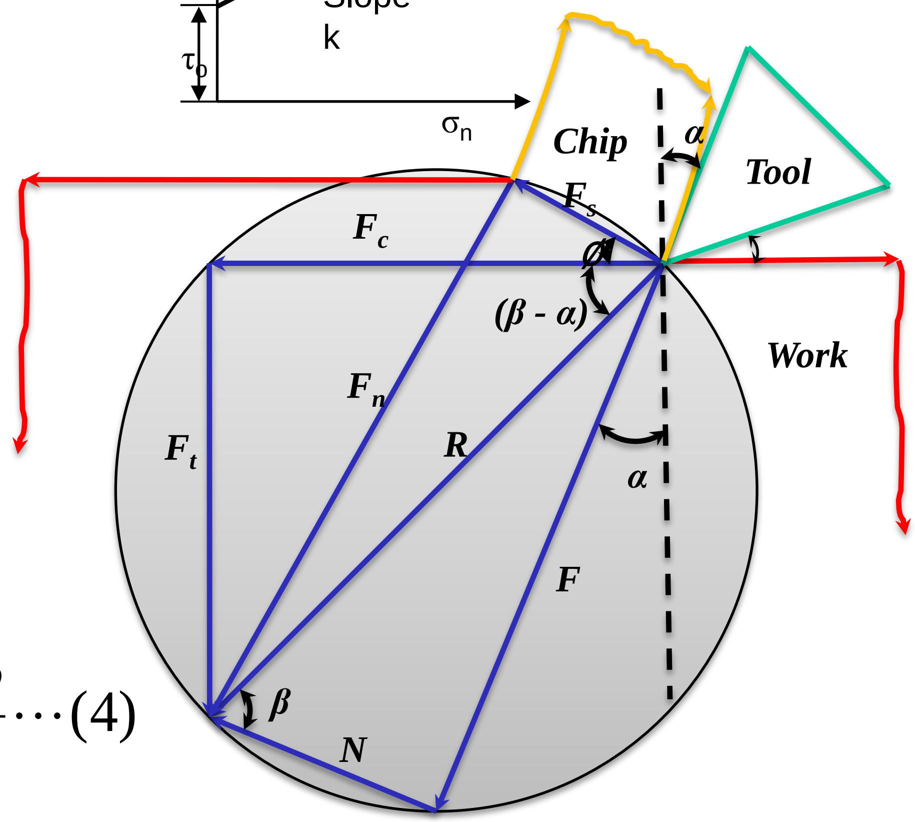
$$\sigma_n = \tau_s \tan(\phi + \beta - \alpha) \ldots (2)$$

From equation (1) and (2), we get

$$\tau_s = \tau_0 + k\tau_s \tan(\phi + \beta - \alpha)$$

$$\Rightarrow \tau_s = \frac{\tau_0}{1 - k\tan(\phi + \beta - \alpha)} \cdots (3)$$

$$\text{We Know, } \tau_s = \frac{F_c \sec(\beta - \alpha)\cos(\phi + \beta - \alpha)\sin\phi}{w \times t_0} \cdots (4)$$



$$\textit{From}\text{ equation (3) and (4), we get } F_c = \frac{w \times t_0 \cos(\beta - \alpha)}{\cos(\phi + \beta - \alpha)\sin\phi[1 - k\tan(\phi + \beta - \alpha)]}$$

Merchant's second solution (contd..)

$$From\ \text{principle of minimun energy}, F_c \text{ is minimum, when denominator is maximum.}$$

$$\text{Therfore if } y = \cos(\phi+\beta-\alpha)\sin\phi[1-k\tan(\phi+\beta-\alpha)]$$

$$\Rightarrow y = \cos(\phi+\beta-\alpha)\sin\phi - k\sin(\phi+\beta-\alpha)\sin\phi$$

$$\frac{dy}{d\phi} = 0$$

$$= \cos(\phi+\beta-\alpha)\cos\phi - \sin(\phi+\beta-\alpha)\sin\phi - k\sin(\phi+\beta-\alpha)\cos\phi - k\cos(\phi+\beta-\alpha)\sin\phi$$

$$\Rightarrow \cos(\phi+\beta-\alpha)\cos\phi - \sin(\phi+\beta-\alpha)\sin\phi$$

$$= k[\sin(\phi+\beta-\alpha)\cos\phi + \cos(\phi+\beta-\alpha)\sin\phi]$$

$$\Rightarrow \cos(2\phi+\beta-\alpha) = k\sin(2\phi+\beta-\alpha)$$

$$\Rightarrow \cot(2\phi+\beta-\alpha) = k$$

$$\Rightarrow 2\phi+\beta-\alpha = \cot^{-1}k = C$$

$$\Rightarrow 2\phi+\beta-\alpha = C$$

where C is machining constant

Stress and Strain acting on the chip

$$Mean\ shear\ stress\ \tau_s = \frac{F_s}{A_s}$$

$$Mean\ normal\ stress\ \sigma_s = \frac{F_n}{A_s}$$

The shear strain be γ.

Considering no loss of work during shearing

We Know,

Work done in shearing unit volume of the metal = shear stress × shear strain

$$\Rightarrow \frac{F_s \times v_s}{t_0 \times w \times v_c} = \tau_s \times \gamma$$

$$\Rightarrow \gamma = \frac{F_s \times v_s}{\tau_s \times t_0 \times w \times v_c}$$

$$\Rightarrow \gamma = \frac{F_s \times v_s}{\frac{F_s}{A_s} \times t_0 \times w \times v_c}$$

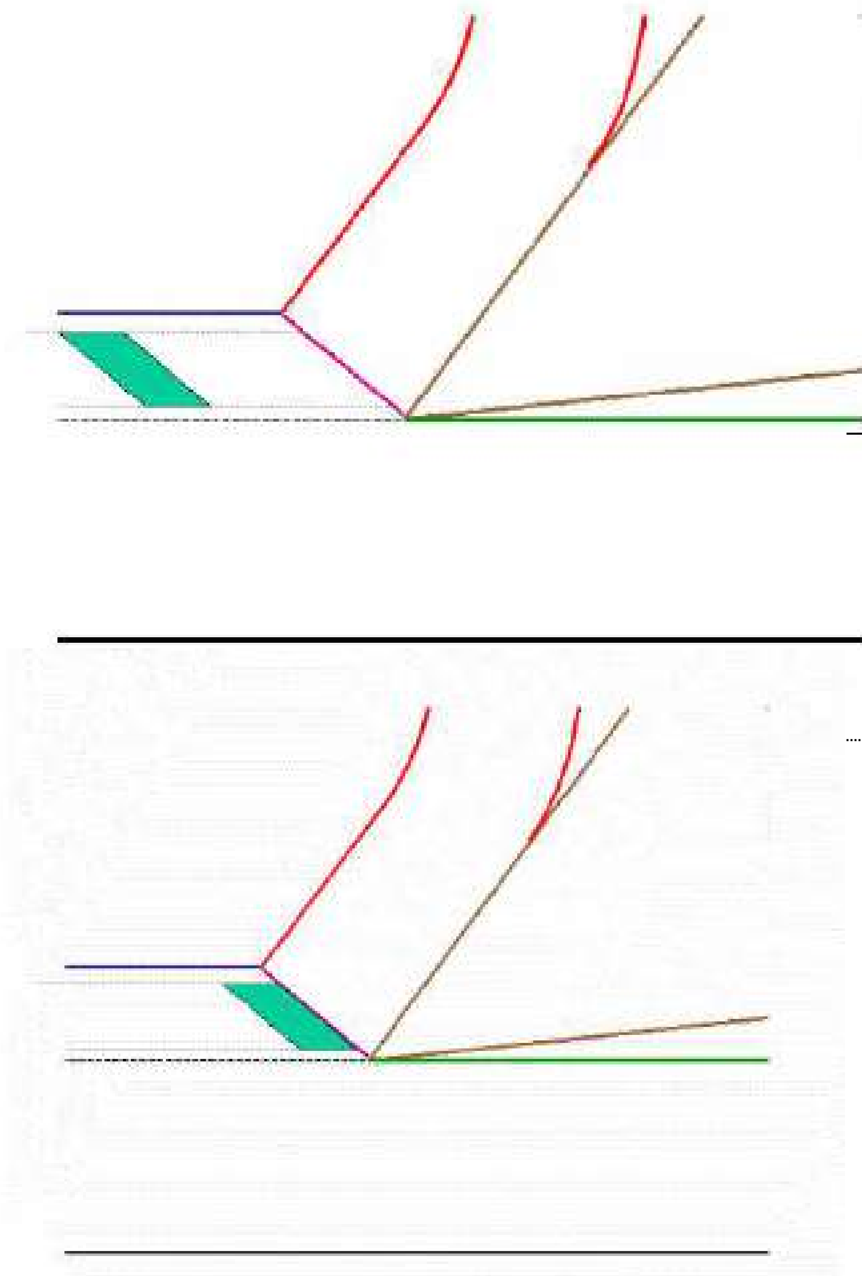
$$\Rightarrow \gamma = \frac{F_s \times v_s}{\frac{F_s}{t_0 \times w / \sin\phi} \times t_0 \times w \times v_c}$$

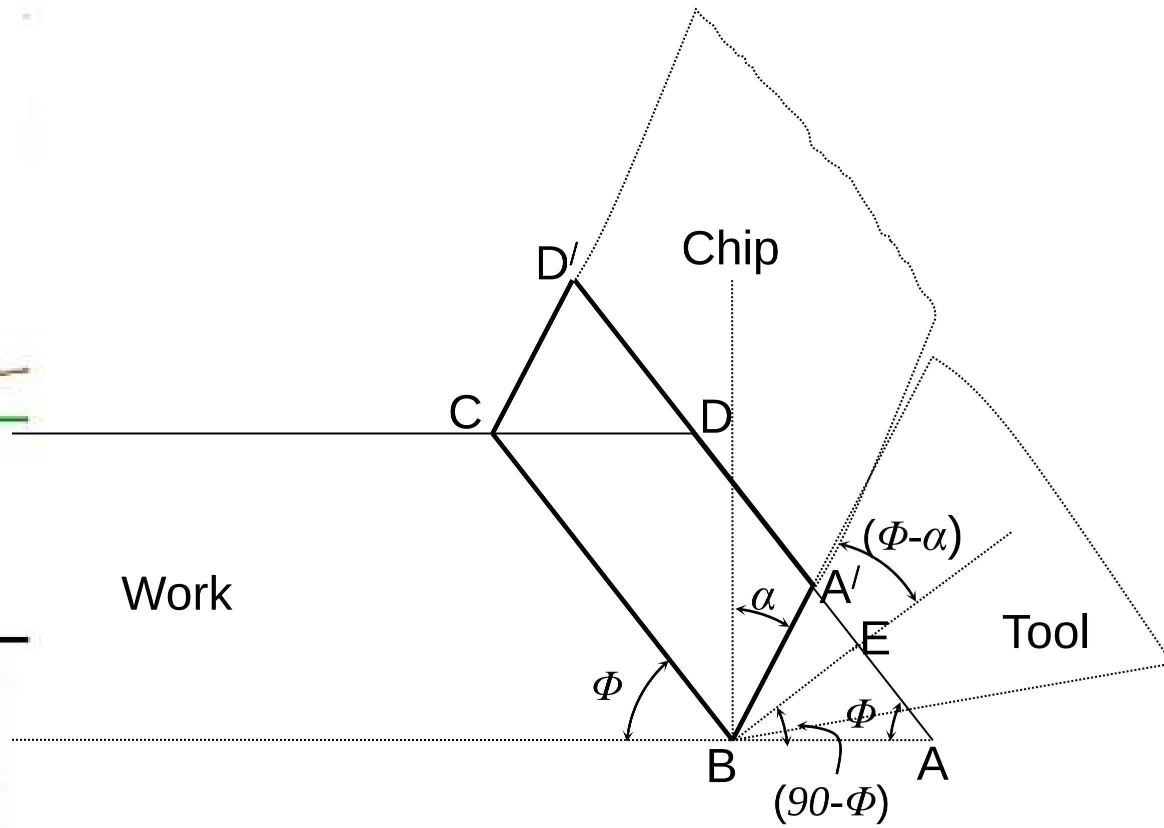
$$\Rightarrow \gamma = \frac{v_s}{v_c} \times \frac{1}{\sin\phi}$$

$$But\ \frac{v_s}{v_c} = \frac{\cos\alpha}{\cos(\phi - \alpha)},\ therefore$$

$$\Rightarrow \gamma = \frac{\cos\alpha}{\cos(\phi - \alpha)\sin\phi}$$

Stress and Strain acting on the chip





Shearing of chip

Stress and Strain acting on the chip (contd..)

The magnitude of shear strain γ

$$\approx \tan\angle ABE + \tan\angle A^{/}BE = \frac{AE}{BE} + \frac{A^{/}E}{BE}$$

$$\Rightarrow \gamma = \frac{AE}{BE} + \frac{A^{/}E}{BE}$$

$$\angle A^{/}BE = 90 - (90 - \phi) - \alpha = \phi - \alpha$$

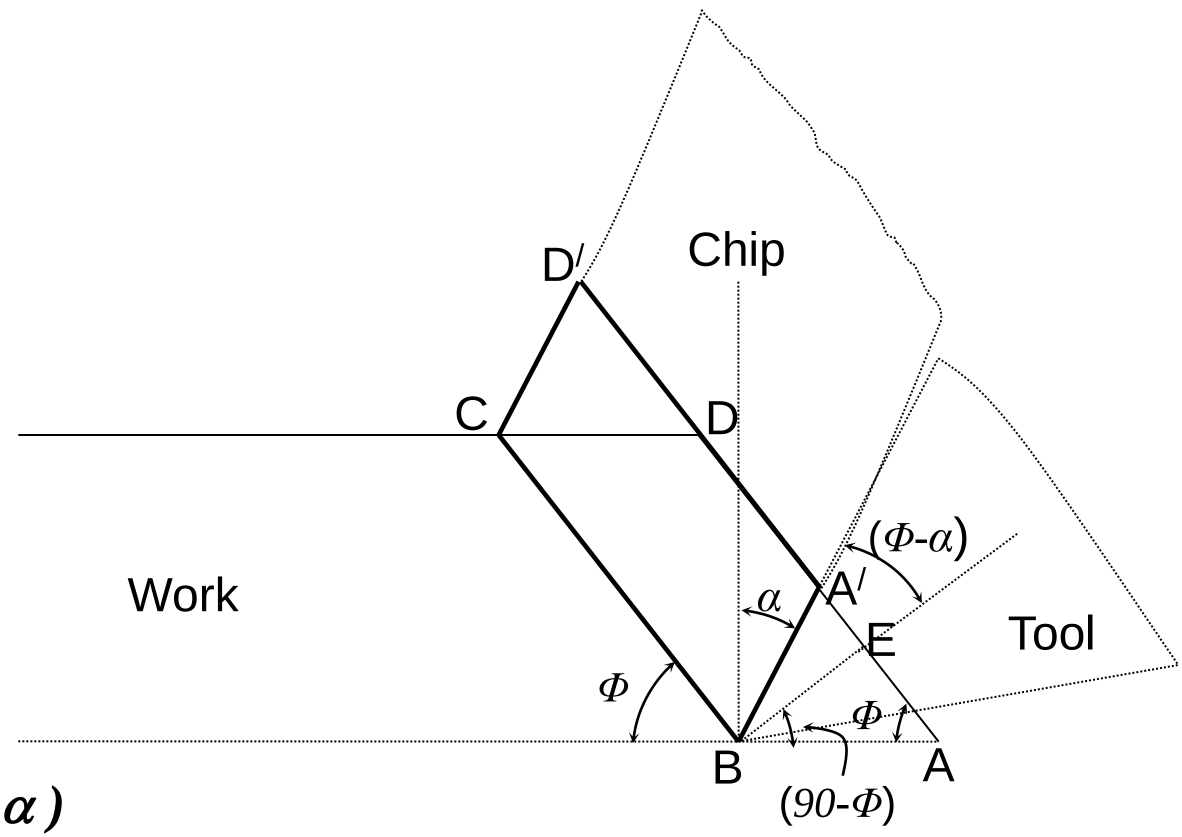
$$\Rightarrow \gamma = \cot\phi + \tan(\phi - \alpha)$$

$$\Rightarrow \gamma = \frac{\cos\phi}{\sin\phi} + \frac{\sin(\phi - \alpha)}{\cos(\phi - \alpha)}$$

$$\Rightarrow \gamma = \frac{\cos\phi\cos(\phi - \alpha) + \sin\phi\sin(\phi - \alpha)}{\sin\phi\cos(\phi - \alpha)}$$

$$\Rightarrow \gamma = \frac{\cos(\phi - \phi + \alpha)}{\sin\phi\cos(\phi - \alpha)}$$

$$\Rightarrow \gamma = \frac{\cos\alpha}{\sin\phi\cos(\phi - \alpha)}$$



Shearing of chip

Thrust Force vs Rake Angle

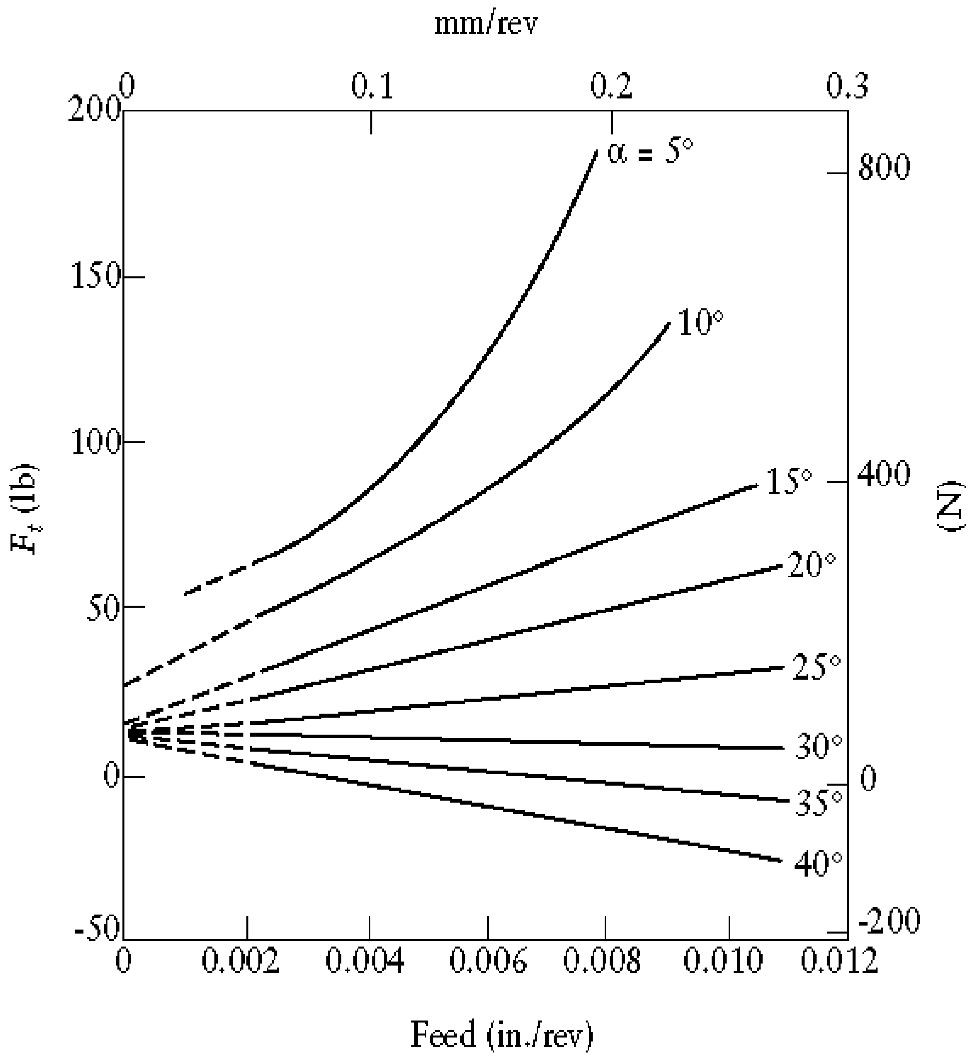
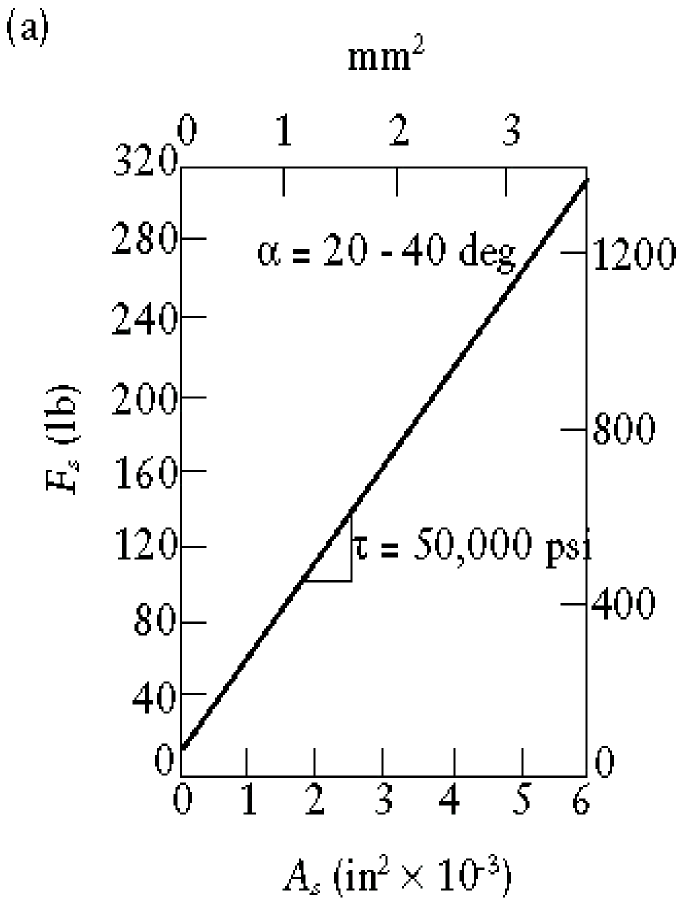


FIGURE Thrust force as a function of rake angle and feed in orthogonal cutting of AISI 1112 cold-rolled steel. Note that at high rake angles, the thrust force is negative. A negative thrust force has important implications in the design of machine tools and in controlling the stability of the cutting processes. *Source*: After S. Kobayashi and E. G. Thomsen.

Figure from: " Manufacturing Processes for Engineering Materials", 4th edition, Kalpakjian, Schmid, Prentice Hall 2003

Shear and Normal Force



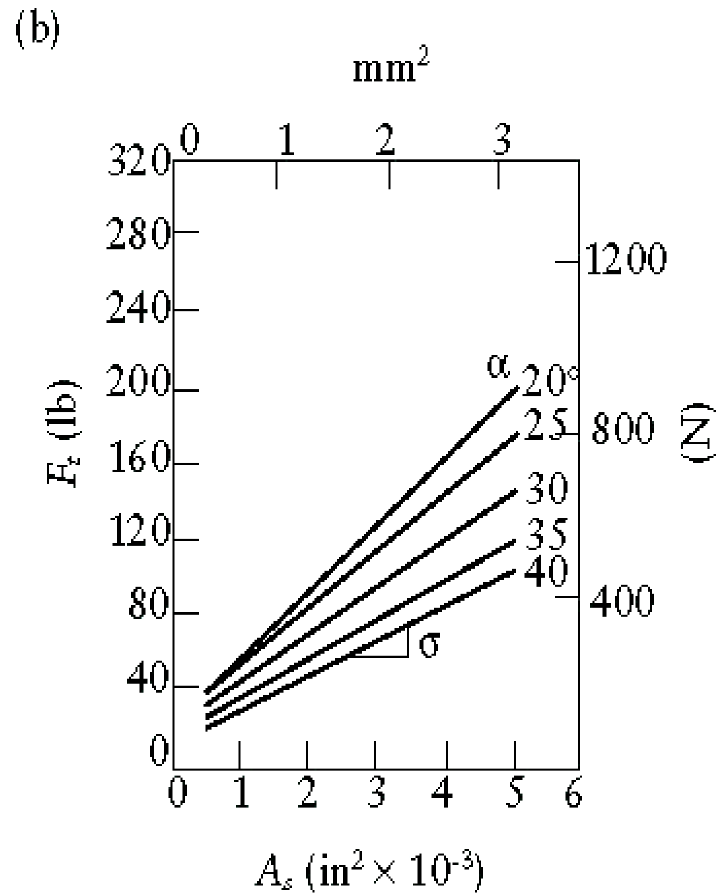


FIGURE Shear force and normal force as a function of the area of the shear plane and the rake angle for 85-15 brass. Note that the shear stress in the shear plane is constant, regardless of the magnitude of the normal stress. Thus, normal stress has no effect on the shear flow stress of the material. *Source*: After S. Kobayashi and E. G. Thomsen, *J. Eng. Ind*., 81: 251-262, 1959.

Figure from: " Manufacturing Processes for Engineering Materials", 4th edition, Kalpakjian, Schmid, Prentice Hall 2003

Shear and Normal Force

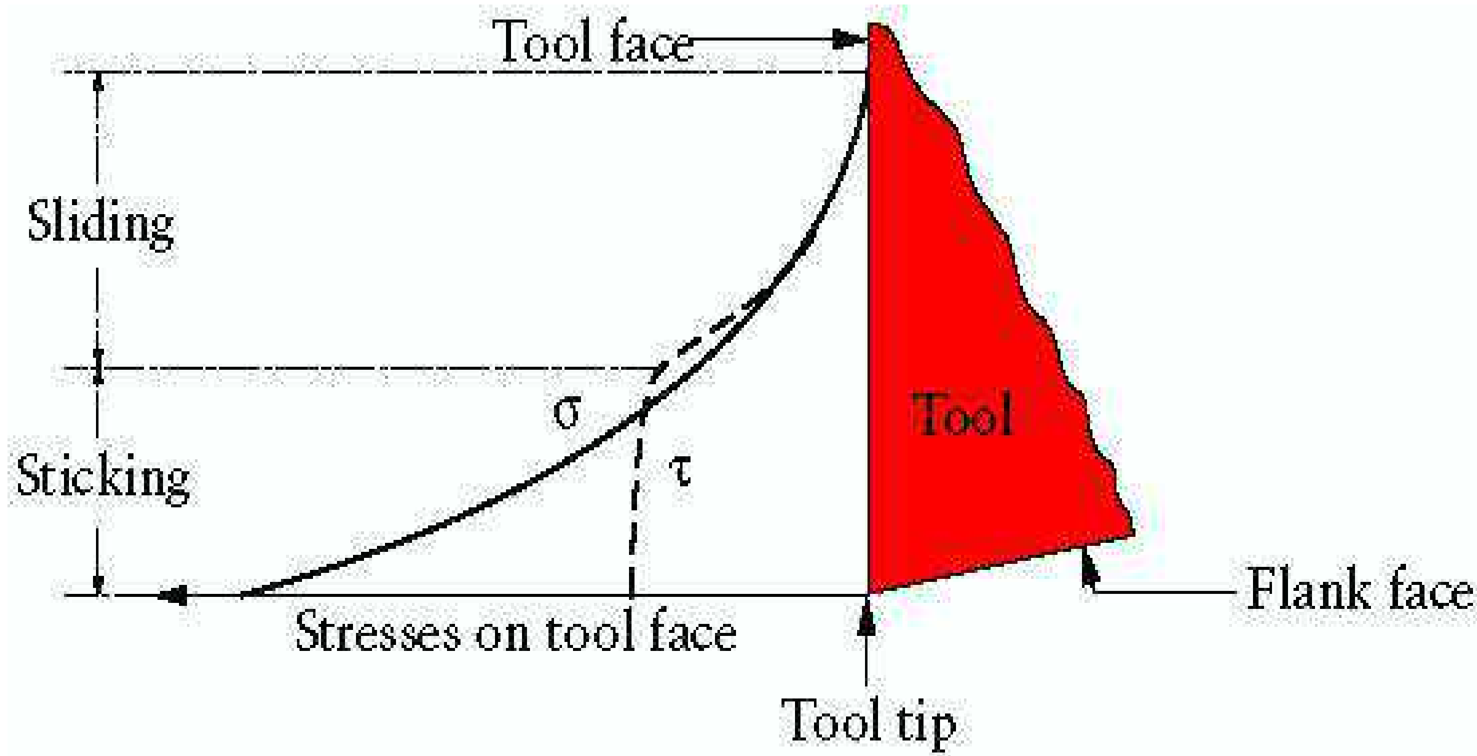


FIGURE: Schematic illustration of the distribution of normal and shear stresses at the tool-chip interface (rake face). Note that, whereas the normal stress increases continuously toward the tip of the tool, the shear stress reaches a maximum and remains at that value (a phenomenon know as *sticking*).

Figure from: “ Manufacturing Processes for Engineering Materials”, 4th edition, Kalpakjian, Schmid Prentice Hall 2003

Temperature Distribution in the Cutting Zone

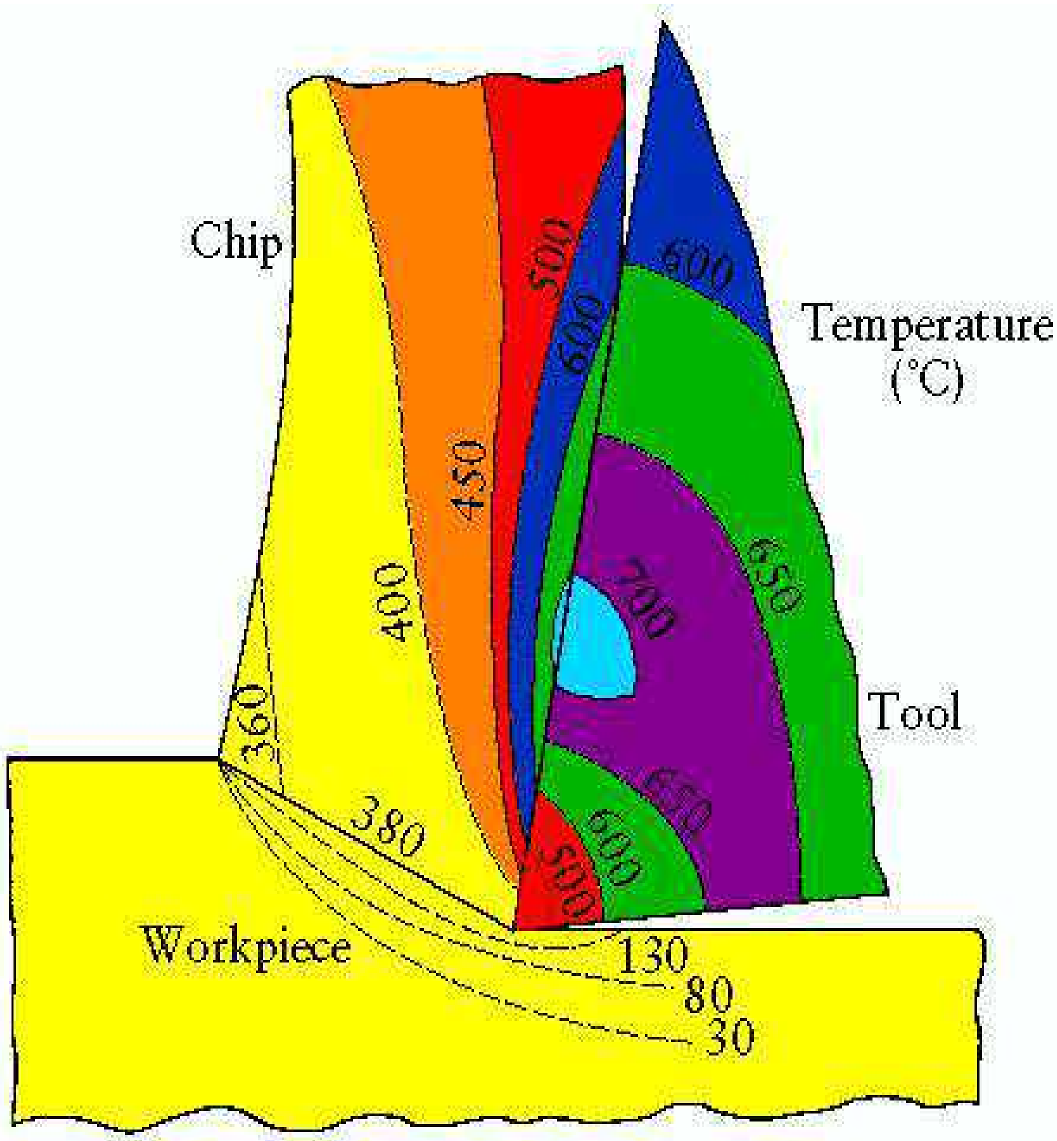


FIGURE: Typical temperature distribution in the cutting zone. Note that the maximum temperature is about halfway up the face of the tool and that there is a steep temperature gradient across the thickness of the chip. Some chips may become red hot, causing safety hazards to the operator and thus necessitating the use of safety guards. *Source*: After G. Vieregge.

Figure from: " Manufacturing Processes for Engineering Materials", 4th edition, Kalpakjian, Schmid, Prentice Hall 2003

Temperature Distribution in Turning

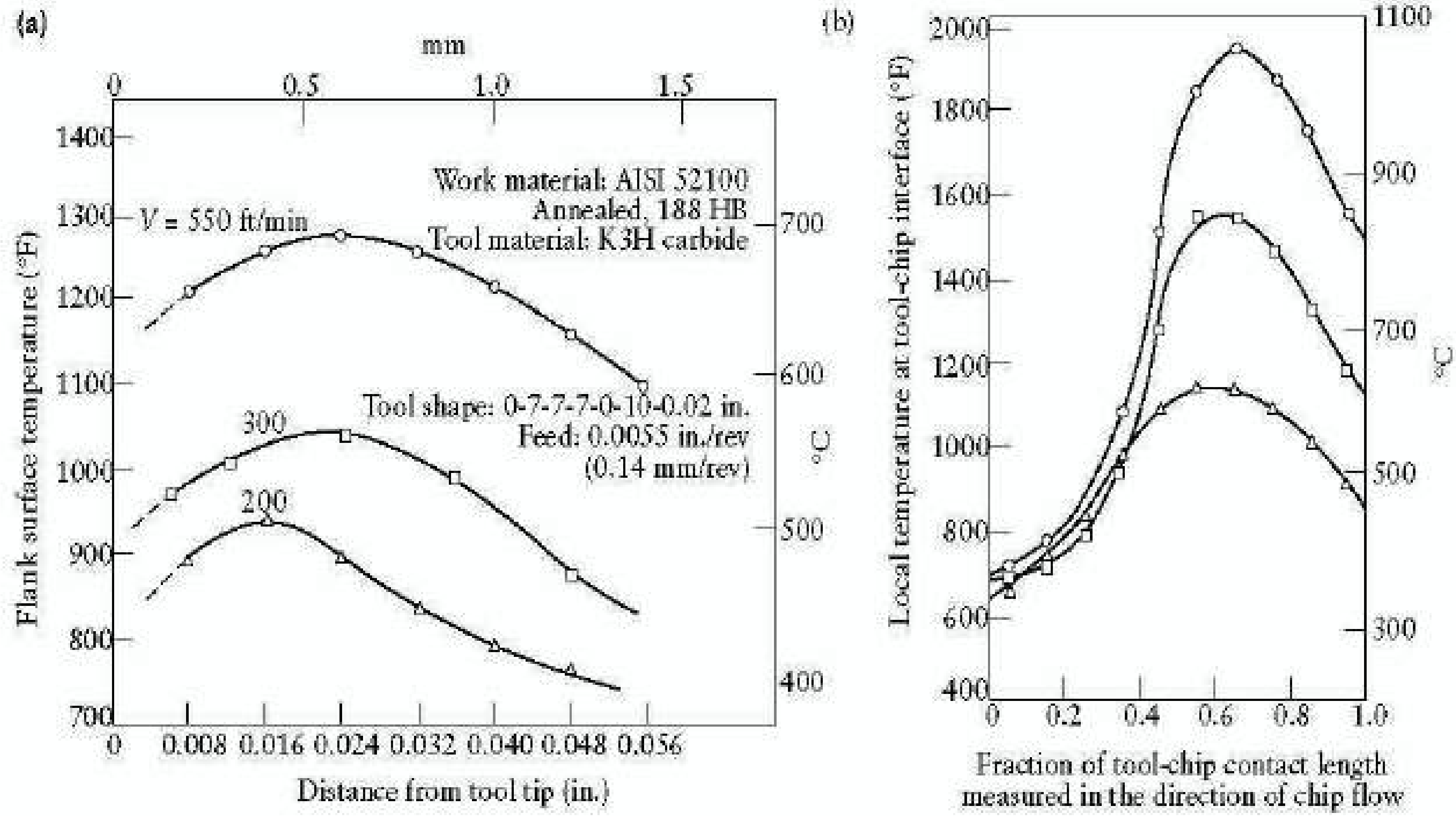


FIGURE : Temperature distribution in turning: (a) flank temperature for tool shape (b) temperature of the tool-chip interface. Note that the rake face temperature is higher than that at the flank surface. *Source*: After B. T. Chao and K. J. Trigger.

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Hardness Distribution in the Cutting Zone

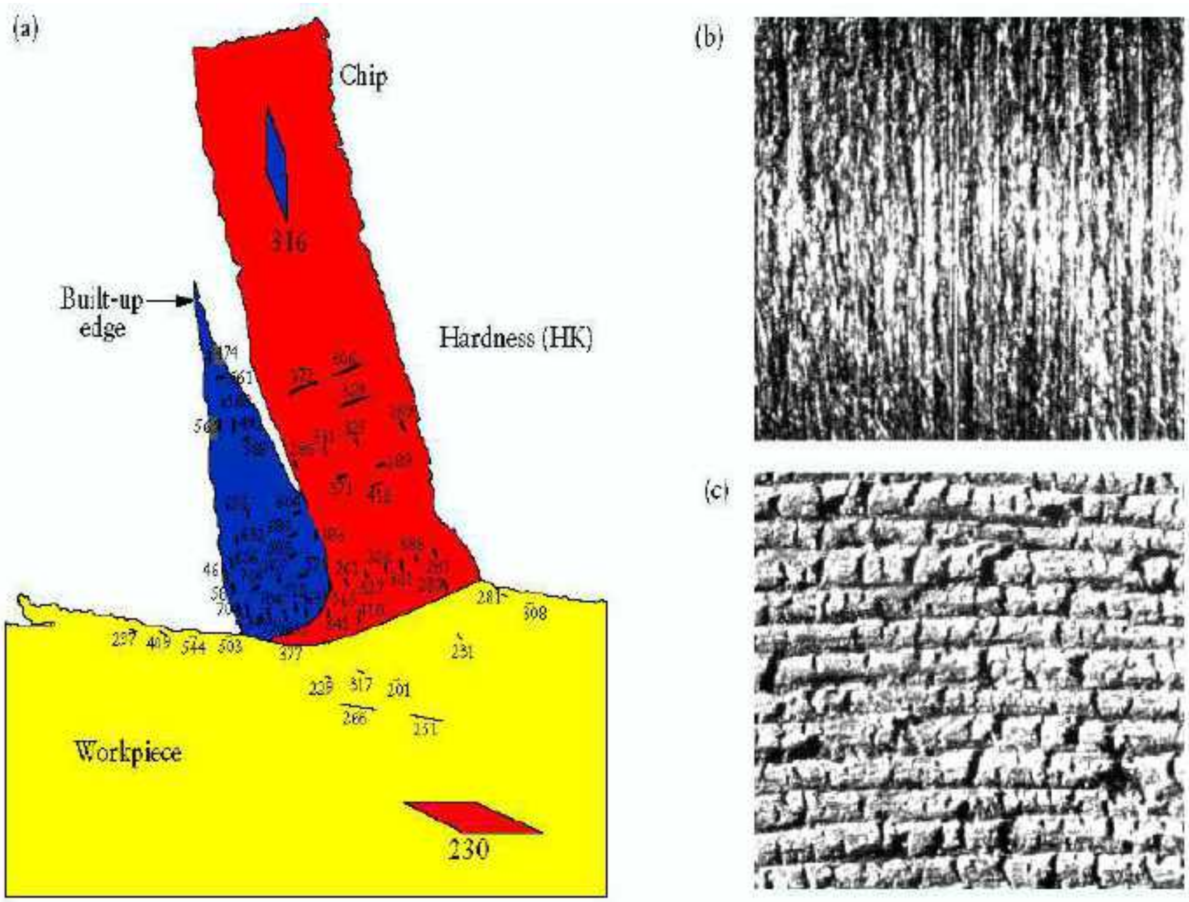

FIGURE : (a) Hardness distribution in the cutting zone for 3115 steel. Note that some regions in the built-up edge are as much as three times harder than the bulk metal. (b) Surface finish in turning 5130 steel with a built-up edge. (c) Surface finish on 1018 steel in face milling. Magnifications: 15X. *Source*: Courtesy of Institute of Advanced Manufacturing Sciences, Inc.

Figure from: " Manufacturing Processes for Engineering Materials", 4th edition, Kalpakjian, Schmid, Prentice Hall 2003

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What is a CNC Machine?

CNC : Computerised Numerical Control

(Computer + Numerical Control)

- Numerical control is a programmable automation in which process is controlled by Numbers, Letters, and symbols.
- CNC Machining is a process used in the manufacturing sector that involves the use of computers to control machine tools like lathes, mills and grinders.

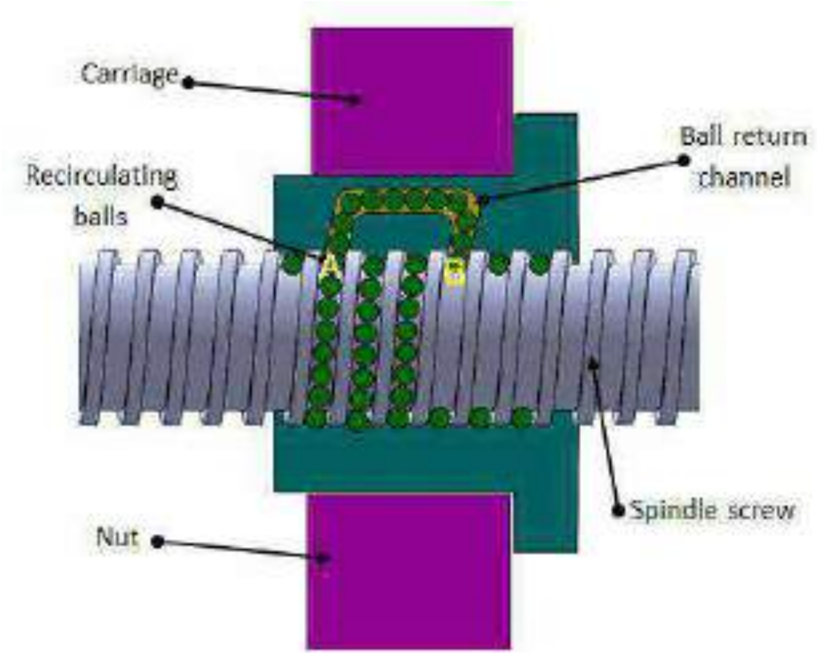
Why is CNC Machining necessary?

- To manufacture complex curved geometries in 2D or 3D was extremely expensive by mechanical means (which usually would require complex jigs to control the cutter motions)
- Machining components with high Repeatability and Precision
- Unmanned machining operations
- To improve production planning and to increase productivity
- To survive in global market CNC machines are must to achieve close tolerances.

Ball screw / ball bearing screw / recirculating ballscrew Mechanism

- It consists of a screw spindle, a nut, balls and integrated ball return mechanism a shown in Figure .

- The flanged nut is attached to the moving part of CNC machine tool. As the screw rotates, the nut translates the moving part along the guide ways.



Ballscrew configuration

- However, since the groove in the ball screw is helical, its steel balls roll along the helical groove, and, then, they may go out of the ball nut unless they are arrested at a certain spot.

- Thus, it is necessary to change their path after they have reached a certain spot by guiding them, one after another, back to their “starting point” (formation of a recirculation path). The recirculation parts play that role.

- When the screw shaft is rotating, as shown in Figure, a steel ball at point (A) travels 3 turns of screw groove, rolling along the grooves of the screw shaft and the ball nut, and eventually reaches point (B).

- Then, the ball is forced to change its pathway at the tip of the tube, passing back through the tube, until it finally returns to point (A).

- Whenever the nut strokes on the screw shaft, the balls repeat the same recirculation inside the return tube.

- When debris or foreign matter enter the inside of the nut, it could affect smoothness in operation or cause premature wearing, either of which could adversely affect the ball screw's functions.

- To prevent such things from occurring, seals are provided to keep contaminants out. There are various types of seals viz. plastic seal or brush type of seal used in ball-screw drives.

Characteristics of ball screws

- **High mechanical efficiency**

In ball screws, about 90% or more of the force used to rotate the screw shaft can be converted to the force to move the ball nut.

Since friction loss is extremely low, the amount of force used to rotate the screw shaft is as low as one third of that needed for the acme thread lead screw.

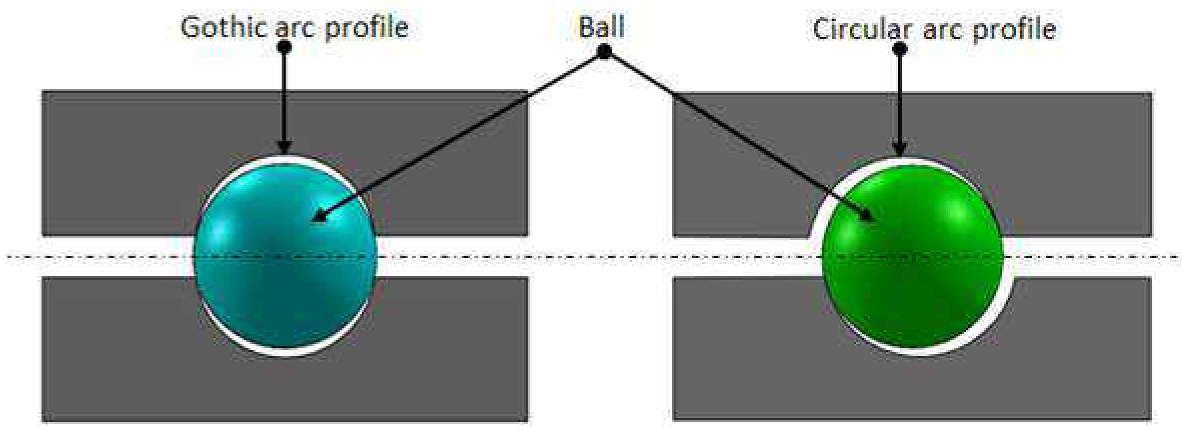
- **Low in wear**

Because of rolling contact, wear is less than that of sliding contact. Thus, the accuracy is high.

Ball screws move smoothly enough under very slow speed. They run smoothly even under a load.

- **Thread Form**

The thread form used in these screws can either be gothic arc type (fig.a) or circular arc type (fig.b). The friction in this kind of arrangement is of rolling type. This reduces its wear as comparison with conventional sliding friction screws drives.



Thread forms (a) Gothic arc (b) Circular arc

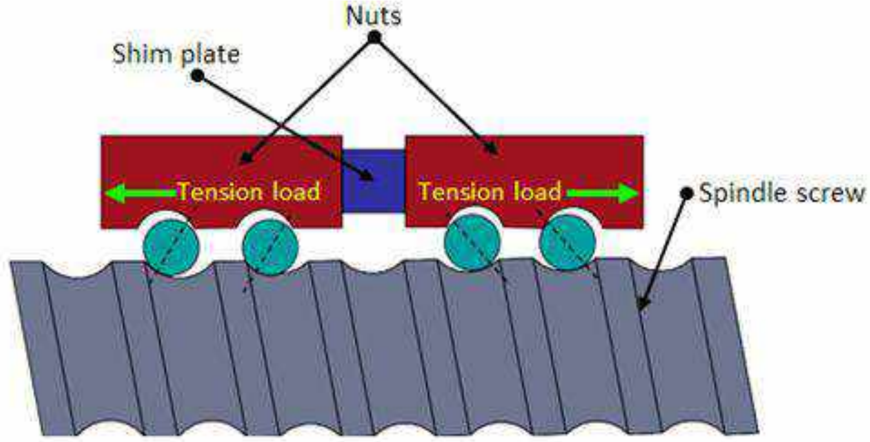
Recirculating ball screws are of two types. In one arrangement the balls are returned using an external tube. In the other arrangement the balls are returned to the start of the thread in the nut through a channel inside the nut.

- **Preloading**

In order to obtain bidirectional motion of the carriage without any positional error, the backlash between the nut and screw should be minimum.

Zero backlash can be obtained by fitting two nuts with preloading (tension or compression) or by applying a load which exceeds the maximum operating load.

Figure shows double nut preloading system. A shim plate (spacer) is inserted between two nuts for preloading. Preload is to create elastic deformations (deflections) in steel balls and ball grooves in the nut and the screw shaft in advance by providing an axial load.



Double nut preloading system

As a result the balls in one of the nuts contact the one side of the thread and balls in the other nut contact the opposite side.

Effects of preload

- Zero backlash: It eliminates axial play between a screw shaft and a ball nut.
- It minimizes elastic deformation caused by external force, thus the rigidity enhances.
- In case mounting errors, misalignment between the screw shaft and the nut may occur this further generates distortion forces.
- This could lead to the problems such as,

  Shortened service life

  Adverse effect on smooth operation

  Reduced positioning accuracy

  Generation of noise or vibration

  Breakage of screw shaft

Advantages of ball screws

- Highly efficient and reliable.
- Less starting torque.
- Lower co efficient of friction compared to sliding type screws and run at cooler temperatures
- Power transmission efficiency is very high and is of the order of 95 %.
- Could be easily preloaded to eliminate backlash.
- The friction force is virtually independent of the travel velocity and the friction at rest is very small; consequently, the stick-slip phenomenon is practically absent, ensuring uniformity of motion.
- Has longer thread life hence need to be replaced less frequently.
- Ball screws are well -suited to high through output, high speed applications or those with continuous or long cycle times.
- Smooth movement over full range of travel.

Disadvantages of ball screws

- Tend to vibrate.
- Require periodic overhauling to maintain their efficiency.
- Inclusion of dirt or foreign particles reduces the life of the screws.
- Not as stiff as other power screws, thus deflection and critical speed can cause difficulties.
- They are not self-locking screws hence cannot be used in holding devices such as vices.
- Require high levels of lubrication.

Applications of ball screws

- Ball screws are employed in cutting machines, such as machining center and NC lathe where accurate positioning of the table is desired

- Used in the equipment's such as lithographic equipment or inspection apparatus where precise positioning is vital

- High precision ball screws are used in steppers for semiconductor manufacturing industries for precision assembly of micro parts.

- Used in robotics application where precision positioning is needed.

- Used in medical examination equipment's since they are highly accurate and provide smooth motion.

DIFFERENCES BETWEEN CNC MACHINES TOOLS AND CONVENTIONAL MACHINE TOOLS

➢ Constructional details:

- Basically conventional machine have 2 axes, known as X & Y axis.
- There is also a Z axis long which only the bed moves vertically.
- The spindle along with the tool does not move as it is fixed with the machine body .

But in case of CNC machine, there are minimum 3 axes with Spindle moving parallel to Z axis.

- CNC machines have more rigid construction when compared to the conventional machine.

- The slide ways, guide and spindles of the CNC machine all look over proportioned when compared to the conventional machine.

The structure of the CNC machine is therefore designed to cope with the torsional forces and heavy duty cutting imposed on these machines.

Recirculating ball lead screws and anti friction slide ways

CONVENTIONAL

- The slide ways on a conventional machine operate under the conditions of sliding friction.

- The lead screws are usually of the Acme thread form, which are inefficient due to the high frictional resistance between the flanks of the screw and the nut. There is also backlash, because of the clearance between the screw and the nut.

CNC

- Rolling friction can be used instead of sliding friction, where re-circulating roller bearings are positioned under the slide ways.

- A recirculating ball lead screw, where both the lead screw and the nut have a precision ground radiused shaped thread. The space or track between the lead screw and nut is filled with an endless stream or ball bearings.

The advantages are longer life, less frictional resistance, lower torque required, more precise positioning of slides, where backlash is almost completely eliminated.

➢ Use of Stepping Motors in Slide Movement

The slides and spindle of the CNC machine are driven by stepper motors.

STEPPER MOTOR – A digital signal is sent from the controller to the motor in the form of pulses, which will cause the motor to rotate through a specified angle, which causes the slide to move by the required distance.

Example:

If five digital pulses are sent to the stepper motor then it will rotate by five steps, which is converted to linear movement by the lead screw. The speed by which the pulses are sent to the stepper motor will determine the velocity of the slide movement. As the distance moved by the slide and the feed can be accurately controlled by the CNC control system, there is no need for positional or velocity feedback

MAJOR COMPONENTS RELATED TO CNC MACHINE TOOLS

Any CNC machine tool essentially consists of the following parts:

❑ Part program:

- A series of coded instructions required to produce a part.
- Controls the movement of the machine tool and on/off control of auxiliary functions such as spindle rotation and coolant.
- The coded instructions are composed of letters, numbers and symbols.

❑ Program input device

- The program input device is the means for part program to be entered into the CNC control.

- Three commonly used program input devices are punch tape reader, magnetic tape reader, and computer via RS-232-C communication.

❑ Machine Control Unit

The machine control unit (MCU) is the heart of a CNC system. It is used to perform the following functions:

- To read the coded instructions.
- To decode the coded instructions.
- To implement interpolations (linear, circular, and helical) to generate axis motion commands.
- To feed the axis motion commands to the amplifier circuits for driving the axis mechanisms.
- To receive the feedback signals of position and speed for each drive axis.
- To implement auxiliary control functions such as coolant or spindle on/off and tool change.

❑Machine Tool

- CNC controls are used to control various types of machine tools.

- Regardless of which type of machine tool is controlled, it always has a slide table and a spindle to control position and speed.

- The machine table is controlled in the X and Y axes, while the spindle runs along the Z axis.

❑Feed Back System

- The feedback system is also referred to as the measuring system.
- It uses position and speed transducers to continuously monitor the position at which the cutting tool is located at any particular instant.
- The MCU uses the difference between reference signals and feedback signals to generate the control signals for correcting position and speed errors.

❑Drive System

- Drives are used to provide controlled motion to CNC elements

- A drive system consists of amplifier circuits, drive motors, and ball lead-screws.

- The MCU feeds the control signals (position and speed) of each axis to the amplifier circuits.

- The control signals are augmented to actuate drive motors which in turn rotate the ball lead-screws to position the machine table.

➢ POWER DRIVES

- In machine tools, power is generally required for driving the main spindle, saddles and carriages and to some auxiliary units.

- The motors used for CNC system are of two kinds
  - ✓ Electrical - AC , DC or Stepper motors
  - ✓ Fluid - Hydraulic or Pneumatic

- In CNC, usually stepper and servo electrical drives are used

- They exhibit favourable torque-speed characteristics and are relatively inexpensive.

✓ STEPPER MOTOR

A stepper motor is a pulse-driven motor that changes the angular position of the rotor in steps.

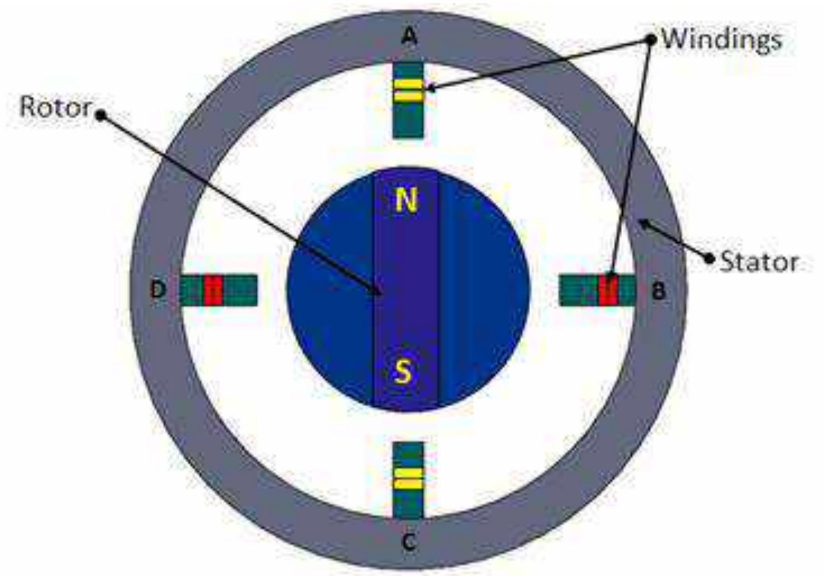
Due to this nature of a stepper motor, it is widely used in low cost, open loop position control systems.

Types of stepper motors:

- Permanent Magnet
  - Employ permanent magnet
  - Low speed, relatively high torque
- Variable Reluctance
  - Does not have permanent magnet
  - Low torque

Permanent magnet (PM) stepper motor

- Rotor is a permanent magnet.
- PM motor rotor has no teeth and is designed to be magnetized at a right angle to its axis.
- Figure shows a simple, 90^0 PM motor with four phases (A-D).
- Applying current to each phase in sequence will cause the rotor to rotate by adjusting to the changing magnetic fields.
- Although it operates at fairly low speed, the PM motor has a relatively high torque characteristic.



Permanent magnet stepper

- These are low cost motors with typical step angle ranging between 7.5^0 to 15^0

Variable Reluctance Motor

- The cylindrical rotor is made of soft steel and has four poles
- It has four rotor teeth, 90^0 apart and six stator poles, 60^0 apart.
- Electromagnetic field is produced by activating the stator coils in sequence.
- It attracts the metal rotor. When the windings are energized in a reoccurring sequence of 2, 3, 1, and so on, the motor will rotate in a 30^0 step angle.
- In the non-energized condition, there is no magnetic flux in the air gap, as the stator is an electromagnet and the rotor is a piece of soft iron; hence, there is no detent torque.

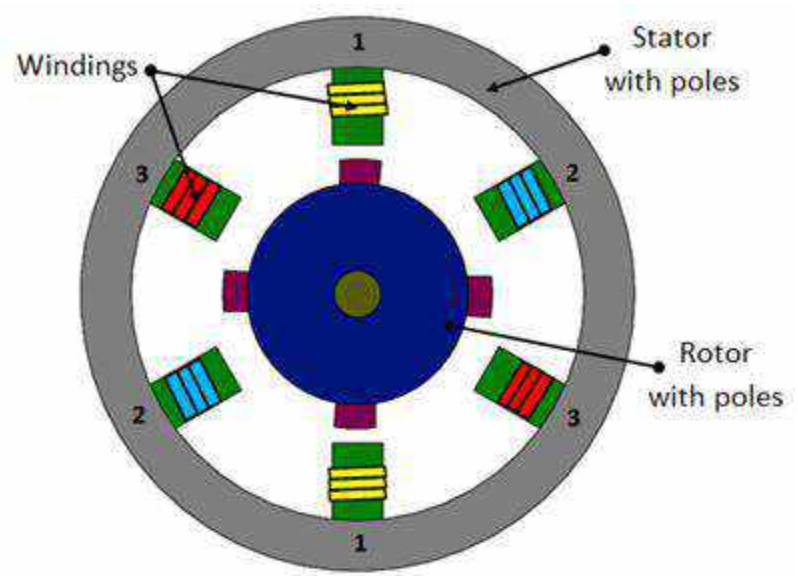
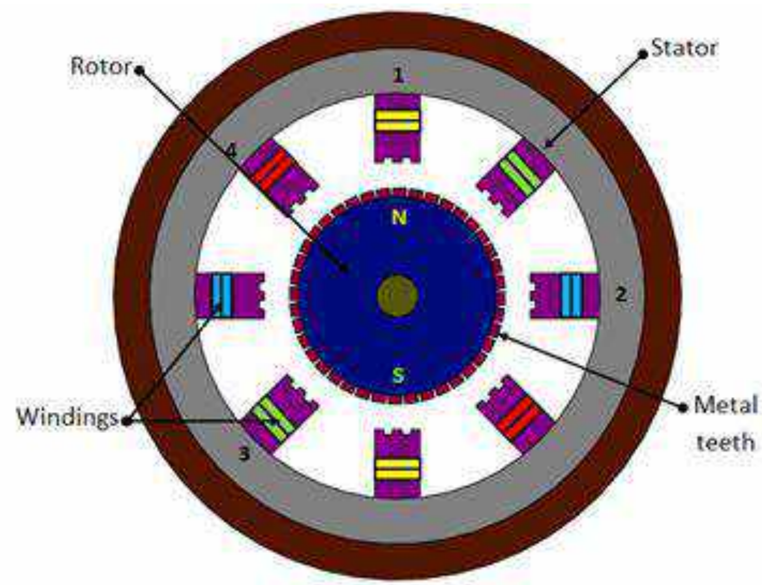


Fig. Variable reluctance stepper motor

Hybrid stepper motor

- Hybrid stepping motors combine a permanent magnet and a rotor with metal teeth to provide features of the variable reluctance and permanent magnet motors together.

- The number of rotor pole pairs is equal to the number of teeth on one of the rotor's parts. The hybrid motor stator has teeth creating more poles than the main poles windings



Hybrid stepper

- Rotation of a hybrid stepping motor is produced in the similar fashion as a permanent magnet stepping motor, by energizing individual windings in a positive or negative direction.

- When a winding is energized, north and south poles are created, depending on the polarity of the current flowing.

- These generated poles attract the permanent poles of the rotor and also the finer metal teeth present on rotor.

- The rotor moves one step to align the offset magnetized rotor teeth to the corresponding energized windings.

- Hybrid motors are more expensive than motors with permanent magnets, but they use smaller steps, have greater torque and maximum speed.

- Step angle of a stepper motor is given by,

$$\boxed{\text{Step angle} = \frac{360^0}{number\ of\ poles}}$$

Advantages of stepper motors

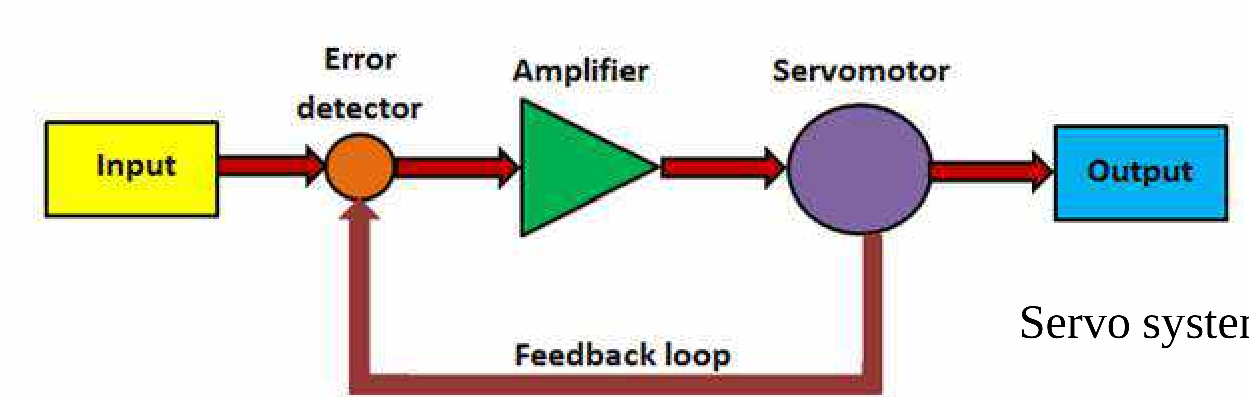
- Low cost
- Ruggedness
- Simplicity of construction
- Low maintenance
- Less likely to stall or slip
- Will work in any environment
- Excellent start-stop and reversing responses

Disadvantages of stepper motors

- Low torque capacity compared to DC motors
- Limited speed
- During overloading, the synchronization will be broken. Vibration and noise occur when running at high speed.

✓ SERVO MOTORS

- Servomotors are special electromechanical devices that produce precise degrees of rotation.
- A servo motor is a DC or AC or brushless DC motor combined with a position sensing device.
- Servomotors are also called control motors as they are involved in controlling a mechanical system.
- The servomotors are used in a closed-loop servo system as shown in Figure A reference input is sent to the servo amplifier, which controls the speed of the servomotor.



Servo system block diagram

- A feedback device is mounted on the machine, which is either an encoder or resolver.
- This device changes mechanical motion into electrical signals and is used as a feedback.
- This feedback is sent to the error detector , which compares the actual operation with that of the reference input.
- If there is an error, that error is fed directly to the amplifier, which will be used to make necessary corrections in control action.

- In many servo systems, both velocity and position are monitored.

- Servomotors provide accurate speed, torque, and have ability of direction control.

DC servomotors

DC operated servomotors are usually respond to error signal abruptly and accelerate the load quickly. A DC servo motor is actually an assembly of four separate components, namely:

  - DC motor
  - gear assembly
  - position-sensing device
  - control circuit

AC servo motor

- Magnetic force is generated by a permanent magnet and current which further produce the torque.
- It has no brushes so there is little noise/vibration. This motor provides high precision control with the help of high resolution encoder.
- The stator is composed of a core and a winding. The rotor part comprises of shaft, rotor core and a permanent magnet.
- Digital encoder can be of optical or magnetic type. It gives digital signals, which are in proportion of rotation of the shaft.

Advantages of servo motors

- Provides high intermittent torque, high torque to inertia ratio, and high speeds
- Work well for velocity control
- Available in all sizes
- Quiet in operation
- Smoother rotation at lower speeds

Disadvantages of servo motors

- More expensive than stepper motors
- Require tuning of control loop parameters
- Not suitable for hazardous environments or in vacuum
- Excessive current can result in partial demagnetization of DC type servo motor

➢ LINEAR MOTION DRIVES

- Linear motion drives are mechanical transmission systems which are used to convert rotary motion into linear motion.

- The conventional thread forms like vee or square are not suitable in CNC because of their high wear and less efficiency.

- Therefore CNC machines generally employ ball screw for driving their workpiece carriages.

- These drives provide backlash free operation with low friction-wear characteristics.

- These are efficient and accurate in comparison with that of nut-and-screw drives. Most widely used linear motion drives are ball screws.