DEPARTMENT OF MECHANICAL ENGINEERING,
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UNIVERSITY OF AGRICULTURE, ABEOKUTA.

LECTURE NOTE

COURSE TITLE: MANUFACTURING SCIENCE AND TECHNOLOGY

COURSE CODE: MCE 313
COURSE UNITS: 2

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Course Contents: Basic manufacturing industries and processes including casting, forging, assembling, inspection/attesting and certification; packaging, warehousing and forwarding. Metal working operations; shaping, planning, milling, drilling, turning, reaming, broaching, abrasive machining, chip-less machine processes. Metal cutting tools and cutting fluids; cutting forces and power requirement for cutting. Threads, gears, selection of materials; processing methods and equipment for manufacturing. Fabrication methods including welding, soldering, brazing adhesive bonding and mechanical fastening. Heat treatment. Tools for wood-working. Quality control in manufacturing.

Number of Units: 2

1.0 Introduction

Manufacturing was derived from two Latin words namely *manus* (hand) and *factus* (made). Therefore, manufacturing literally means "made with hand" of "hand made".
Manufacturing engineering can be defined as "the study of the processes required to produce parts and assemble them into machines and mechanisms". Manufacturing engineering produces various machines for the use of a nation and thus, the economic and industrial growth of a nation is dependent on the development of engineering industries. The living condition of the people in terms of shelter, clothing and food is determined by how much they produce and the level of production is dependent on manufacturing capability.
Manufacturing technology techniques are of necessity in modern industries where machines, tools and equipment are produced from basic materials with the use of basic manufacturing processes.

1.1 Basic Manufacturing Processes

Manufacturing may be classified into four based of the scale of production as follows:

(a) Piece or Job or Lot Production: This is when parts are produced in small quantities to satisfy a specific demand. The production is that of 'one-off' part and the companies in this type of manufacturing use mainly general purpose equipment, standard cutting tools and universal measuring facilities. There is compliance with the principle of interchangeability and they use skilled labour for the manufacturing of lots. Examples include companies that manufacture giant hydro- and steam-turbines, aeroplanes, rolling mills, refineries etc.

(b) Medium or Batch Production: This is concerned with the manufacture of parts in repeated lots or batches and to a specific order. The company under this category requires special production facilities and storage space for stock. The equipment used is general purpose type equipped with universal, adjustable and sectional built-up jigs, fixtures and tools which reduce labour input and cost of production substantially. Examples include companies that manufacture machine tools, compressors and print books.

(c) Mass or Flow Production: This involves a continuous and progressive processing of material in such a way that a product-in progress is passed to the next stage as soon as one operation is completed on it. The companies in this category manufacture standardized products in a continuous manner. They make use of specialized and single purpose machine tools with strict compliance with the principle of interchangeability which reduces the time required for assembly operations. In flow production, semi-skilled or unskilled workers are required to operate the machines while the setting up the company requires a high capital, the unit cost of production is low. Examples are companies that manufacture or produce bolts, nuts, washers, automobiles, biros, pencils, matches, beverages etc.

(d) Process Production: Involves the manufacture of bulk quantities of material and the time required for the manufacture is is equal to or is a multiple of the standard time along the production line. Examples include refineries, oil plant, continuous chemical plant etc.

1.2 Classification of Manufacturing Processes

Manufacturing processes may be grouped into the following main categories:

(i) Casting Processes: This is a process whereby molten metal is poured into a prepared temporary or permanent mould and is allowed to solidify and take the shape of the mould. Examples include sand casting, permanent mould casting, centrifugal casting etc.

(ii) Machining processes: This is also known as metal cutting and is the removal of metal in the form of chips from a work piece to get the required shape. Examples of machining processes include the conventional methods such as milling, drilling, turning, broaching and non-conventional methods such as Electro-Discharge Machining (EDM), Abrasive Jet Machining (AJM) and Water Jet Machining (WJM).

(iii) Powder Metallurgy: This involves the pressing and sintering of various sizes of particles of ceramics, polymers, glass, etc. to obtain the final product. It may also be referred to as 'Particulate Method'.

(iv) Plastic Materials/Polymers Processing Methods: This include various methods for processing plastic materials /polymers and various moulding processes (compression moulding, injection moulding, thermoforming, etc)

(v) Deformation Processes: These operations induce shape changes on the work piece by plastic deformation under the action of forces applied by various tools and dies to produce a required shape. The deformation may be hot or cold. During this process, there is no removal of material but displacement to get the final shape. Deformation processes include metal working/forming processes such as forging, rolling, extrusion, drawing; sheet metal working processes such as deep drawing and bending etc; unconventional forming processes such as High Energy Rate Forming (HERF) and High Velocity Forming (HVF) are part of these processes.

(vi) Joining Processes: These are the joining of two or more components to produce a required product. It includes welding, brazing, soldering, diffusion, bonding, riveting, bolting and adhesive bonding.

(vii) Heat Treatment and Surface Treatment Processes: These are the processes employed to improve the properties of a work piece. The processes include annealing, normalising, hardening, and tempering methods. Surface treatment methods include electro-plating and painting etc.

(viii) Assembly Processes: The assembly processes for machines and mechanisms are the parts of manufacturing process concerned with the consecutive joining of the finished parts into assembly units and complete machines of a quality that meets the manufacturing specifications.

(ix) Inspection and Certification: Inspection of assembled parts is done to ensure that the products certify the quality requirements. Quality products are then certified OK for packaging.

(x) Packaging, Warehousing and Forwarding Processes: Packaging involves putting the products into cartons for onward transfer to warehouse (warehousing) and for delivery to the consumers/customers.

2.0 METAL WORKING PROCESSES

2.1 Casting Processes

Casting is a process in which molten metal flows into a mould where it solidifies in the shape of the mould cavity. The part produced is also called *casting*.

Advantages
Complex shapes
Net-shape ability
Very large parts
Variety of metals
Mass production

Disadvantages
Poor accuracy
Poor surface
Internal defects
Mechanical properties
Environmental impact

2.1.1 Sand Casting

The basic production steps in sand casting are:
(i) Preparation of sand (ii) Making of mould (iii) Melting of metal (iv) Pouring of molten metal into Mould (v) Solidification and Cooling of molten metal (iv) Removal of cast material

Casting technology involves the following steps:

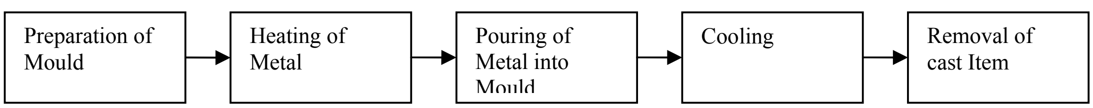


Figure 1: Steps in Casting Technology

2.1.1.1 Casting nomenclature

Figure 2.1 shows the nomenclature of mould and castings in sand casting.

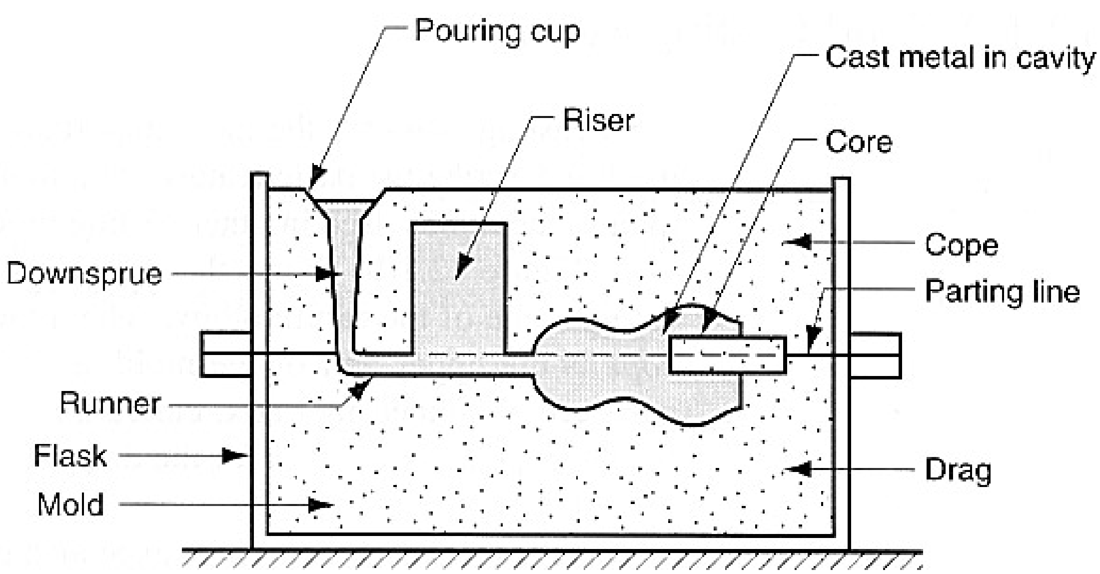


Figure 2.2: Nomenclature in Casting

The pouring cup, downsprue, runners, etc., are known as the *mould gating system*, which serves to deliver the molten metal to all sections of the mould cavity.

2.1.2 Expendable Mould Casting

In expendable mould casting, the mould is destroyed to remove the casting and a new mould is required for each new casting.

Patterns

Patterns in sand casting are used to form the mould cavity. One major requirement is that patterns (and therefore the mould cavity) must be oversized (i) to account for shrinkage in cooling and solidification, and (ii) to provide enough metal for the subsequence machining operation(s).

Cores

Cores serve to produce internal surfaces in castings in some cases; they have to be supported by *chaplets* for more stable positioning. Cores are made of foundry sand with addition of some resin for strength by means of *core boxes*.

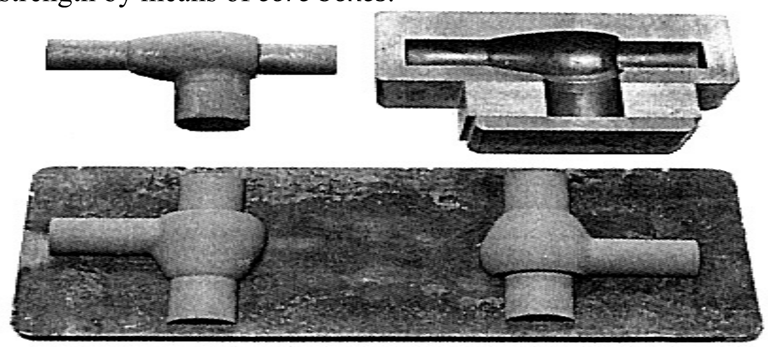


Figure 2.3: Cores used in casting

Foundry sands

The typical foundry sand is a mixture of fresh and recycled sand, which contains 90% silica ($SiO2$), 3% water, and 7% clay.

The *grain size* and *grain shape* are very important as they define the surface quality of casting and the major mould parameters such as strength and permeability

Shell moulding

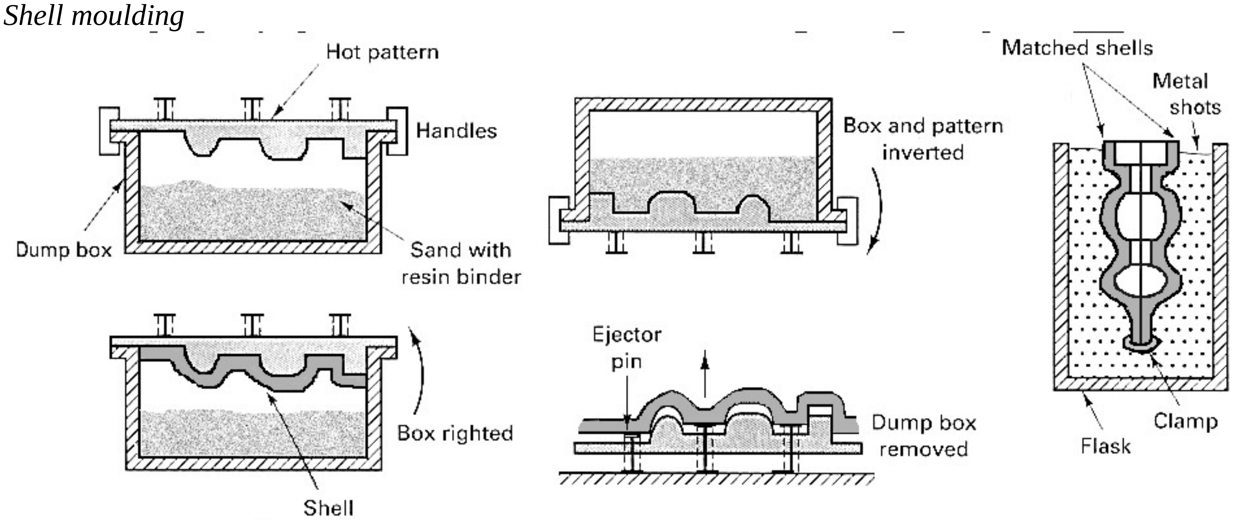


Figure2.4: Steps in shell moulding

Advantages:
Good surface finish (up to 2.5 mm)
Good dimensional accuracy (±0.25 mm)
Suitable for mass production

Disadvantages:
Expensive metal pattern
Area of application:
Mass production of steel casting of less than 10 kg

2.1.3 Investment casting (lost wax casting)

In investment casting, the pattern is made of wax, which melts after making the mold to produce the mould cavity. Steps in Investment casting are shown in Figure 5:

Steps in investment casting: (1) wax patterns are produced; (2) several patterns are attached to a sprue to form a pattern tree; (3) the pattern tree is coated with a thin layer of refractory material; (4) the full mold is formed by covering the coated tree with sufficient refractory material to make it rigid; (5) the mold is held in an inverted position and heated to melt the wax and permit it to drip out of the cavity; (6) the mold is preheated to a high temperature, which ensures that all contaminants are eliminated from the mold; it also permits the liquid metal to flow more easily into the detailed cavity; the molten metal is poured; it solidifies and (7) the mold is broken away from the finished casting. Parts are separated from the sprue.

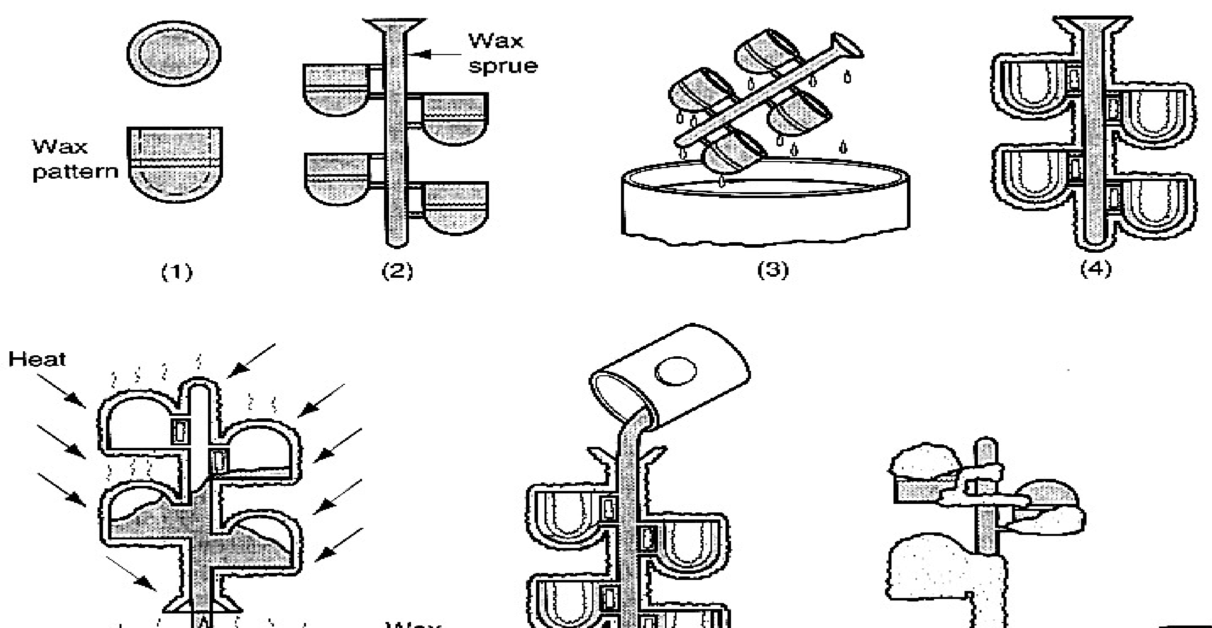


Figure 2.5: Steps in Investment casting

Advantages:
Arbitrary complexity of castings
Good dimensional accuracy
Good surface finish
No or little additional machining (net or near-net process)
Wax can be reused

Disadvantages:
Very expensive process

Requires skilled labour

Area of application:
Can be used to produce small, complex parts such as art pieces, jewellery, and dental fixtures from all types of metals. Used to produce machine elements such as gas turbine blades, pinion gears, etc. which do not require or require only little subsequent machining.

2.1.4 Permanent Mould Casting Processes
In contrary to sand casting, in permanent mould casting the mould is used to produce not a single but many castings.
Steps in permanent mould casting

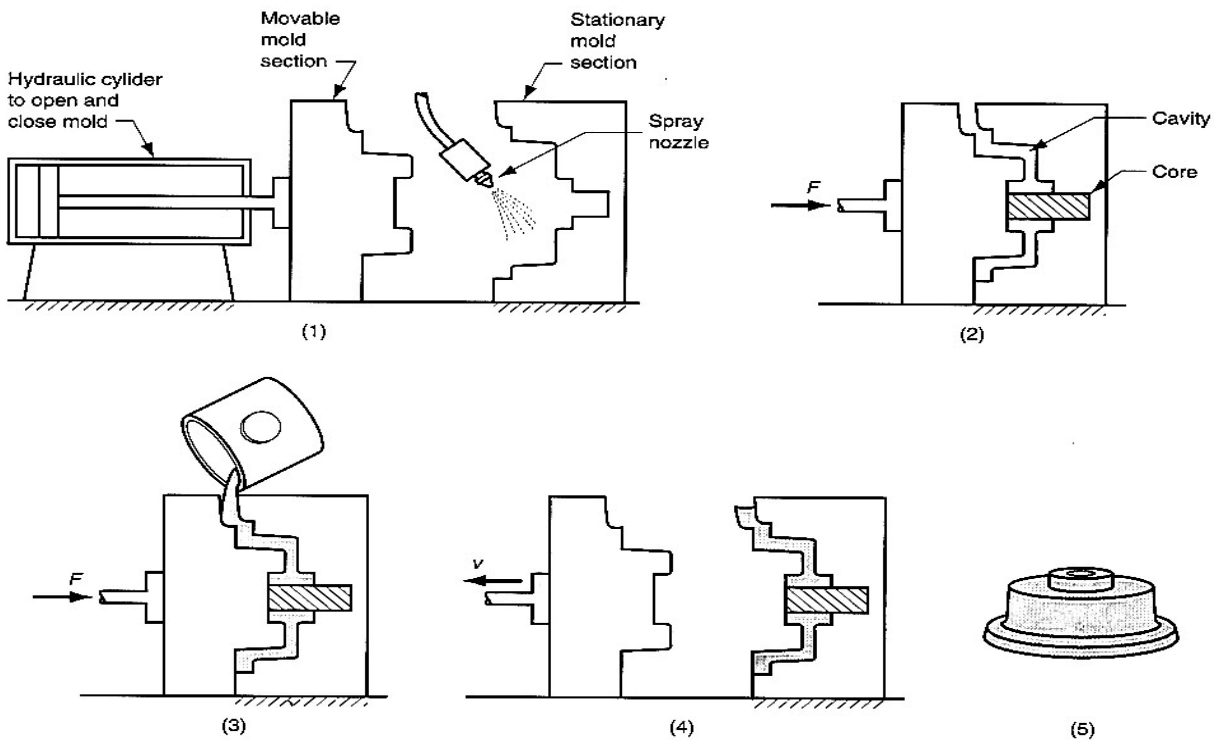


Figure2.6: Steps in permanent mould casting: (1) mould is preheated and coated with lubricant for ease of separation of the casting; (2) cores (if used) are inserted and mould is closed; (3) molten metal is poured into the mould; and (4) mould is open and finished part removed. Finished part is shown in (5)

Advantages:
Good dimensional accuracy
Good surface finish
Finer grain structure (stronger casting)
Possibility for automation
Disadvantages:
Only for metals with low melting point
Castings with simple geometry
Area of application:
Mass production of non-ferrous alloys and cast iron

2.1.5 Die-casting

Hot-chamber die-casting in hot chamber die-casting, the metal is melted in a container attached to the machine, and a piston is used to inject the liquid metal under high pressure into the die.

Advantages:
High productivity (up to 500 parts per hour)
Close tolerances
Good surface finish
Disadvantages:
The injection system is submerged in the molten metal
Only simple shapes
Area of application:
Mass production of non-ferrous alloys with very low melting point (zinc, tin, lead)

Cold chamber die casting
In cold-chamber die-casting, molten metal is poured into the chamber from an external melting container, and a piston is used to inject the metal under high pressure into the die cavity.
Advantages:
Same as in hot chamber die-casting, but less productivity.
Disadvantages:
Only simple shapes
Area of application:
Mass production of aluminium and magnesium alloys, and brass

2.1.5 Centrifugal casting

True centrifugal casting

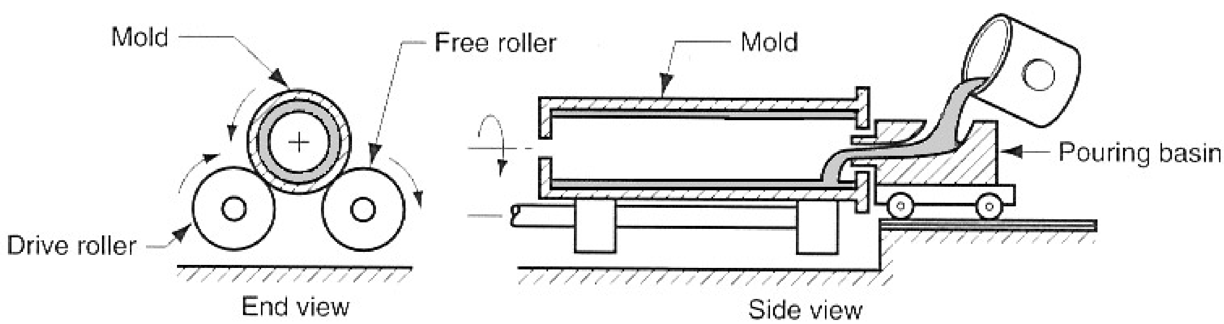


Figure 2.7: True horizontal centrifugal casting

In true centrifugal casting, molten metal is poured into a rotating mold to produce tubular parts such as pipes, tubes, and rings.

Semi-centrifugal casting

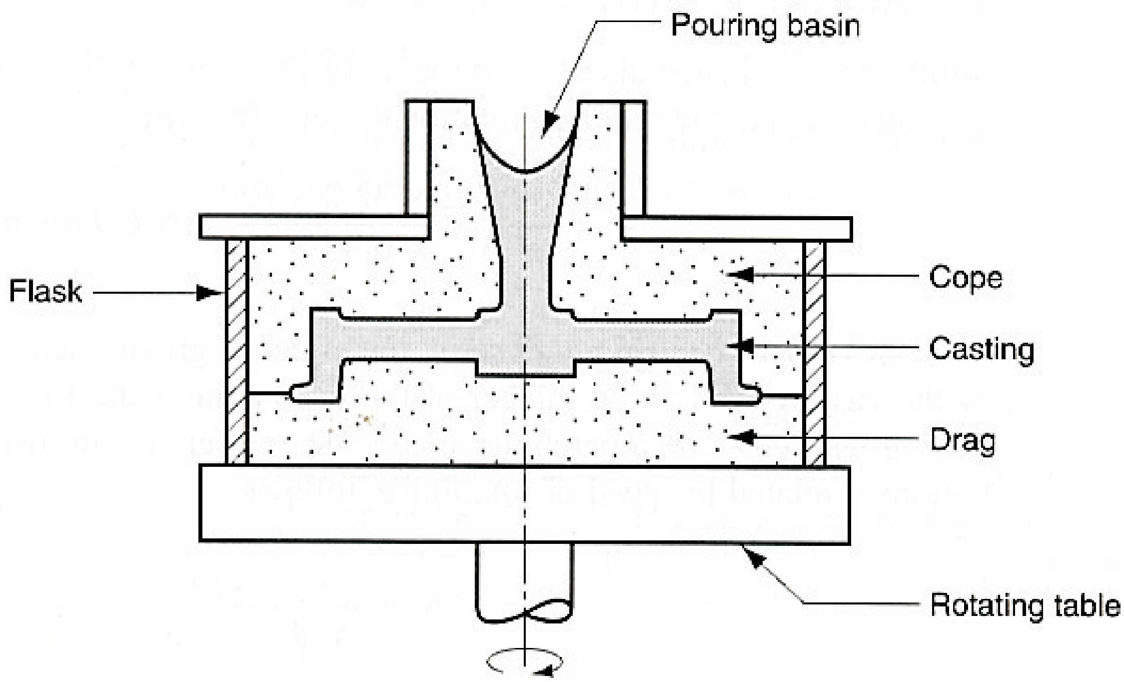


Figure 2.8: Semi-centrifugal casting

In this method, centrifugal force is used to produce solid castings rather than tubular parts. Density of the metal in the final casting is greater in the outer sections than at the centre of rotation. The process is used on parts in which the centre of the casting is machined away, such as wheels and pulleys.

2.1.6 Casting Quality

There are numerous opportunities in the casting operation for different defects to appear in the cast product. Some of them are common to all casting processes:

Misruns: Casting solidifies before completely fill the mould. Reasons are low pouring temperature, slow pouring or thin cross section of casting.

Cold shut: Two portions flow together but without fusion between them. Causes are similar to those of a misrun.

Cold shots: When splattering occurs during pouring, solid globules of metal are entrapped in the casting. Proper gating system designs could avoid this defect.

Shrinkage cavity: Voids resulting from shrinkage. Proper riser design can often solve the problem but may require some changes in the part design as well.

Microporosity: Network of small voids distributed throughout the casting. The defect occurs more often in alloys, because of the manner they solidify.

Hot tearing: These are cracks caused by low mould collapsibility. They occur when the material is restrained from contraction during solidification. A proper mould design can solve the problem.

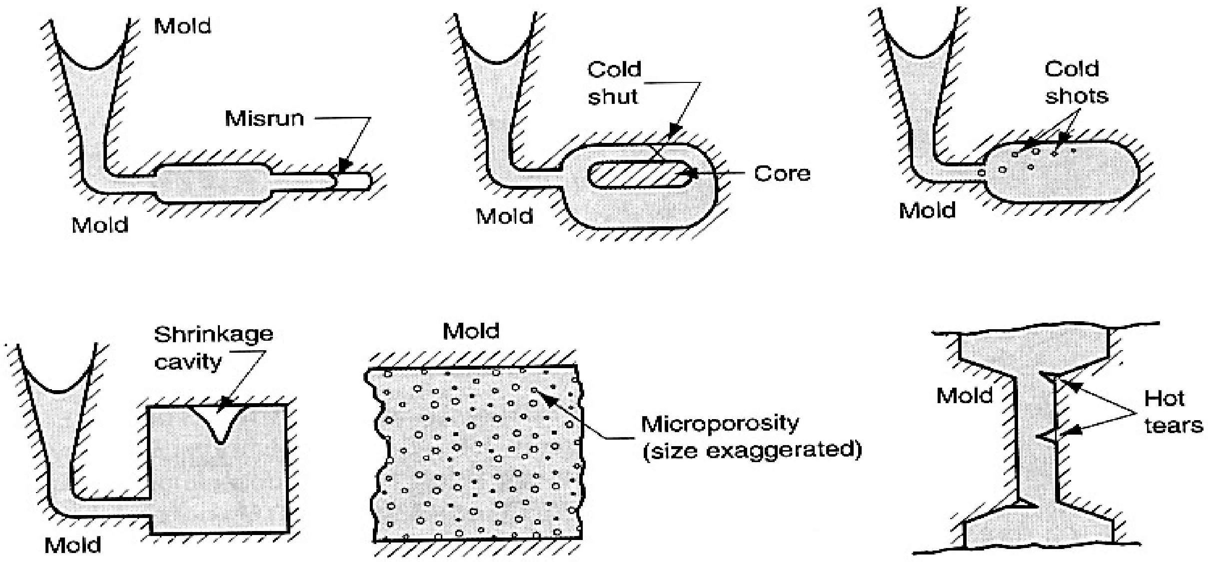


Figure 2.9: Some defects of casting

Some defects are typical only for some particular casting processes, for instance, many defects occur in sand casting because of interaction between the sand mould and the molten metal. Defect found primarily in sand casting are gas cavities, rough surface areas, shift of the two halves of the mould, or shift of the core, etc.

2.1.7 Heating and pouring

Heating

The estimated total heat required is the sum of the following:

(i) Heat to raise the temperature to the melting point

(ii) Heat of fusion

(iii) Heat to raise the molten metal temperature to the temperature of pouring

Pouring

The major factors that affect the pouring action are:

(i) Pouring temperature

(ii) Pouring rate

(iii) Turbulence

Some important equations in pouring:

The following equations are necessary in pouring during a casting operation:

(i) Velocity of the liquid metal at the base of the sprue, v is given by:

$v \ \sqrt{2gh}$ *where g=acceleration due to gravity and h is the sprue height*

(ii) Volumetric flow rate, *Q = vA where A=Casting's cross-sectional area and v is as above*

(iii) Mould filling time: *MFT = V/Q, where V=Mould cavity volume*

Fluidity

Fluidity is a measure of the capability of a metal to flow into and to fill the mould before freezing. It defines to the great extend the quality of casting.

The factors that affect fluidity are:

(i) Pouring temperature

(ii) Metal composition

(iii) Heat transfer to the surroundings
(iv) Viscosity of the liquid metal

In the foundry practice, test for fluidity is carried out for each ladle just before pouring the molten metal into the mould.

Solidification and cooling

Solidification of metals

Pure metals solidify at a constant temperature equal to their freezing point as shown in Figure 10

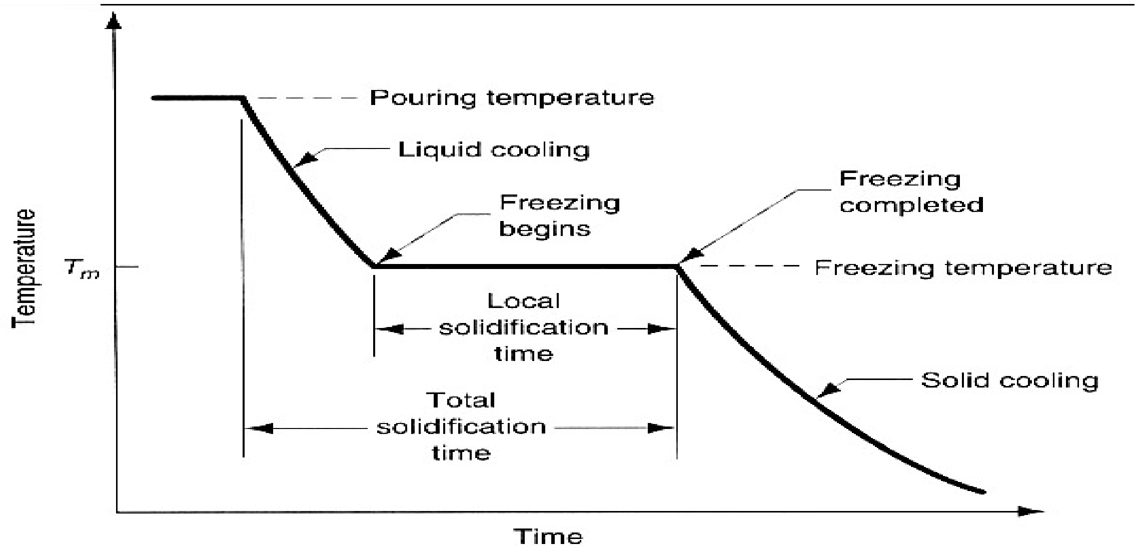


Figure2.10: Graph of freezing time against temperature

Most *alloys* freeze over a temperature range for example copper as shown in Figure 11

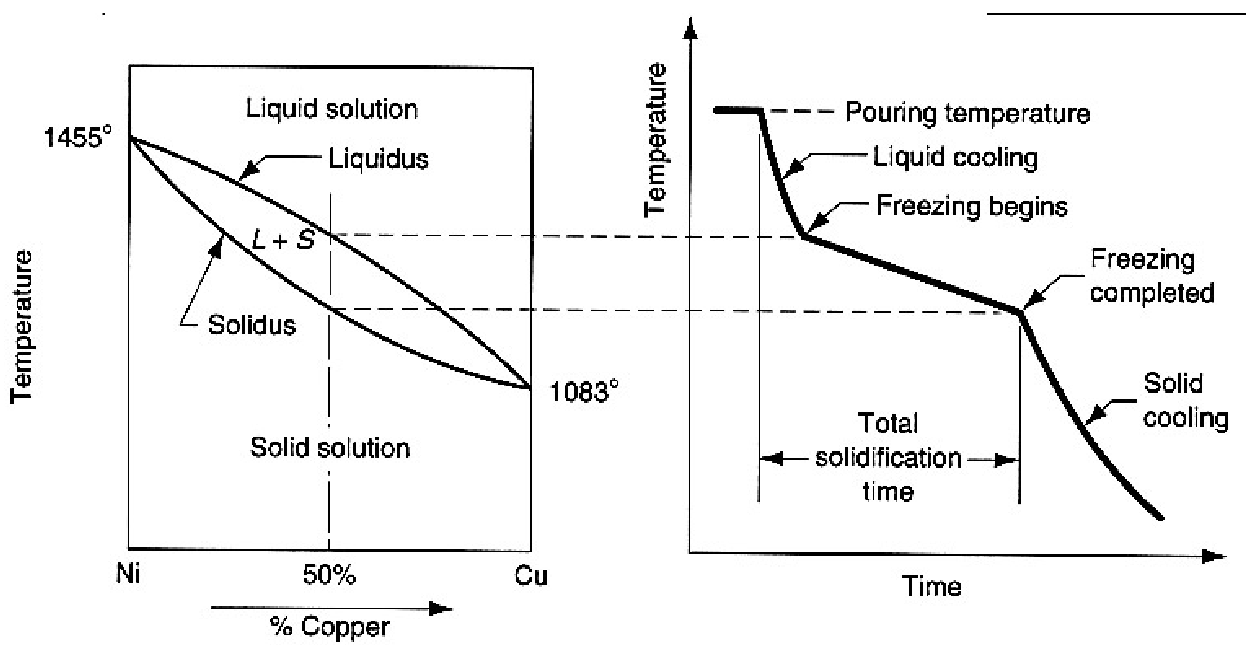


Figure 2.11: Freezing temperature of copper against time.

Solidification time
The following equation can be used to calculate the solidification time during casting:
Chvorinov's rule

TST—total solidification time
Cm—mould constant
V—volume of the casting
A—surface area of the casting
n—constant, usually n=2
TST = $\mathrm{Cm}\left(V / A^{n}\right)$

2.2 Deformation Processes
These processes involve large amount of plastic deformation. The cross-section of work piece changes without volume change. The ratio *cross-section area/volume* is small. For most operations, hot or warm working conditions are preferred although some operations are carried out at room temperature.

2.3 Sheet-Forming Processes
In sheet metalworking operations, the cross-section of work piece does not change—the material is only subjected to shape changes. The ratio *cross-section area/volume* is very high. Sheet metalworking operations are performed on thin (less than 6 mm) sheets, strips or coils of metal by means of a set of tools called punch and die on machine tools called stamping presses. They are always performed as cold working operations.

Cold working is metal forming performed at room temperature.
Advantages: better accuracy, better surface finish, high strength and hardness of the part, no heating is required.
Disadvantages: higher forces and power, limitations to the amount of forming, additional annealing for some material is required, and some material are not capable of cold working.
Warm working is metal forming at temperatures above the room temperature but below the recrystallization one.
Advantages: lower forces and power, more complex part shapes, no annealing is required.
Disadvantages: some investment in furnaces is needed.
Hot working involves deformation of preheated material at temperatures above the re-crystallization temperature.
Advantages: big amount of forming is possible, lower forces, power is required, forming of materials with low ductility, no work hardening, and therefore, no additional annealing is required.
Disadvantages: lower accuracy and surface finish, higher production cost, and shorter tool life.

2.4 Plastic Deformation Processes
Operations that induce shape changes on the work piece by plastic deformation under forces applied by various tools and dies.

Classification of Deformation Processes
Basic deformation processes
(a) rolling, (b) forging, (c) extrusion, (d) drawing

2.4.1Rolling: Compressive deformation process in which the thickness of a plate is reduced by squeezing it through two rotating cylindrical rolls.

Rolling is a deformation process in which the thickness of the work is reduced by compressive forces exerted by two opposing rolls.

Flat rolling

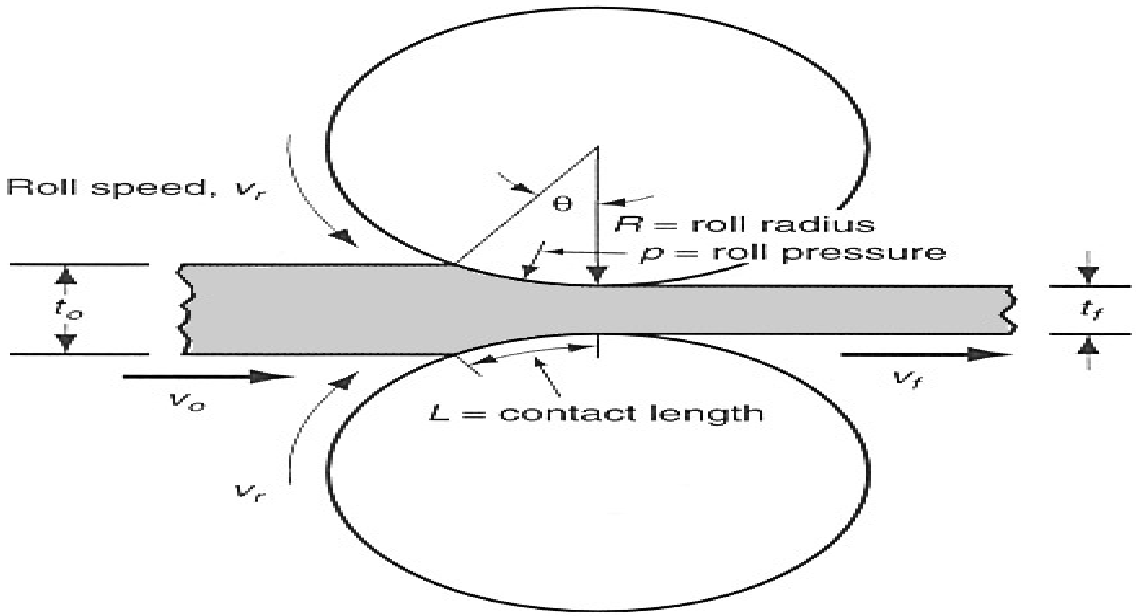


Figure 2.12: Flat rolling process

2.4.2 Forging: The work piece is compressed between two opposing dies so that the die shapes are imparted to the work.

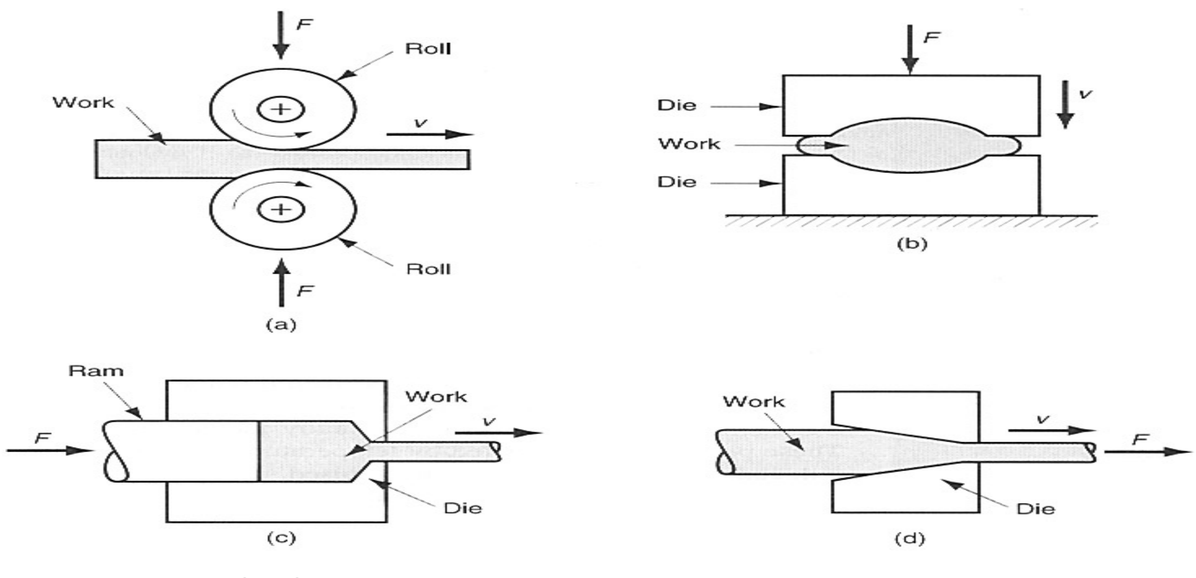


Figure 2.13: Types of Deformation processes

Extrusion: The work material is forced to flow through a die opening taking its shape

***Drawing*:** The diameter of a wire or bar is reduced by pulling it through a die opening (bar drawing) or a series of die openings (wire drawing)

2.5 Classification of Sheet Metalworking Processes

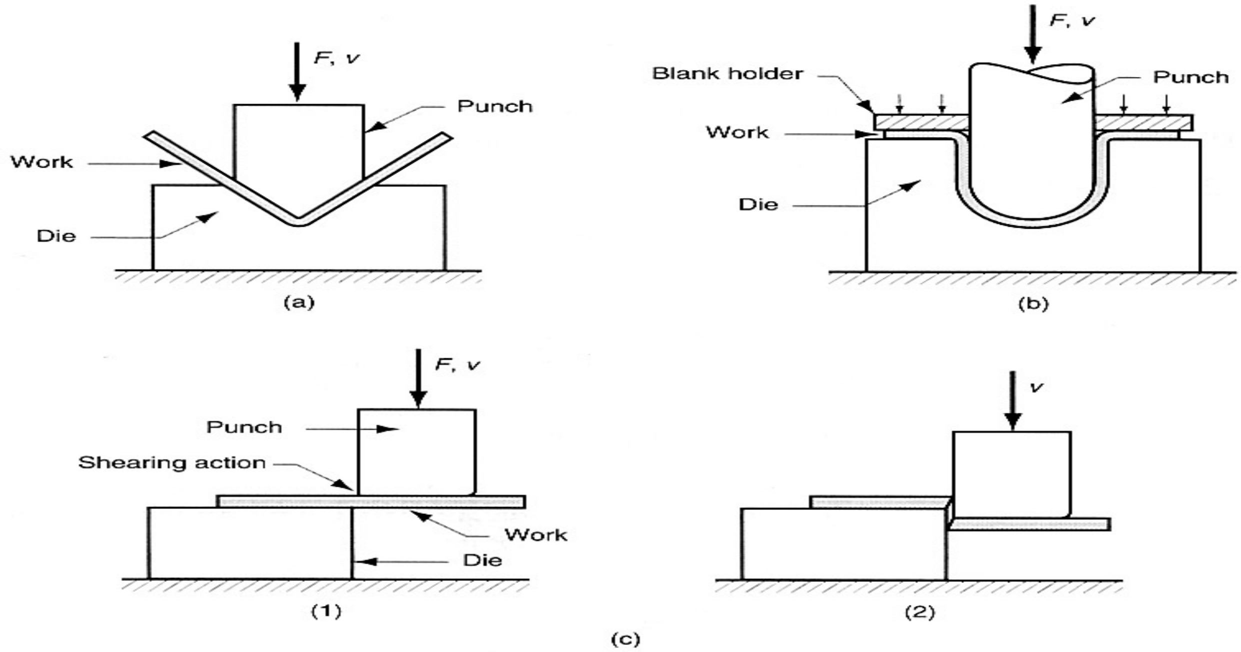


Figure 2.14: Basic sheet metalworking operations: (a) bending, (b) drawing, and (c) shearing; (1) as punch first contacts sheet and (2) after cutting. In the Figure, F and v indicate force and relative motion

2.6 *Turning*

Turning is a machining process to produce parts round in shape by a single point tool on *lathes*. The tool is fed in either the direction parallel or perpendicular to the axis of rotation of the work piece, or along a specified path to produce complex rotational shapes. The *primary* motion of cutting in turning is the rotation of the work piece, and the *secondary* motion of cutting is the feed motion.

Cutting conditions in turning

Cutting speed in turning V in m/s is related to the rotational speed of the work piece by the equation:
$V = \pi DN$, where D is the diameter of the work piece, m; N is the rotational speed of the work piece, rev/s.
One should remember that cutting speed V is always a linear vector. In the process planning of a turning operation, cutting speed V is first selected from appropriate reference sources or calculated, and the rotational speed N is calculated taking into account the work piece diameter D. Rotational speed, not cutting speed, is then used to adjust lathe setting levers.
Feed in turning is generally expressed in mm (millimetres per revolution).
The turning operation reduces the diameter of the work piece from the initial diameter Do to the final diameter D_f. The change in diameter is actually two times *depth of cut*, d:
$2d = D_o - D_f$
The volumetric rate of material removal (so-called *material removal rate*, *mrr*) is defined by
$mrr = Vfd$
When using this equation, care must be exercised to assure that the units for V are consistent with those for f and d.

Operations in turning

Turning is not a single process but class of many and different operations performed on a lathe.

Turning of cylindrical surfaces
The lathe can be used to reduce the diameter of a part to a desired dimension. The resulting machined surface is cylindrical.

Turning of flat surfaces
A lathe can be used to create a smooth, flat face very accurately perpendicular to the axis of a cylindrical part. Tool is fed radially or axially to create a flat machined surface.

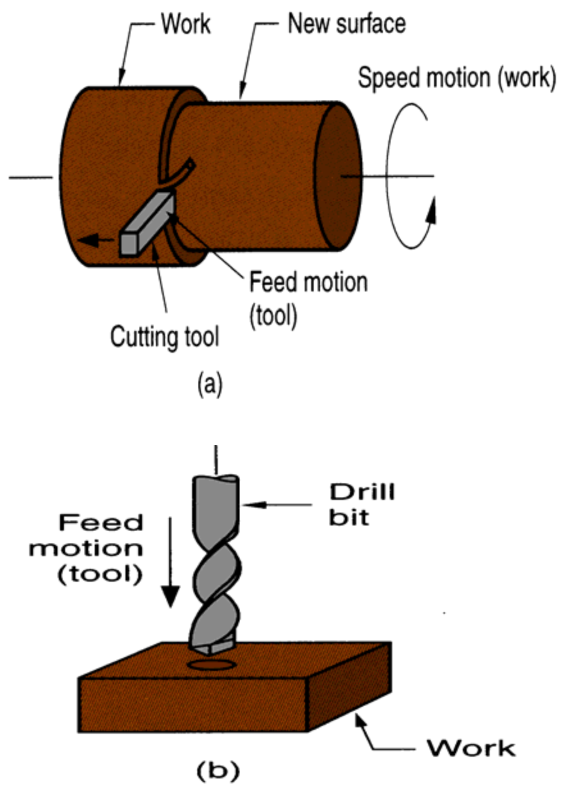


Figure 2.15: (a) Turning operation   (b) Drilling operation
Source: Groover (2007)
Threading
Different possibilities are available to produce a thread on a lathe. Threads are cut using lathes by advancing the cutting tool at a feed exactly equal to the thread pitch. The single-point cutting tool cuts in a helical band, which is actually a thread. The procedure calls for correct settings of the machine, and also that the helix be restarted at the same location each time if multiple passes are required to cut the entire depth of thread. The tool point must be ground so that it has the same profile as the thread to be cut. Another possibility is to cut threads by means of a *thread die* (external threads), or a *tap* (internal threads). These operations are generally performed manually for small thread diameters.

Knurling
This is not a machining operation at all, because it does not involve material removal. Instead, it is a metal forming operation used to produce a regular crosshatched pattern in the work surface.

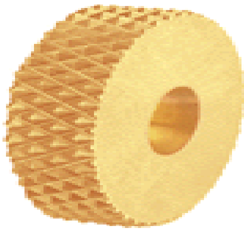


Figure 2.15: Knurling wheel

Lathes

A lathe is a machine tool that rotates the work piece against a tool whose position it controls. The *spindle* is the part of the lathe that rotates. Various work-holding attachments such as *three jaw chucks*, *collets*, and *centers* can be held in the spindle. The spindle is driven by an electric motor through a system of belt drives and gear trains. Spindle rotational speed is controlled by varying the geometry of the drive train.

The *tailstock* can be used to support the end of the work piece with a *centre*, or to hold tools for drilling, reaming, threading, or cutting tapers. It can be adjusted in position along the *ways* to accommodate different length work pieces. The *tailstock barrel* can be fed along the axis of rotation with the *tailstock hand wheel*.

The *carriage* controls and supports the cutting tool. It consists of:

(i) a *saddle* that slides along the *ways*;

(ii) an *apron* that controls the feed mechanisms;

(iii) a *cross slide* that controls transverse motion of the tool (toward or away from the operator);

(iv) a *tool compound* that adjusts to permit angular tool movement;

(v) a *tool post* that holds the cutting tools.

Engine lathes

This is the basic, simplest, and most versatile lathe. This machine tool is manually operated that is why it requires skilled operators. Suitable for low and medium production and for repair works.

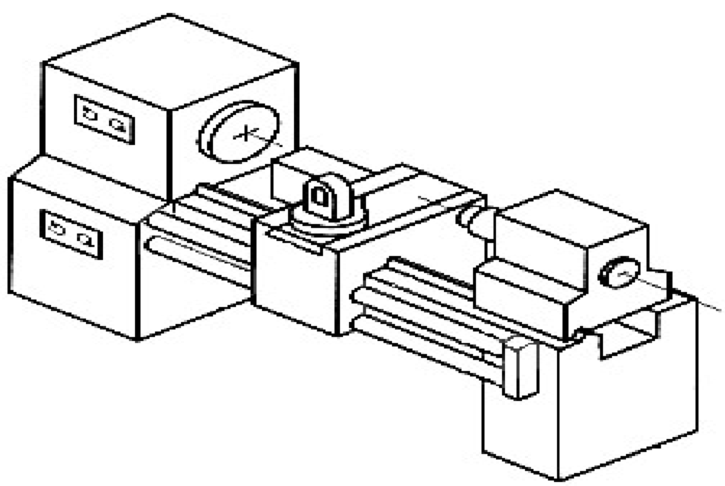


Figure 2.16: The principal components of an engine lathe

There are two tool feed mechanism in the engine lathes. These cause the cutting tool to move when engaged.

(i) The *lead screw* will cause the apron and cutting tool to advance quickly. This is used for cutting threads, and for moving the tool quickly.
(ii) The *feed rod* will move the apron and cutting tool slowly forward. This is largely used for most of the turning operations.

Work is held in the lathe with a number of methods,
(i) Between two *centres*. A device called a dog drives the work piece; the method is suitable for parts with high *length-to-diameter ratio*.
(ii) A *3 jaw self-centering chuck* is used for most operations on cylindrical work parts. For parts with high *length-to-diameter ratio* the part is supported by centre on the other end.
(iii) *Collet* consists of tubular bushing with longitudinal slits. Collets are used to grasp and hold barstock. A collet of exact diameter is required to match any barstock diameter.
(iv) A *face plate* is a device used to grasp parts with irregular shapes:

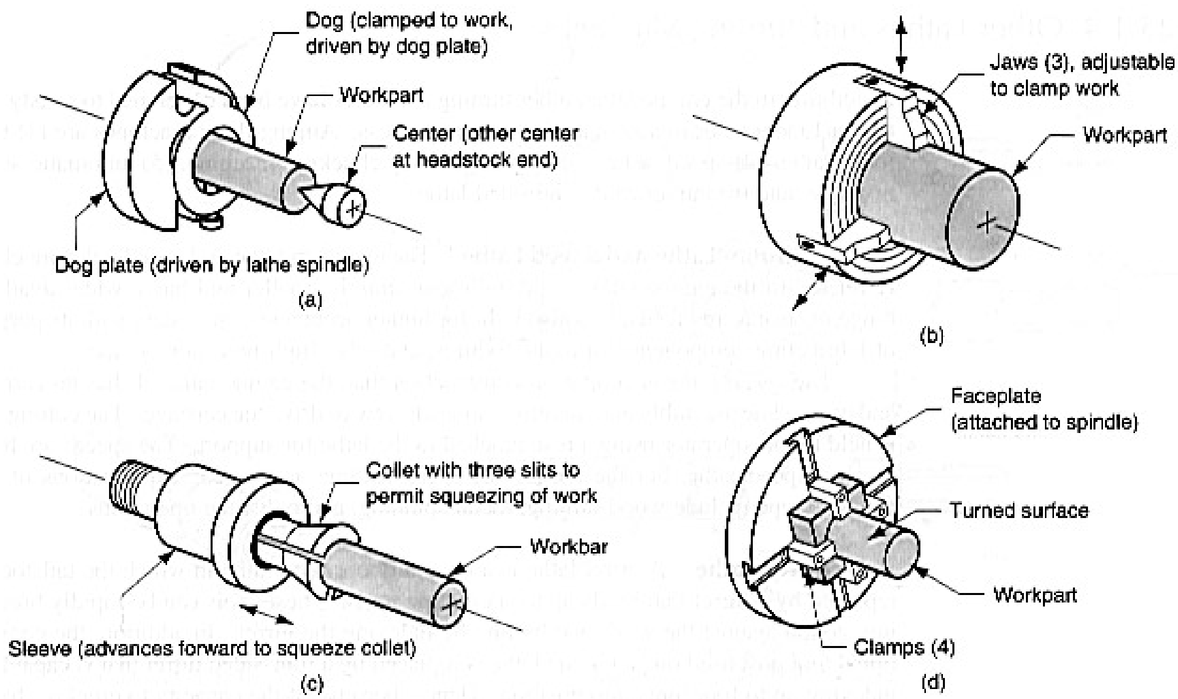


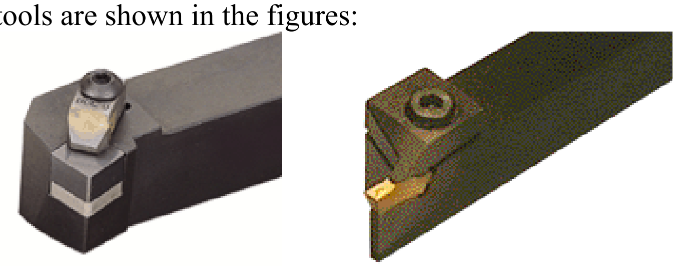
Figure 2.17: Four Work-holding methods used in lathes: (a) mounting the work between centres using a dog, (b) three-jaw chuck, (c) collet, and (d) face plate for noncylindrical work parts.

Computer-controlled lathes (CNC lathes)
Computer-controlled (*numerically controlled*, *NC*, *CNC*) lathes incorporate a computer system to control the movements of machine components by directly inserted coded instructions in the form of numerical data. A CNC lathe is especially useful in contour turning operations and precise machining. There are also not chuck but bar modifications. A CNC lathe is essentially a turret lathe. The major advantage of these machines is in their versatility - to adjust the CNC lathe for a different part to be machined requires a simple change in the computer program and, in some cases, a new set of cutting tools.

Figure 2.18: CNC Lathe Machine

Cutting tools

Cutting tool are available in different brazed or clamped designs for different operations. Some of the clamped tools are shown in the figures:



Cutting tool for grooving

Cutting tool for straight turning

Figure 2.19: Cutting tools on tool post

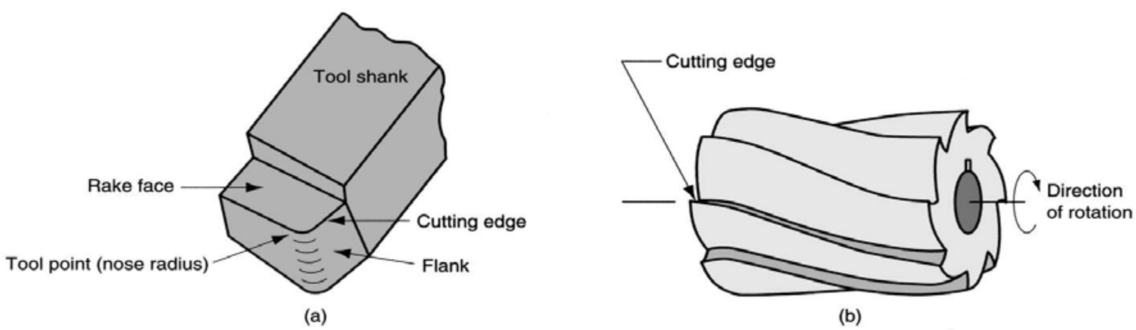


Figure 2.20: (a) A single-point tool showing rake face, flank, and tool point; and (b) a helical milling cutter, representative of tools with multiple cutting edges.

2.7 Milling

Milling is a process of producing flat and complex shapes with the use of multi-tooth cutting tool, which is called a *milling cutter* and the cutting edges are called *teeth*. The axis of rotation of the cutting tool is perpendicular to the direction of feed, either parallel or perpendicular to the machined surface.

The machine tool that traditionally performs this operation is a *milling machine*.

Milling is an interrupted cutting operation: the teeth of the milling cutter enter and exit the work during each revolution. This interrupted cutting action subjects the teeth to a cycle of impact force and thermal shock on every rotation. The tool material and cutter geometry must be designed to withstand these conditions. Cutting fluids are essential for most milling operations.

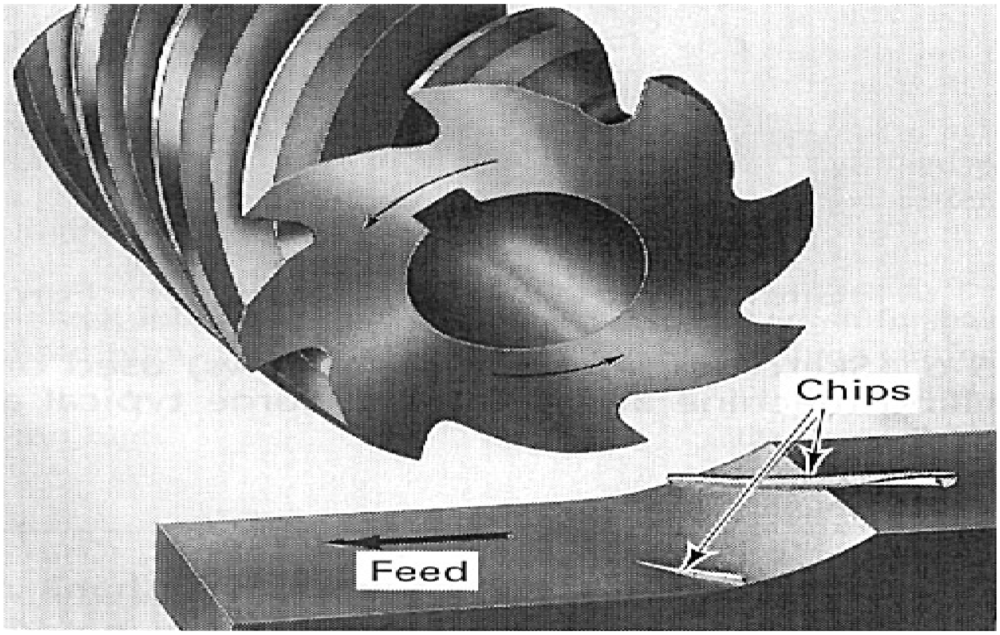


Figure 2.20: Milling operation.
The cutter in Figure 2.20 is lifted to show the chips, and the work, transient, and machined surfaces.

2.7.1Cutting conditions in milling
In milling, each tooth on a tool removes part of the stock in the form of a chip. The basic interface between tool and workpart is shown in Figure 2.20. This shows a only a few teeth of a peripheral milling cutter:

Cutting velocity V is the peripheral speed of the cutter is defined by
$V = \pi DN$, where D is the cutter outer diameter, and N is the rotational speed of the cutter.
As in the case of turning, cutting speed V is first calculated or selected from appropriate reference sources, and then the rotational speed of the cutter N,
which is used to adjust milling machine controls is calculated. Cutting speeds are usually in the range of 0.1~4 m/s, lower for difficult-to-cut materials and for rough cuts, and higher for non-ferrous easy-to-cut materials like aluminium and for finishing cuts.
Three types of *feed* in milling can be identified as follows:
(i) *feed per tooth* f_z: the basic parameter in milling equivalent to the feed in turning. Feed per tooth is selected with regard to the surface finish and dimensional accuracy
required . Feeds per tooth are in the range of 0.05~0.5 mm/tooth, lower feeds are for finishing cuts;
(ii) *feed per revolution* f_r: it determines the amount of material cut per one full revolution
of the milling cutter. Feed per revolution is calculated as
$f_r = f_z z$, z being the number of the cutter's teeth;
(iii) *feed per minute* fm: Feed per minute is calculated taking into account the rotational
speed N and number of the cutter's teeth z, $f_m = f_z zN = f_r N$
Feed per minute is used to adjust the feed change gears.

2.7.2 Types of milling
There are two basic types of milling:
(i) *down* (*climb*) milling, when the cutter rotation is in the same direction as the motion of the work piece being fed. In down milling, the cutting force is directed into the work table, which allows thinner

work parts to be machined. Better surface finish is obtained but the stress load on the teeth is abrupt, which may damage the cutter.

(ii) *up* (*conventional*) milling, in which the work piece is moving towards the cutter, opposing the cutter direction of rotation. In up milling, the cutting force tends to lift the work piece. The work conditions for the cutter are more favourable. Because the cutter does not start to cut when it makes contact (cutting at zero cut is impossible), the surface has a natural waviness.

2.7.3 Milling Operations

Owing to the variety of shapes possible and its high production rates, milling is one of the most versatile and widely used machining operations. The geometric form created by milling fall into three major groups:
(i) *Plane surfaces*: the surface is linear in all three dimensions. The simplest and most convenient type of surface;
(ii) *Two-dimensional surfaces*: the shape of the surface changes in the direction of two of the axes and is linear along the third axis. Examples include cams;
(iii) *Three-dimensional surfaces*: the shape of the surface changes in all three directions. Examples include die cavities, gas turbine blades, propellers, casting patterns, etc.

2.7.3.1Peripheral Milling

In *peripheral milling*, also called *plain milling*, the axis of the cutter is parallel to the surface being machined, and the operation is performed by cutting edges on the outside periphery of the cutter. The primary motion is the rotation of the cutter. The feed is imparted to the work piece. Several types of peripheral milling as shown in Figures 21 and 22 are:
(i) *slab milling*, the basic form of peripheral milling in which the cutter width extends beyond the work piece on both sides;
(ii) *slotting*, also called *slot milling*, in which the width of the cutter, usually called *slotter*, is less than the work piece width, creating a slot in the work piece. The slotter has teeth on the periphery and over the both end faces. When only the one-side face teeth are engaged, the operations is known as the *side milling*, in which the cutter machines the side of the work piece;
(iii) *straddle milling*, which is the same as side milling, only cutting takes place on both sides of the work. In straddle milling, two slotters mounted on an arbor work together;
(iv) when the slotter is very thin, the operation called *slitting* can be used to mill narrow slots (slits) or to cut a work part into two. The slitting cutter (*slitter*) is narrower than the slotter and has teeth only on the periphery.

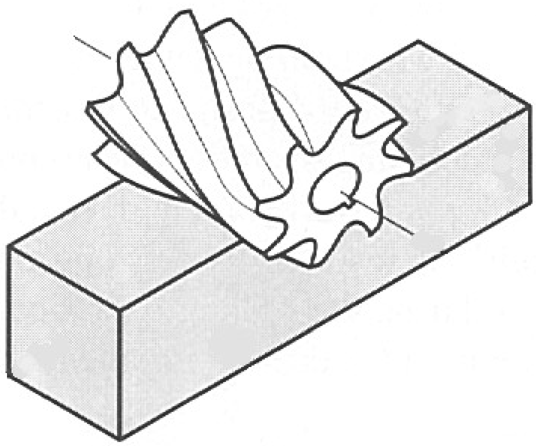
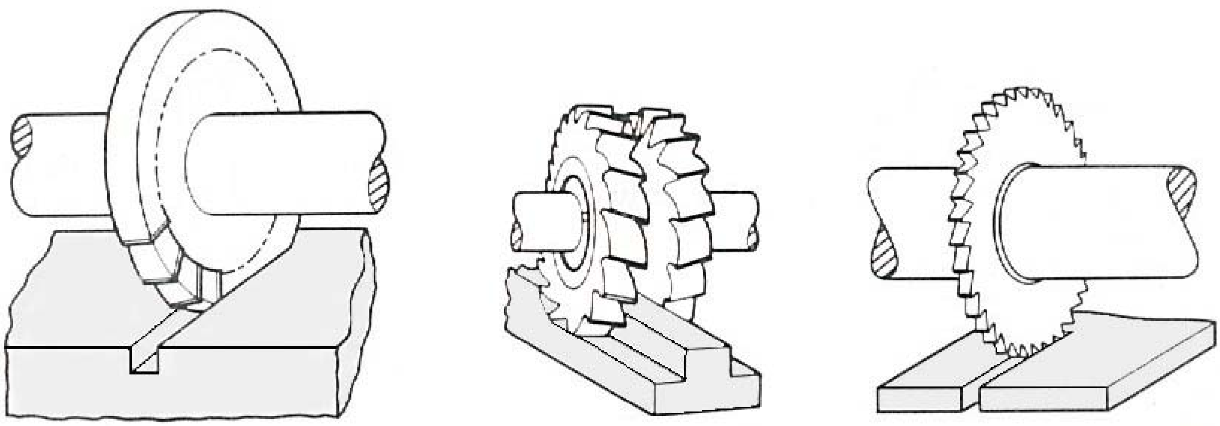


__Figure 2.21: Peripheral slab milling operation__



(a) (b) (c)

Figure 2.22: Peripheral milling operations with narrow cutters: (a) slotting, (b) straddle milling, and (c) slitting.

Some of the advantages of peripheral milling include,

(i) More stable holding of the cutter. There is less variation in the arbor torque;

(ii) Lower power requirements;

(iii) Better work surface finish.

2.7.4 Face milling

In *face milling*, cutter is perpendicular to the machined surface. The cutter axis is vertical, but in the newer CNC machines it often is horizontal. In face milling, machining is performed by teeth on both the end and periphery of the face-milling cutter. Again up and down types of milling are available, depending on directions of the cutter rotation and feed.

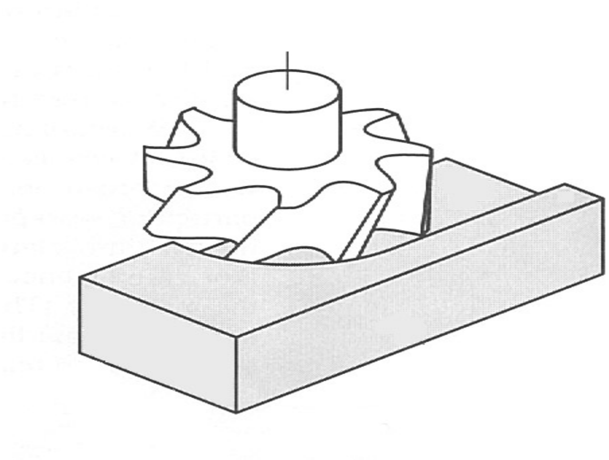


Figure 2.23: Partial face milling operation.
The face-milling cutter machines only one side of the work piece.

Face milling is usually applied for rough machining of large surfaces. Surface finish is worse than in peripheral milling, and feed marks are inevitable. One advantage of the face milling is the high production rate because the cutter diameter is large and as a result the material removal rate is high. Face milling with large diameter cutters requires significant machine power.

2.7.5 End milling
In *end milling*, the cutter, called *end mill*, has a diameter less than the workpiece width. The end mill has helical cutting edges carried over onto the cylindrical cutter surface. End mills with flat ends (so called *squire-end mills*) are used to produce pockets, closed or end key slots, etc.

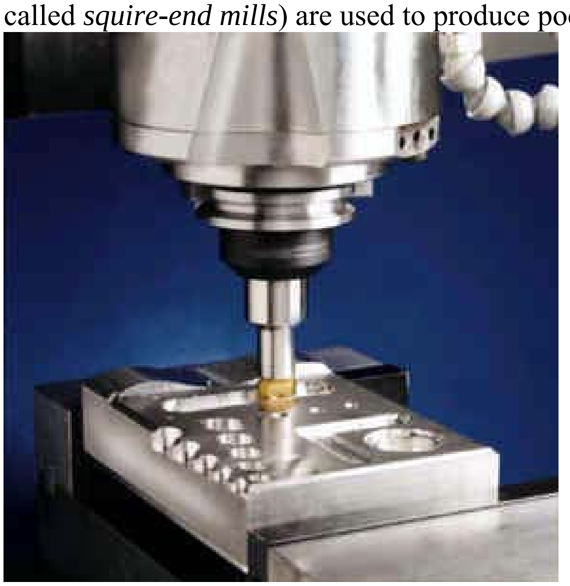


Figure 2.24: End milling operation used to cut a pocket in an aluminium work part.

2.7.6 Milling machines
The conventional milling machines provide a primary rotating motion for the cutter held in the spindle, and a linear feed motion for the workpiece, which is fastened onto the worktable. Milling machines for machining of complex shapes usually provide both a rotating primary motion and a curvilinear feed motion for the cutter in the spindle with a stationary workpiece. Various machine

designs are available for various milling operations. In this section we discuss only the most popular ones, classified into the following types:
(i) Column-and-knee milling machines;
(ii) Bed type milling machines;
(iii) Machining centers.

Column-and-knee milling machines
The *column-and-knee milling machines* are the basic machine tool for milling. The name comes from the fact that this machine has two principal components, a *column* that supports the spindle, and a *knee* that supports the work table. There are two different types of column-and-knee milling machines according to position of the spindle axis: horizontal, and vertical.

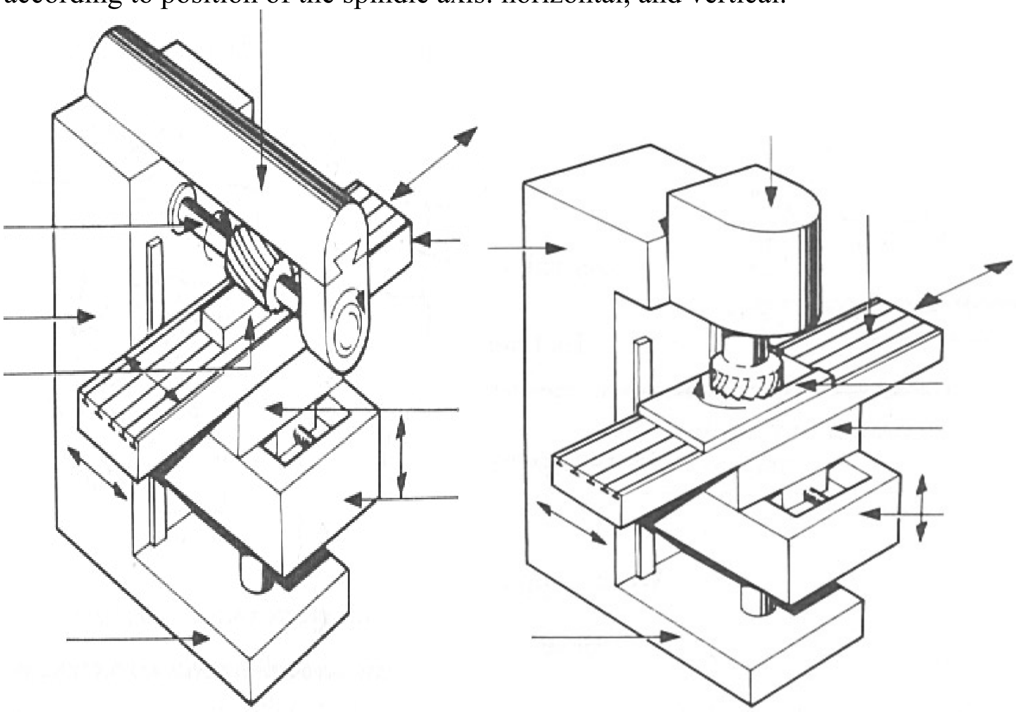


Figure 2.25: Two basic types of column-and-knee milling machines, (Left) horizontal, and (Right) vertical.

2.8 Drilling and Reaming
Drilling is a process of producing round holes in a solid material or enlarging existing holes with the use of multi-tooth cutting tools called *drills* or *drill bits*. Various cutting tools are available for drilling, but the most common is the *twist drill*.
Reaming is a process of improving the quality of already drilled holes by means of cutting tools called *reamers*. Drilling and reaming are performed on a *drilling press*, although other machine tools can also perform this operation, for instance lathes, milling machines, machining centers.
In drilling and reaming, the primary motion is the rotation of the cutting tool held in the spindle. Drills and reamers execute also the secondary feed motion. Some finishing reaming operations are manual.

2.8.1Cutting conditions in drilling
The twist drill is a cutting tool with two symmetrical opposite cutting edges, each removing part of the material in the form of chip.
Cutting velocity V in drilling is not a constant along the major cutting edge as opposed to the other machining operations. It is zero at the center of the twist drill, and has a maximum value at the drill corner. The maximum cutting speed is given by

$V = \pi DN$, where D is the drill diameter, and N is the rotational speed of the drill.
Two types of *feed* in drilling can be identified:
(i) *feed per tooth* f_z: has the same meaning as in the other multi-tooth cutting tools. Feeds per tooth are roughly proportional to drill diameter, higher feeds for larger diameter drills.
(ii) *feed per minute* fm: feed per minute is calculated taking into account the rotational speed N and is $f_m = 2f_zN$
Feed per minute is used to adjust the feed change gears.
In drilling, *depth of cut* d is equal to the half of drill diameter, $d = 1/2\ D$, where D is the drill diameter.
In core drilling, a drilling operation used to enlarge an existing hole of diameter D_{hole}, depth of cut is given by $d = 1/2\ (D_{drill} - D_{hole})$ where D_{drill} is the drill diameter, and D_{hole} is the diameter of the hole being enlarged.

Figure 2.26: Drilling Machine

2.9 Planning, Shaping and Broaching

These are machining operations that are used to machine straight and open external or internal surfaces.

2.9.1 Planning and Shaping

These operations are used to machine straight open mainly external surfaces with a single-point cutting tool *Planning* and *shaping* are similar operations, which differ in the kinematics of the process. Planning is a machining operation in which the primary cutting motion is performed by the work piece and feed motion is imparted to the cutting tool. In shaping, the primary motion is performed by the tool, and feed by the work piece:

2.9.2 Broaching

Broaching is a machining operation that involves the use of a multiple-tooth cutting tool moved linearly relative to the work piece in the direction of the tool axis. *Broaching* is used to machine straight and open internal surface of complex cross-section shapes by means of a special tool called a *broach* (Figure 2.27)

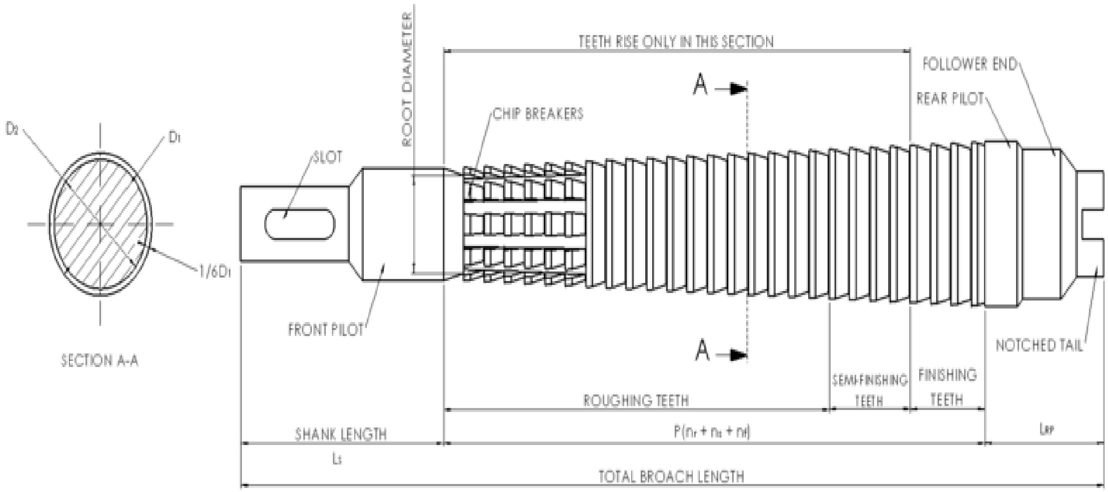


Figure 8.27: A broach

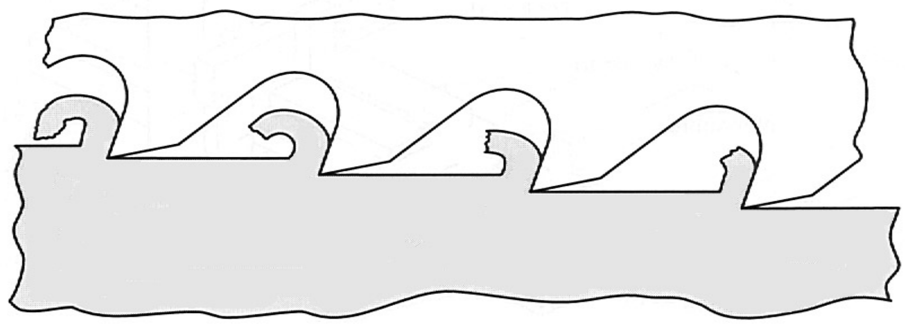


Figure 2.28: The broaching operation.

The broaching operation (Figure 2.18) is carried out on a machine tool that is called a *broaching machine*. The shape of the machined surface is determined by the contour of the cutting edges on the broach, particularly the shape of final cutting teeth. Broaching is a highly productive method of machining. Advantages include good surface finish, close tolerances, and the variety of possible machined surface shapes, some of them can be produced only by broaching. Owing to the complicated geometry of the broach, tooling is expensive. Broaching is a typical mass production operation.

Broaching can be used for machining of various integrate shapes which can not be otherwise machined with other operations. Some of the typical examples of shapes produced by internal broaching are shown in Figure 2.29.

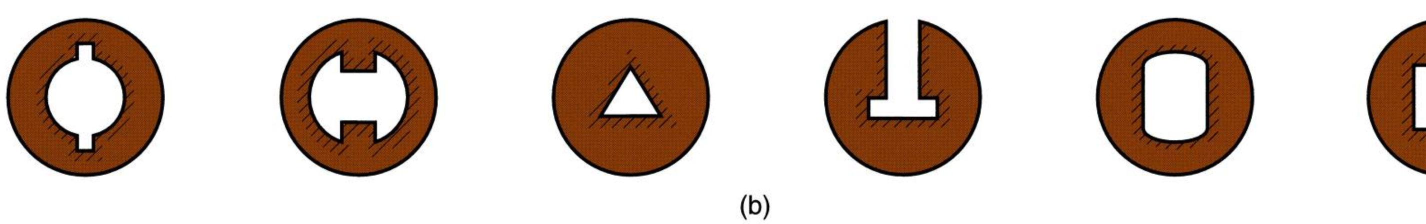


Figure 2.29: Internal Shapes cut by broaching

Productivity improvement to ten times or even more is common, as the metal removal rate by broaching is vastly greater. Roughing, semi finishing and finishing of the component is done just in one pass by broaching, and this pass is generally accomplished in seconds.

2.9.2.1 Cutting conditions in broaching

The *cutting speed* motion is accomplished by the linear travel of the broach past the work surface.
Feed in broaching is unique among machining operations, since is accomplished by the increased step between successive teeth on the broach. This step is actually the *feed per tooth*, fz. The feed per tooth is not a constant for all the teeth. The total material removed in a single pass of the broach or the *total feed* f is the cumulative result of all the steps in the tool. Since not all of the broach teeth are engaged simultaneously in cutting but only a part of them, the term *active cumulative feed* can be introduced, defined as the sum of all the steps only of the active teeth.
Depth of cut in broaching is defined as the length of the active cutting edge. In internal broaching, which is the most common type of broaching, the entire length of a single broach tooth is engaged in cutting and the depth of cut is actually the tooth circumference.
From the definitions of feed and depth of cut, it follows that the total area of cut and respectively the cutting force in broaching will be substantial.

2.10 Boring

Boring is a process of producing circular internal profiles on a hole made by drilling or another process. It uses single point cutting tool called a *boring bar*. In boring, the boring bar can be rotated, or the work part can be rotated. Machine tools which rotate the boring bar against a stationary workpiece are called *boring machines* (also *boring mills*). Boring can be accomplished on a turning machine with a stationary boring bar positioned in the tool post and rotating workpiece held in the lathe chuck.

2.11 Grinding

Abrasive machining is a material removal process that involves the use of abrasive cutting tools. Three principle types of abrasive cutting tools according to the degree to which abrasive grains are:
(i) *Bonded abrasive tools*: abrasive grains are closely packed into different shapes; the most common is the *abrasive wheel*. Grains are held together by bonding material. Abrasive machining process that use bonded abrasives includes *grinding*, *honing*, *super finishing;*
(ii) *Coated abrasive tools*: abrasive grains are glued onto a flexible cloth, paper, or resin backing. Coated abrasives are available in sheets, rolls, endless belts. Processes include *abrasive belt grinding*, *abrasive wire cutting*; *free abrasives*: abrasive grains are not bonded or glued. Instead, they are introduced either in oil-based fluids (*lapping*, *ultrasonic machining*), or in water (*abrasive water jet cutting*) or air (*abrasive jet machining*), or contained in a semi soft binder (*buffing*).
Regardless the form of the abrasive tool and machining operation considered, all abrasive operations could be considered as material removal processes with *geometrically undefined cutting edges*.
Abrasive machining can be likened to the other machining operations with multipoint cutting tools. Each abrasive grain acts like a small single cutting tool with undefined geometry but usually with high negative rake angle.
Abrasive machining involves a number of operations, used to achieve ultimate dimensional precision and surface finish. From the principal abrasive operations, grinding is covered in the present section, and some other operations are discussed in the next two sections.
Grinding is a material removal process in which abrasive particles arc contained in a bonded grinding wheel that operates at very high surface speeds. The grinding wheel is usually disk shaped and is precisely balanced for high rotational speeds.
The *cutting velocity* V in grinding is very high. It is related to the rotational speed of the wheel by

$V = \pi DN$ where d is the wheel diameter, and N is the rotational speed of the grinding wheel.
Depth of cut d is called *infeed* and is defined as the distance between the machined and work surfaces. As the operation proceeds, the grinding wheel is fed laterally across the work surface on each pass by the workpart. The distance at which the wheel is fed is called a *crossfeed*. The crossfeed is actually the *width of cut* w. The crossfeed multiplied by infeed determines the *cross-sectional area of cut*, CSA:
CSA = crossfeed × infeed = wd
The cross-sectional area in grinding is relatively small compared to other traditional machining operations. The work part moves past the wheel at a certain linear or rotational velocity called a *feed* Vw.
The *material removal rate*, mrr, is defined by
mrr = VwCSA

2.11.1 Wheel Wear
Three mechanisms are recognized as the principal causes of wear in grinding wheels:
(i) *grain fracture*,
(ii) *attritious wear*, and
(iii) *bond fracture*.
Grain fracture occurs when a portion of the grain breaks off but the rest of the grain remains bonded in the wheel. The edges of the fractured area become new sharp cutting edges on the grinding wheel. This makes the grinding wheel *self-sharpening*, a unique property of a cutting tool.
Attritious wear involves dulling of the individual grains, resulting in flat spots and rounded edges. Attritious wear is analogous to tool wear in a conventional cutting tool.
Bond fracture occurs when the individual grains are pulled out of the bonding material. Bond fracture usually occurs because the grain has become dull due to attritious wear and the resulting cutting force is excessive. Sharp grains cut more efficiently with lower cutting forces; hence, they remain attached in the bond structure.

2.11.2 Surface finish and effects of cutting temperature
Abrasive operations are performed to achieve a surface finish, which cannot be achieved by conventional machining processes. From the concept of composite cutting edge, it can be concluded that the surface finish is basically affected by the following process and tool parameters,
(i) *Abrasive grain size*: smaller grit size will produce lower surface roughness;
(ii) *Structure*: more dense structure of the grinding will, i.e., more abrasive grains per cubic millimetre will increase the number of active grains in contact with the work surface thus improving the surface finish;
(iii) *Cutting velocity*: The surface finish will be improved by increasing the number of abrasive grains per unit time, therefore by increasing the cutting speed.
The ultimate surface finish in grinding with fine grit size is about 0.2 μm.
The influence of these parameters is deducted from simple geometrical considerations. But in a discussion on surface finish in grinding, the influence of the cutting temperature cannot be omitted. Temperature rise in grinding can significantly affect surface properties. Furthermore, the heat generated and conducted into the workpiece expands the workpart and causes dimensional errors.
Tempering: excessive temperatures can temper and soften the material on the surfaces, which is often ground in the hardened state.
Burning: if the temperature is excessive the surface may burn. Burning produces a bluish colour on steels, which indicates high temperature oxidation with all the negative changes in the surface material properties.
Thermal cracks: high temperatures may also lead to thermal cracking of the surface of the work piece. Cracks are usually perpendicular to the grinding direction; however, under severe grinding conditions, parallel cracks may also develop.

Residual stresses: temperature change and gradients within the work piece are mainly responsible for residual stresses in grinding.
Excessive temperature has a negative effect on the work surface. Grinding process parameters must therefore be chosen carefully to avoid excessive temperature rise. The use of grinding fluids can effectively control cutting temperatures.

2.11.3 Grinding wheel
A *grinding wheel* consists of abrasive particles and bonding material. The bonding material holds the particles in place and establishes the shape and structure of the wheel.

The way the abrasive grains, bonding material, and the air gaps are structured, determines the parameters of the grinding wheel, which are
(i) *abrasive material*,
(ii) *grain size*,
(iii) *bonding material*,
(iv) *wheel grade*, and
(v) *wheel structure*.
To achieve the desired performance in a given application, each parameter must be carefully selected.

2.11.4 Abrasive material
The *abrasive materials* of greatest commercial importance today are listed in the table:

Abrasive material	Work material
Aluminum oxide	
97-99% Al_2O_3 hardened steels, 87-96% Al_2O_3	hardened steels, HSS steels, cast iron
Silicon carbide	
96-99% SiC	HSS, cemented carbides
<96% SiC	aluminum, brass, brittle materials
Cubic boron nitride (CBN)	tool steels, aerospace alloys
Synthetic diamond	ceramics, cemented carbides

2.11.5 Grain size
The *grain size* of the abrasive particle is an important parameter in determining surface finish and material removal rate. Small grit sizes produce better finishes while larger grain sizes permit larger material removal rates.
Grain sizes used in grinding wheels typically range between 6 and 600. Grit size 6 is very coarse and size 600 is very fine. Finer grit sizes up to 1000 are used in some finishing operations.
Bonding Materials
The *bonding material* holds the abrasive grains and establishes the shape and structural integrity of the grinding wheel. Desirable properties of the bond material include strength, toughness, hardness, and temperature resistance.
Bonding materials commonly used in grinding wheels include the following:
(i) *vitrified bond*: vitrified bonding material consists chiefly of ceramic materials. Most

grinding wheels in common use are vitrified bonded wheels. They are strong and rigid, resistant to elevated temperatures, and relatively unaffected by cutting fluids;
(ii) *rubber bond*: rubber is the most flexible of the bonding materials. It is used as a bonding material in cutoff wheels;
(iii) *resinoid bond*: this bond is made of various thermosetting resin materials. They have very high strength and are used for rough grinding and cut off operations;
(iv) *shellac bond*: shellac-bonded grinding wheels are relatively strong but not rigid. They are often used in applications requiring a good finish;
(v) *metallic bond*: metal bonds, usually bronze, are the common bond material for diamond and CBN grinding wheels. Diamond and CBN abrasive grains are bond material to only the outside periphery of the wheel, thus conserving the costly abrasive materials.

2.11.6 Wheel grade

Wheel grades indicate the wheel bond strength. It is measured on a scale ranging from *soft* to *hard*. Soft wheels loose grains easily and are used for low material removal rates and grinding of hard materials. Harder grades are preferred for high productivity and grinding of relatively soft materials,

2.11.7 Structure

The *wheel structure* indicates spacing of the abrasive grains in the wheel. It is measured on a scale that anges from *open* to *dense*. Open structure means more pores and fewer grains per unit wheel volume, and vice versa. Open structure is recommended for work materials that tend to produce continuous chips, while denser structure is used for better surface finish and dimensional precision.

Grinding wheel specification

Grinding wheels are marked with a standardized system of letters and numbers, which specifies the parameters of the grinding wheel.

2.11.8 Grinding operations

Grinding operations are carried out with a variety of wheel-workpart configurations. The basic types of grinding are
(i) *surface grinding*,
(ii) *cylindrical grinding*, and
(iii) *centerless grinding*.

Surface grinding

Surface grinding is an abrasive machining process in which the grinding wheel removes material from the plain flat surfaces of the work piece. In surface grinding, the spindle position is either *horizontal* or *vertical*, and the relative motion of the work piece is achieved either by *reciprocating* the workpiece past the wheel or by *rotating* it.

3.0 CUTTING FLUIDS, CUTTING FORCES AND POWER REQUIREMENTS FOR CUTTING

3.1 Cutting Fluids

Cutting fluid (*coolant*) is any liquid or gas that is applied to the chip and/or cutting tool to improve cutting performance. A very few cutting operations are performed dry, i.e., without the application of cutting fluids. Generally, it is essential that cutting fluids be applied to all machining operations.

Cutting fluids serve three principle functions:

(i) to *remove heat* in cutting: the effective cooling action of the cutting fluid depends on the method of application, type of the cutting fluid, the fluid flow rate and pressure. The most effective cooling is provided by *mist application* combined with *flooding*. Application of fluids to the tool flank, especially under pressure, ensures better cooling that typical application to the chip but is less convenient.
(ii) to *lubricate* the chip-tool interface: cutting fluids penetrate the tool-chip interface improving lubrication between the chip and tool and reducing the friction forces and temperatures.
(iii) to *wash away* chips: this action is applicable to small, discontinuous chips only. Special devices are subsequently needed to separate chips from cutting fluids.

3.1.1 Methods of application

Manual application
This is the application of a fluid from a can manually by the operator. It is not acceptable even in job-shop situations except for tapping and some other operations where cutting speeds are very low and friction is a problem. In this case, cutting fluids are used as *lubricants*.

Flooding
In flooding, a steady stream of fluid is directed at the chip or tool-work piece interface. Most machine tools are equipped with a recirculating system that incorporates filters for cleaning of cutting fluids. Cutting fluids are applied to the chip although better cooling is obtained by applying it to the flank face under pressure:

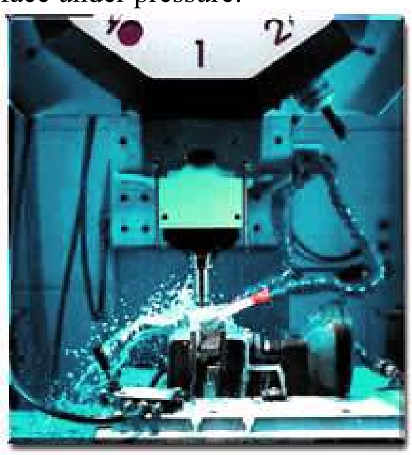


Figure 3.1: Application of flooding in milling

Coolant-fed tooling
Some tools, especially drills for deep drilling, are provided with axial holes through the body of the tool so that the cutting fluid can be pumped directly to the tool cutting edge.

Mist applications
Fluid droplets suspended in air provide effective cooling by evaporation of the fluid. Mist application in general is not as effective as flooding, but can deliver cutting fluid to inaccessible areas that cannot be reached by conventional flooding.

3.1.2 Types of cutting fluid
Cutting Oils

Cutting oils are cutting fluids based on mineral or fatty oil mixtures. Chemical additives like sulphur improve oil lubricant capabilities. Areas of application depend on the properties of the particular oil but commonly, cutting oils are used for heavy cutting operations on tough steels.

Soluble Oils

The most common, cheap and effective form of cutting fluids consisting of oil droplets suspended in water in a typical ratio water to oil 30:1. Emulsifying agents are also added to promote stability of emulsion. For heavy-duty work, extreme pressure additives are used. Oil emulsions are typically used for aluminium and cooper alloys.

Chemical fluids

These cutting fluids consist of chemical diluted in water. They possess good flushing and cooling abilities. Tend to form more stable emulsions but may have harmful effects to the skin.

3.1.3Environmental issues

Cutting fluids become contaminated with garbage, small chips, bacteria, etc., over time. Alternative ways of dealing with the problem of contamination are:
(i) replace the cutting fluid at least twice per month,
(ii) machine without cutting fluids (dry cutting),
(iii) use a filtration system to continuously clean the cutting fluid.
Disposed cutting fluids must be collected and reclaimed. There are a number of methods of reclaiming cutting fluids removed from working area. Systems used range from simple settlement tanks to complex filtration and purification systems. Chips are emptied from the skips into a pulverizer and progress to centrifugal separators to become a scrap material. Neat oil after separation can be processed and returned, after cleaning and sterilizing to destroy bacteria.

3.2 Cutting Forces

The forces that act during a cutting operation are:

(i) The normal force F_n that is perpendicular to the shear plane.
(ii) The shear force F_s
(iii) The cutting force F_c that is responsible for the total work done in cutting.
(iv) The trust force, F_t which is perpendicular to F_c

Friction force *F* and Normal force to friction *N*
Shear force F_s and Normal force to shear F_n
Vector addition of *F* and *N* = resultant *R*
Vector addition of F_s and F_n = resultant *R*'
Forces acting on the chip must be in balance:
R' must be equal in magnitude to *R*
R' must be opposite in direction to *R*
R' must be collinear with *R*
Coefficient of friction between tool and chip:

$$\mu = \frac{F}{N}$$

Friction angle related to coefficient of friction as follows:

$$\mu = \tan \beta$$

Shear stress acting along the shear plane:

$$S = \frac{F_s}{A_s}$$

where As = area of the shear plane

$$A_s = \frac{t_o w}{\sin \phi}$$

Shear stress = shear strength of work material during cutting

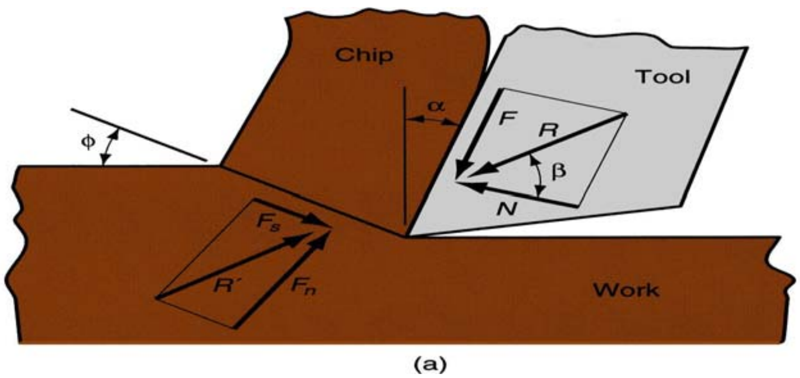


Figure 3.2: Forces in metal cutting: (a) forces acting on the chip in orthogonal cutting

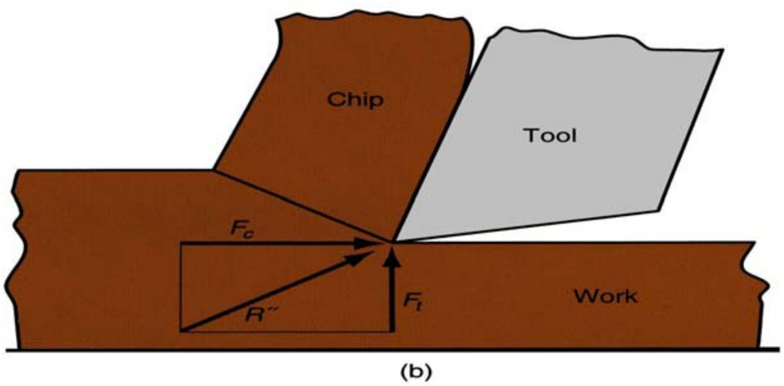


Figure 3.3: Forces in metal cutting: (b) forces acting on the tool that can be measured

Source: Groover (2007)

The following equations can be derived to relate the forces that cannot be measured to the forces that can be measured:

$$F = F_c \sin\alpha + F_t \cos\alpha$$

$$R = F_c \cos\alpha - F_t \sin\alpha$$

$$F_s = F_c \cos\phi - F_t \sin\phi$$

$$F_n = F_c \sin\phi + F_t \cos\phi$$

3.3 Power requirements for cutting

The power to perform machining can be computed from:

$$P_c = F_c v$$

where P_c = cutting power; F_c = cutting force; and v = cutting speed

In U.S. customary units, power is traditional expressed as horsepower (dividing ft-lb/min by 33,000)

$$HP_c = \frac{F_c v}{33{,}000}$$

where HP_c = cutting horsepower, hp

Gross power to operate the machine tool P_g or HP_g is given by

$$P_g = \frac{P_c}{E} \quad \text{or} \quad HP_g = \frac{HP_c}{E}$$

where E = mechanical efficiency of machine tool
Typical E for machine tools ~ 90%

4.0 CUTTING TOOL MATERIALS

4.1 Requirements of cutting tool materials

The cutting tool materials must possess a number of important properties to avoid excessive wear, fracture failure, and high temperatures in cutting. The following characteristics are essential for cutting materials to withstand the heavy conditions of the cutting process and to produce high quality and economical parts:
(i) *hardness* at elevated temperatures (so-called *hot hardness*) so that hardness and strength of the tool edge are maintained in high cutting temperatures. This is the ability of the material to with stand very high temperature without loosing its cutting edge. The hardness of the tool material can be improved by adding molybdenum, tungsten, vanadium, chromium etc that form hard carbides. High hardness gives good wear resistance but poor mechanical shock resistance.

(ii) *toughness*: ability of the material to absorb energy without failing. Cutting if often accompanied by impact forces especially if cutting is interrupted, and cutting tool may fail very soon if it is not strong enough.
(iii) *wear resistance*: although there is a strong correlation between hot hardness and wear resistance, later depends on more than just hot hardness.
(iv) surface finish on the tool,
(v) *chemical inertness* of the tool material with respect to the work material, and
(vi) *thermal conductivity* of the tool material, which affects the maximum value of the cutting temperature at tool-chip interface.

4.2 Types of cutting tool materials

Carbon Steels

It is the oldest of tool material. The carbon content is 0.6~1.5% with small quantities of silicon, chromium, manganese, and vanadium to refine grain size. Maximum hardness is about HRC 62. This material has low wear resistance and low hot hardness. The use of these materials now is very limited.

High-speed steel (HSS)

This was first produced in 1900s. They are highly alloyed with vanadium, cobalt, molybdenum; tungsten and chromium added to increase hot hardness and wear resistance. Can be hardened to various depths by appropriate heat treating up to cold hardness in the range of HRC 63-65. The cobalt component gives the material a hot hardness value much greater than carbon steels. The high toughness and good wear resistance make HSS suitable for all type of cutting tools with complex shapes for relatively low to medium cutting speeds. The most widely used tool material today for taps, drills, reamers, gear tools, end cutters, slitting, broaches, etc.

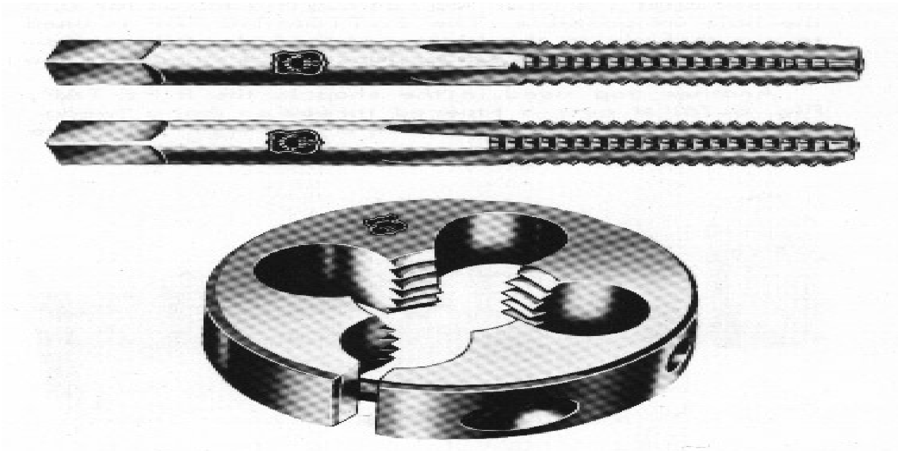


Figure 4.1: Thread tap and die made of high-speed steel

Cemented Carbides

Cemented carbides were introduced in the 1930s. These are the most important tool materials today because of their high hot hardness and wear resistance. The main disadvantage of cemented carbides is their low toughness. These materials are produced by powder metallurgy methods, sintering grains of *tungsten carbide* (WC) in a *cobalt* (Co) matrix (it provides toughness). There may be other carbides in the mixture, such as *titanium carbide* (TiC) and/or *tantalum carbide* (TaC) in addition to WC.

Figure 4.2: Various Inserts

In spite of more traditional tool materials, cemented carbides are available as inserts produced by powder metallurgy process. Inserts are available in various shapes, and are usually mechanically attached by means of clamps to the tool holder, or brazed to the tool holder. The clamping is preferred because after a cutting edge is worn, the insert is indexed (rotated in the holder) for another cutting edge. When all cutting edges are worn, the insert is thrown away. The indexable carbide inserts are never reground. If the carbide insert is brazed to the tool holder, indexing is not available, and after reaching the wear criterion, the carbide insert is reground on a tool grinder.

One advance in cutting tool materials involves the application of a very thin coating (~ 10 μm) to a K-grade substrate, which is the toughest of all carbide grades. Coating may consists of one or more thin layers of wear-resistant material, such as *titanium carbide* (TiC), *titanium nitride* (TiN), *aluminium oxide* (Al_2O_3), and/or other, more advanced materials. Coating allows increasing significantly the cutting speed for the same tool life.

Ceramics

Ceramic materials are composed primarily of fine-grained, high-purity aluminum oxide (Al2O3), pressed and sintered with no binder. Two types are available:
(i) *white*, or *cold-pressed ceramics*, which consists of only Al_2O_3 cold pressed into inserts and sintered at high temperature.
(ii) *black*, or *hot-pressed ceramics*, commonly known as *cermet* (from ceramics and metal).
This material consists of 70% Al_2O_3 and 30% TiC.
Both materials have very high wear resistance but low toughness, therefore they are suitable only for continuous operations such as finishing turning of cast iron and steel at very high speeds. There is no occurrence of built-up edge, and coolants are not required.

Cubic boron nitride (CBN) and synthetic diamonds
Diamond is the hardest substance ever known of all materials. It is used as a coating material in its polycrystalline form, or as a single-crystal diamond tool for special applications, such as mirror finishing of non-ferrous materials. Next to diamond, CBN is the hardest tool material. CBN is used mainly as coating material because it is very brittle. In spite of diamond, CBN is suitable for cutting ferrous materials.

4.3 Selection of Cutting Conditions

For each machining operation, a proper set of cutting conditions must be selected during the process planning. Decision must be made about all three elements of cutting conditions,
(i) depth of cut
(ii) feed
(iii) cutting speed

There are two types of machining operations:
(i) *roughing operations*: the primary objective of any roughing operation is to remove as much as possible material from the work piece for as short as possible machining time. In roughing operation, quality of machining is of a minor concern.
(ii) *finishing operations*: the purpose of a finishing operation is to achieve the final shape, dimensional precision, and surface finish of the machined part. Here, the quality is of major importance. Selection of cutting conditions is made with respect to the type of machining operation. Cutting conditions should be decided in the order *depth of cut - feed - cutting speed*.

Selecting depth of cut
Depth of cut is predetermined by work piece geometry and final part shape.
In *roughing* operations, depth of cut is made as large as possible (max depths are in the range of 6~10 mm) with respect to available machine tool, cutting tool strength, and other factors. Often, a series of roughing passes is required. Roughing operations must leave a thin layer of material (~0.5 mm on a side) required for the subsequent finishing operation.
In the *finishing* cut, depth is set to achieve the final dimensions with a single pass removing the excessive material left after roughing.

Selecting feed
In *roughing* operations, feed is made as large as possible to maximize metal removal rate. Upper limits on feed are imposed by cutting forces and setup rigidity. Feeds in roughing can be as big as 0.5 mm.
If the operation is *finishing*, feed should be small to ensure good surface finish.
Typical feeds in finishing are in the range of 0.05~0.15 mm.

Optimizing cutting speed
As with most engineering problems, in machining we want to minimize costs, while increasing

productivity. Efficiency is the key term - it suggests that good quality parts are produced at reasonable cost and at high production rate. Unfortunately, it is almost impossible to combine these contradictable requirements - cutting at high speed increases productivity but reduces tool life, therefore increases the production cost as more cutting tools will be necessary to finish the job.
Hence, the optimal cutting speed has to be calculated for two objectives:
(i) cutting speed for maximum production rate, V_{max}, and
(ii) cutting speed for minimum unit cost, V_{min}.
Both objectives seek to achieve a balance between material removal rate and tool life.

Maximizing production rate
Fox maximum production rate, the speed that minimizes machining time per unit part is determined. Minimizing cutting time is equivalent to maximizing productivity. It can be shown, that the cutting time for one part T_c is minimized at a certain value of cutting speed denoted as Vmax.

Minimizing cost per unit
For minimum cost per unit, the cutting speed that minimizes production cost per part is determined. Again, the total cost of producing one part is minimized at a value of cutting speed denoted as Vmin. In all cases, V_{max} is always greater than V_{min}. Since it is difficult to precisely calculate either values, a general recommendation is to operate within these two values, an interval known as the *high-efficiency range*.

5.0 JOINING METHODS

Manufacturing processes, in which single parts are combined to form an assembly are referred to as *manufacturing processes for joining and assembling*. These processes can be divided into two major classes, *processes for non-permanent combining*, which allow for multiple disassembly and assembly of single parts and/or subassemblies, and *processes for permanent combining* of single parts and/or subassemblies. Eventual disassembly would result in severe damages to the components in the assembly and the subsequent assembly if attempted would not be possible any more.
Further classification is possible with respect to the operational methods used as follows,
(i) *mechanical assembly*, which involves the use of various fastening methods to mechanically attach two (or more) parts and/or subassemblies together. This group includes processes for permanent (*riveting*, *press* or *shrink fitting*) or non-permanent (assembly with *threaded fasteners*) assembly;
(ii) *joining processes*, in which two (or more) parts and/or subassemblies are jointed together to form a permanent assembly. Examples are *welding*, *adhesive bonding*, *brazing* and *soldering*.

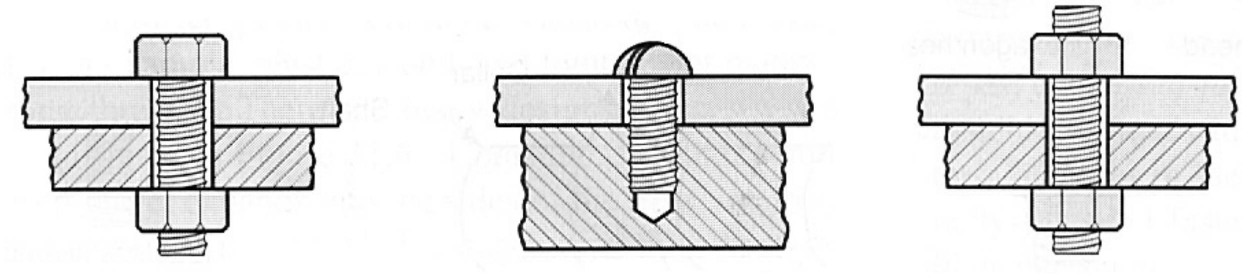
5.1 Mechanical Assembly

For purpose of organization, we divide processes for mechanical assembly into the following categories;
(i) *processes for non-permanent assembly* with threaded fasteners - screws, bolts, studs, and nuts, and
(ii) *processes for permanent assembly*, which include assembly with rivets, and press and shrink fits

5.1.1 Processes for non-permanent assembly

Threaded fasteners are components that have external or internal threads for assembly of parts. The common threaded fastener types are *screws*, *bolts*, *studs* and *nuts*.
(i) *bolt* is an externally threaded fastener that is inserted through holes in the parts and

screwed into a nut on the opposite side;
(ii) *screw* is an externally threaded fastener that is generally assembled into a blind threaded hole and no nut is required;
(iii) *stud* is an externally threaded fastener, but without the usual head possessed by a bolt. Studs can also be used to assemble two parts using a nut. They are available with threads on one end or both;
(iv) *nut* is an internally threaded fastener having standard threads.
The typical assemblies that result from the use of screws, bolts, studs and nuts are shown in the figure:



(a) (b) (c)

Figure 5.1: Typical assemblies using (a) bolt and nut, (b) screw and (c) stud and nut.

Threaded fasteners come in a variety of sizes, threads, and shapes. Also, numerous head styles are available on bolts and screws, some of which are illustrated in the figure. The geometries of these heads, as well as the variety of sizes available, require different hand tools for the operator.

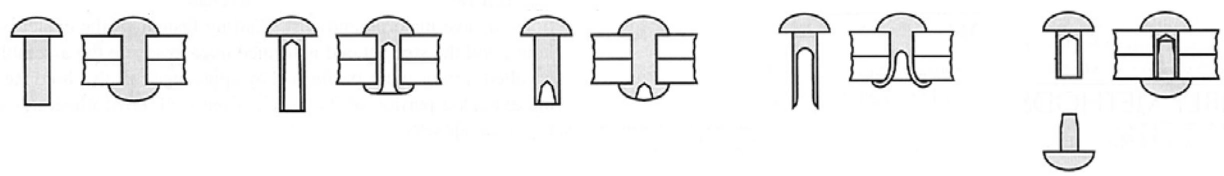
Tightening of threaded fasteners

Whether a threaded fastener serves, its purpose depends to a large degree of the amount of torque applied to tighten it. Once the threaded fastener has been rotated until it is seated against the part surface, additional tightening will increase the amount of tension in the fastener (and simultaneously the amount of compression in the parts being held together) and an increasing torque will resist the tightening.
Various methods are employed to apply the required torque, including
(i) *operator feel*, which is not very accurate, but adequate for most assemblies;
(ii) *torque wrenches*;
(iii) *powered wrenches* designed to stall when the required torque is reached, and
(iv) *torque-turn tightening*, in which the fastener is initially tightened to a low torque level and then rotated a specified additional amount.

5.2 Processes for permanent assembly

5.2.1 Riveting

A rivet is an unthreaded, headed pin used to join two (or more) parts by passing the pin through holes in the parts and then forming (upsetting) a second head in the pin on the opposite side. The deforming operation can be performed hot or cold and by hammering or steady pressing. Once the rivet has been deformed, it cannot be removed except by breaking one of the heads.
Rivet type refers to five basic geometries that affect how the rivet will be upset to form the second head. The five basic types are illustrated in the figure. In addition, there are special rivets for special applications not shown in the figure.



Solid Rivet Tubular Rivet Semitubular Rivet Bifurcated Rivet Compression Rivet

Figure 5.2: Types of Rivets

Riveting is a fastening method that offers high production rates, simplicity, dependability and low cost.
Despite these apparent advantages, its applications have declined in recent decades in favor of threaded fasteners, welding, and adhesive bonding. Riveting is used as one of the primary fastening processes in the aircraft and aerospace industries for joining skins to channels and other structural members.
Much of the equipment used in riveting is portable and manually operated. Automatic drilling and riveting machines are available for drilling the holes and then inserting and upsetting the rivets.

Press and shrink fits

Several assembly methods are based on mechanical interference between the two mating parts being joined. The methods discussed here include press fitting, and shrink fitting.
A *press fit assembly* is one in which the two components have an interference fit between them. The typical case is when a pin of a diameter Dp is pressed into a hole of a slightly smaller diameter Dc:
Applications of press fitting include locating and locking the components such as the assembly of collars, gears, pulleys, and similar components onto shafts.
The major limitations of press fitting include the necessity of a substantial press force, and the possible damage to the surfaces of components during the process of press fitting. These limitations are overcome in the process of shrink fitting.
To assemble by *shrink fitting*, the external part is heated to enlarge by thermal expansion, and the internal part either remains at room temperature or is cooled to contract its size. The parts are then assembled and brought back to room temperature so that the external part shrinks and, if previously cooled, the internal part expands to form a strong interference fit.
A modification of the shrink fitting method is so called *expansion fit*, which occurs when only the internal part is cooled to contract it for assembly. Once inserted into the mating component, it warms to room temperature, expanding to create the interference assembly.
Various methods are used to accomplish the heating and/or cooling of the work parts. Heating equipment includes torches, furnaces, electric resistance heaters, and electric induction heaters. Cooling methods include conventional refrigeration, packing in dry ice, and immersion in cold liquids, including liquid nitrogen. The change in diameter that results from heating or cooling a cylindrical work piece depends on the coefficient of thermal expansion and the temperature difference that is applied to the parts.
The shrink fitting method is used to fit gears, pulleys, sleeves, and other components onto solid and hollow shafts but the most popular application is to fit bearing onto shafts.

5.3 Types of welding processes

Welding is a material joining process for a permanent combining of two (or more) parts that involves melting and subsequent solidification of the material from two parts thus forming a strong joint between them. The assemblage of parts is called a *weldment*.

There are two groups of welding processes according to the state of the base material during the welding process: Liquid-state welding (*fusion welding*), and *Solid-state welding.*
Fusion welding is by far the more important category. In fusion welding, the base material is heat to melt.
The most important processes in this group fall in the following categories:
(i) *Oxyfuel gas welding:* an oxyfuel gas produces a flame to melt the base material;
(ii) *Arc welding:* heating and melting of the material is accomplished by an electric arc;
(iii) *Resistance welding:* the source of heat is the electrical resistance on the interface between two parts held together under pressure.
In *solid-state welding*, two parts are jointed together under pressure or a combination of pressure and heat. If heat is applied, the contact temperature is below the melting point of the base metal. Two welding processes are the most popular from this group,
(i) *Diffusion welding:* parts coalesce by solid-state diffusion;
(ii) *Friction welding:* coalescence is achieved by the heat of friction between two parts;

5.3.1 Oxyfuel gas welding

Oxyfuel gas welding is the term used to describe the group of fusion operations that burn various fuels mixed with oxygen to perform welding or cutting and separate metal plates and other parts. The most important oxyfuel gas welding process is oxyacetylene welding.
Oxyacetylene welding (OAW) is a fusion welding process performed by a high-temperature flame from combustion of acetylene and oxygen. The flame is directed by a welding torch and a filler metal in the form of rod is added if the process is applied to weld. Composition of the filler must be similar to that of the base metal.

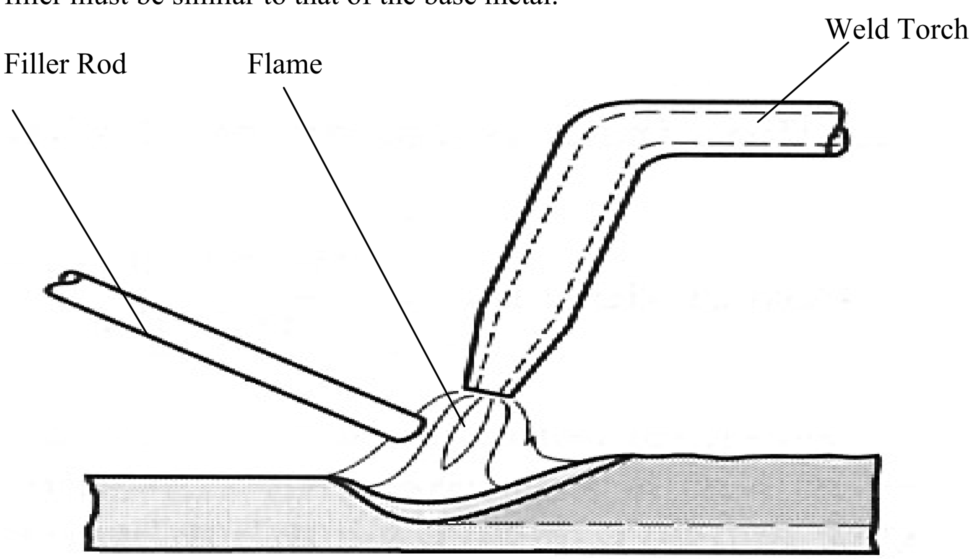


Figure 5.3: Oxyfuel gas welding operation.

Oxyacetylene welding uses equipment that is relatively inexpensive and portable. It is therefore an economical, versatile process that is well suited to low-quantity production and repair jobs. It is rarely used on the welding of sheet and plate stock thicker than 6 mm because of the advantages of arc welding in such applications. Although OAW can be mechanized, it is usually performed manually and is hence dependent on the skill of the welder to produce a high-quality weld joint.

5.3.2 Arc welding with consumable electrodes

Arc welding (AW) is a fusion welding process in which coalescence of the metals is achieved by the heat from an electric arc between an electrode and the work. A generic AW process is shown in the Figure 5.4.
An electric arc is a discharge of electric current across a gap in a circuit. To initiate the arc in an AW process, the electrode is brought into contact with the work and then quickly separated from it by a short distance. The electric energy from the arc thus formed produces temperatures of 5000o C or higher, sufficiently hot to melt any metal. A pool of molten metal, consisting of base metal(s) and filler metal (if one is used), is formed near the tip of the electrode. In most arc welding processes, filler metal is added during the operation to increase the volume and strength of the weld joint. As the electrode is moved along the joint, the molten weld pool solidifies in its wake. Movement of the electrode relative to the work is accomplished by either a human welder (manual welding) or by mechanical means (machine welding, automatic welding, or robotic welding). In manual arc welding, the quality of the weld joint is very dependent on the skill and experience of the human welder. The weld quality is much better in the machine, automatic, and robotic welding.

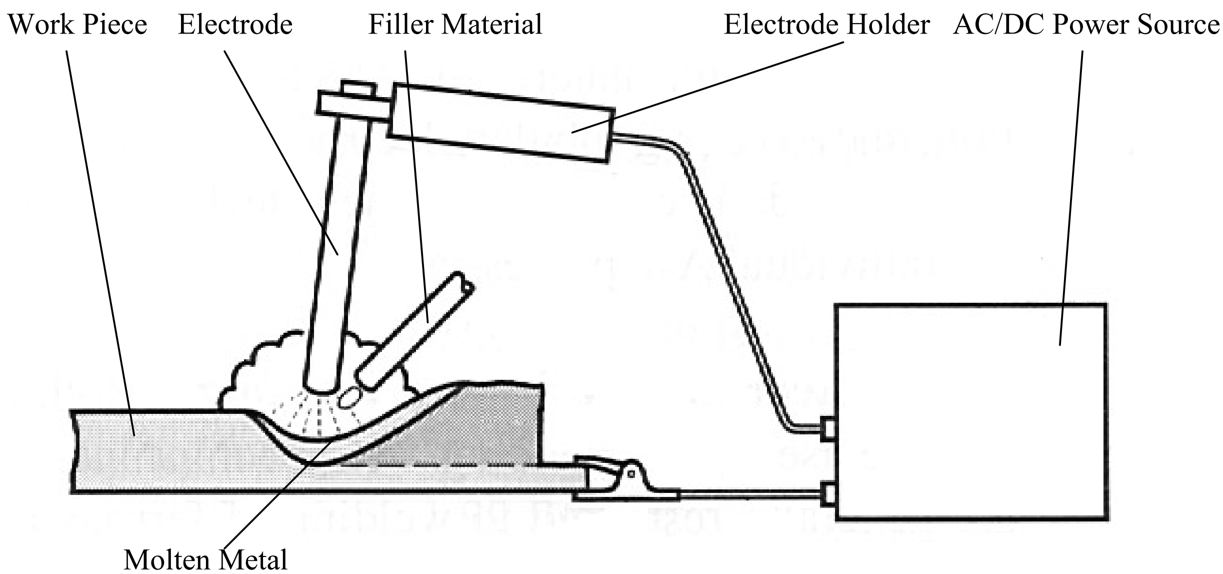


Figure 5.4: Arc Welding Operation

Electrodes in AW process are classified as
(i) *consumable*, which melts continuously in the process of arc welding thus providing the required filler material, and
(ii) *non-consumable*, which resist melting by the arc. The filler material must be supplied separately.

Shielded Metal Arc Welding
Shielded Metal Arc Welding (SMAW) is an arc welding process that uses a consumable electrode consisting of a filler metal rod coated with chemicals that provide flux and shielding.

The coated welding stick (SMAW is sometimes called *stick welding*) is typically 200 to 450 mm long and1.5 to 9.5 mm in diameter. The heat of the welding process melts the coating to provide a protective atmosphere and slag for the welding operation.
During operation the bare metal end of the welding stick is clamped in an electrode holder connected to the power source. The holder has an insulated handle so that it can be held and manipulated by a

human welder. Currents typically used in SMAW range between 30 and 300 A at voltages from I5 to 45 V depending on the metals being welded, electrode type and length and depth of weld penetration required. Shielded metal arc welding is usually performed manually. Common applications include construction, pipelines, machinery structures, shipbuilding, fabrication job shops, and repair work. It is preferred over oxyfuel welding for thicker sections above 5 mm because of its higher power density. The equipment is portable and low cost, making SMAW highly versatile and probably the most widely used of the AW welding processes. Base metals include steels, stainless steels, cast irons, and certain nonferrous alloys.

The process is illustrated in the Figure 5.5.

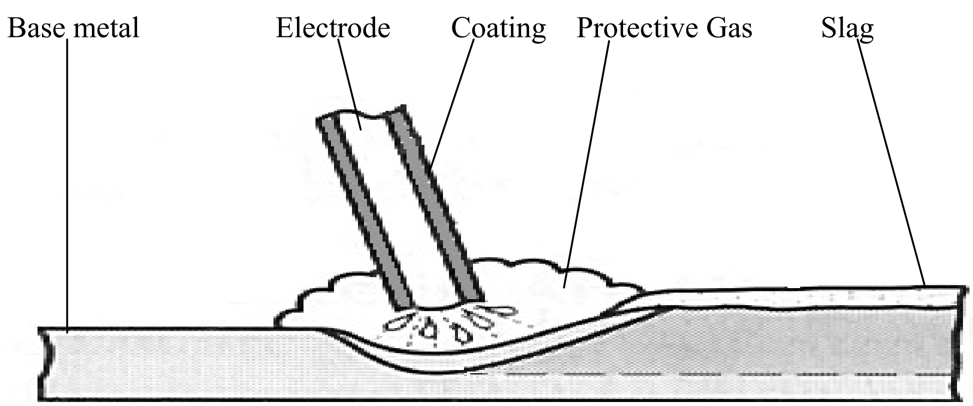
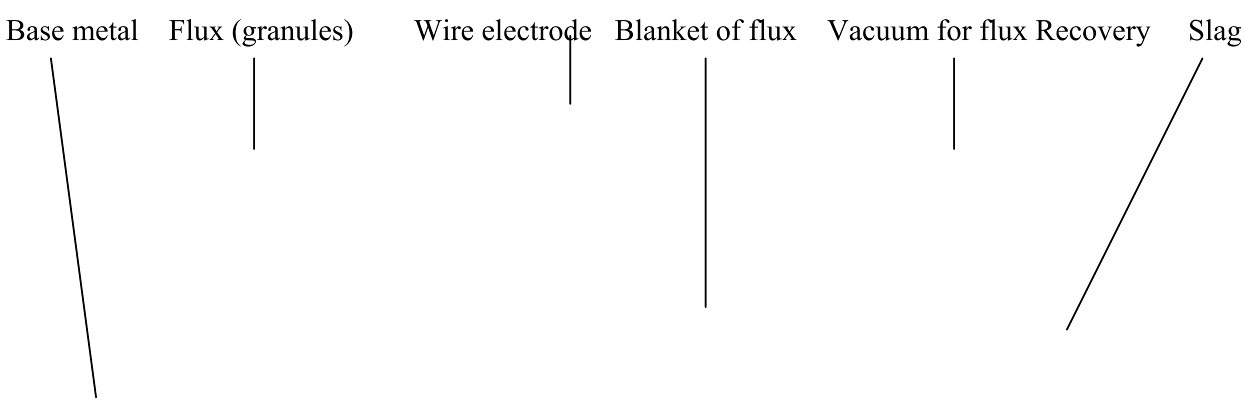


Figure 5.5: Shielded metal arc welding operation

Submerged Arc Welding

Submerged arc welding (SAW) is an arc welding process that uses a continuous, consumable bare wire electrode. The arc shielding is provided by a cover of granular flux. The electrode wire is fed automatically from a coil into the arc. The flux is introduced into the joint slightly ahead of the weld arc by gravity from a hopper, as shown in Figure 5.6.



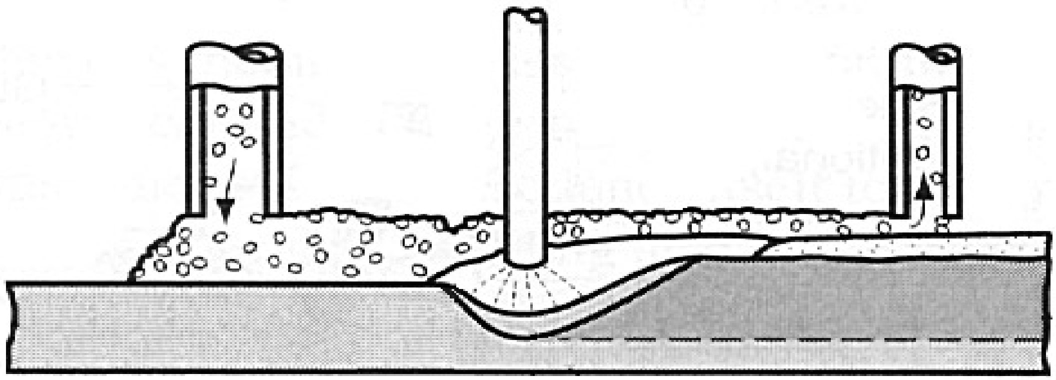


__Figure 5.6: Submerged arc-welding operation.__

The blanket of granular flux completely submerges the arc welding operation, preventing sparks, spatter, and radiation that are so hazardous in other arc welding processes. The portion of the flux closest to the arc is melted, mixing with the molten weld metal to remove impurities and then solidifying on top of the weld joint to form a glasslike slag. The slag and infused flux granules on top provide good protection from the atmosphere and good thermal insulation for the weld area. This result in relatively slow cooling and a high quality weld joint. The infused flux remaining after welding can be recovered and reused. The solid slag covering the weld must be chipped away usually by manual means.

This process is widely used for automated welding of structural shapes, longitudinal and circumferential seams for large-diameter pipes, tanks, and pressure vessels. Because of the gravity feed of the granular flux, the parts must always be in a horizontal orientation.

Gas Metal Arc Welding

Gas Metal Arc Welding (GMAW) is an arc welding process in which the electrode is a consumable bare metal wire and shielding is accomplished by flooding the arc with a gas. The bare wire is fed continuously and automatically from a spool through the welding gun, as illustrated in Figure 5.7.

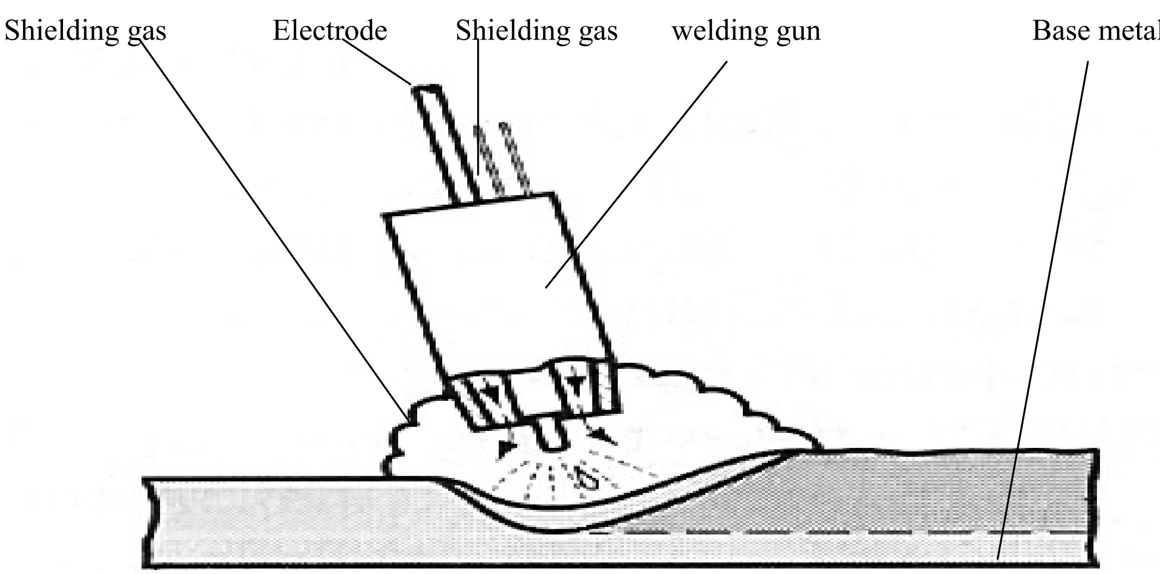


Figure 5.7: Gas metal arc welding operation.

Wire diameters ranging from 1 to 6 mm are used in GMAW, the size depending on the thickness of the parts being joined. Gases used for shielding include inert gases such as argon and helium and active gases such as carbon dioxide. Selection of gases depends mainly on the metal being welded. Inert gases are used for welding aluminium alloys and stainless steel and in this case the process is often referred to as *MIG/MAG welding* (for metal-inert gas/metal-argon welding). In welding steel, carbon dioxide (CO2), which is less expensive than inert gases, is used. Hence, the term *CO2 welding* is applied.

5.3.3 Arc welding with non-consumable electrodes
Gas Tungsten Arc Welding
Gas Tungsten Arc Welding (GTAW) is an arc welding process that uses a non-consumable tungsten electrode and an inert gas for arc shielding. Shielding gases typically used include
argon, helium or a mixture of these gases. The GTAW process can be implemented with or without a filler metal. The figure illustrates the latter case. When thin sheets are welded to close tolerances, filler metal is usually not added. When a filler metal is used, it is added to the weld pool from a separate rod or wire. The term *TIG welding* (tungsten inert gas welding) is often applied to this process.
GTAW is applicable to nearly all metals in a wide range of stock thickness. It can also be used for joining various combinations of dissimilar metals. Its most common applications are for aluminium and stainless steel. The process can be performed manually or by machine and automated methods for all joint types. Advantages of GTAW in the applications to which it is suited include high-quality welds, no weld spatter because no filler metal is transferred across the arc, and little or no post-weld cleaning because no flux is used.

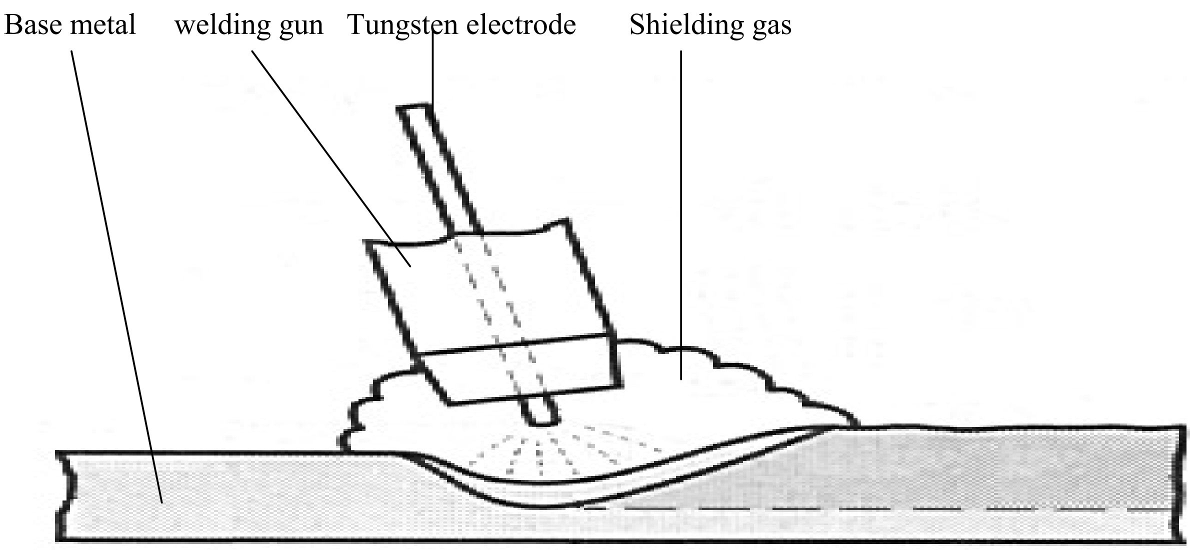


Figure 5.8: Gas tungsten arc welding operation.

Plasma Arc Welding
Plasma Arc Welding (PAW) is a special form of gas tungsten arc welding in which a plasma arc is directed at the weld area. The tungsten electrode is contained in a specially designed nozzle that focuses a high-velocity stream of inert gas (for example, argon or argon-hydrogen mixtures, and helium) into the region of the arc to produce a high-velocity plasma jet of small diameter and very high-energy density, as in Figure 5.9.

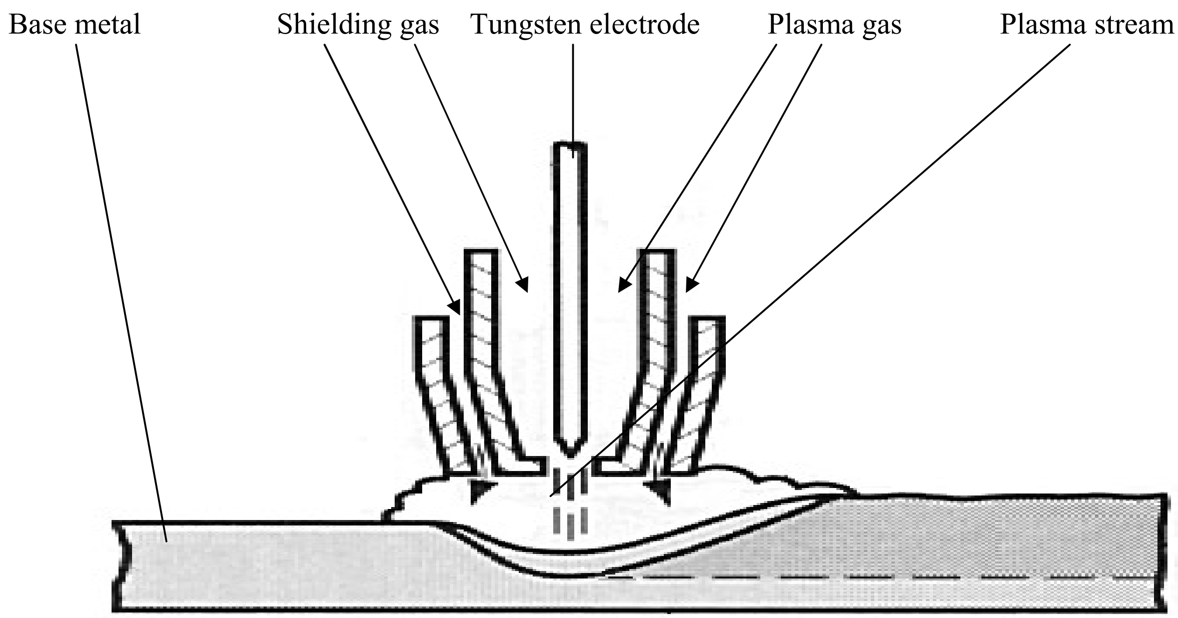


Figure 5.9: Plasma Arc Welding
Temperatures in plasma arc welding reach 30,000^{o}C or greater, hot enough to melt any known metal. Plasma Arc Welding is used as a substitute for GTAW in applications such as automobile subassemblies, metal cabinets, door and window frames, and home appliances. The process can be Temperatures in plasma arc welding reach 30,000o C or greater, hot enough to melt any known metal. Plasma Arc Welding is used as a substitute for GTAW in applications such as automobile subassemblies, metal cabinets, door and window frames, and home appliances. The process can be used to weld almost any metal, including tungsten.

Weld quality in arc welding
The rapid heating localized regions of the work during fusion welding especially arc welding, result in thermal expansion, cooling, and contraction, which cause transverse and longitudinal residual stresses in the weldment. These stresses are likely to cause distortion of the welded assembly: used to weld almost any metal, including tungsten. The welding begins at one end and travels to the opposite end of the welded joint. As it proceeds, the molten metal quickly solidifies behind the moving arc. The portions of the work immediately adjacent to the weld bead become extremely hot and expand, while portions removed from the weld remain relatively cool. Residual stresses and shrinkage also occur along the length of the weld bead.
Various techniques can be employed to minimize distortion in a weldment. Some of these techniques include the following:
(i) *Welding fixtures* that physically restrain movement of the parts during welding;
(ii) *Tack welding* at multiple points along the joint to create a rigid structure prior to continuous welding;
(iii) *Preheating* the base parts which reduces the level of thermal stresses experienced by the parts;
(iv) Stress relief *heat treatment* of the welded assembly.
In addition to residual stresses and distortion in the final assembly, other defects can also occur in welding,
(i) *Cracks*: Fracture-type interruptions either in the weld or in the base metal adjacent to the weld. This type is perhaps the most serious welding defect because it constitutes a discontinuity in the metal that

causes significant reduction in the strength of the weldment. Generally, this defect can and must be repaired.
(ii) *Cavities*: These include various porosity and shrinkage voids. *Porosity* consists of small voids in the weld metal formed by gases entrapped during solidification. Porosity usually results from inclusion of atmospheric gases, or contaminants on the surfaces. *Shrinkage voids* are cavities formed by shrinkage during solidification.
(iii) *Solid inclusions*: Solid inclusions are any non-metallic solid material entrapped in the weld metal. The most common form is slag inclusions generated during the various welding processes that use flux.
(iv) *Incomplete fusion*: Fusion does not occur throughout the entire cross section of the joint.

5.3.4 Resistance welding

Resistance welding (RW) is a group of fusion welding processes that utilizes a combination of heat and pressure to accomplish coalescence. The heat required is generated by electrical resistance to current flow at the interface of two parts to be welded. The resistance welding processes of most commercial importance are *spot* and *seam welding*.

Resistance Spot Welding

Resistance spot welding (RSW) is a resistance welding process in which fusion of the base metal is achieved at one location by opposing electrodes. The cycle in a spot welding operation consists of the steps depicted in Figure 5.10.

(a) (b) (c) (d) (e)

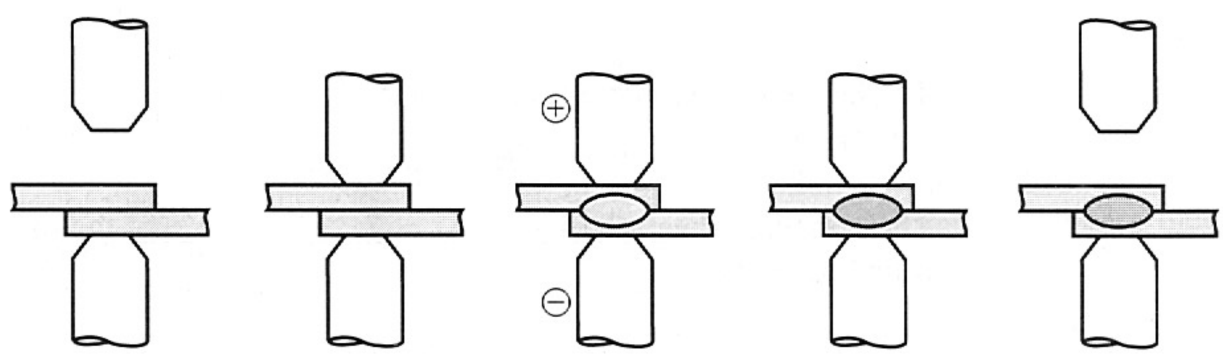


Figure 5.10: Steps in a spot welding cycle: (a) parts inserted between open electrodes, (b) electrodes close and force is applied, (c) weld time (current is switched), (d) current is turned off but force is maintained, and (e) electrodes are opened, and the welded assembly is removed.

Resistance spot welding is widely used in mass production of automobiles, appliances, metal furniture, and other products made of sheet metal of thickness 3 mm or less.

Because of its widespread industrial use, various machines and methods are available to perform spot welding operations. The equipment includes rocker arm and press-type spot welding machines for larger work. For large, heavy work, portable spot welding guns are available in various sizes and configurations. They are widely used in automobile final assembly plants to spot-weld the sheet-metal car bodies. Human workers operate some of these guns, but industrial robots have become the preferred technology.

6.0 HEAT TREATMENT

Heat treatment of a metal or alloy is a technological procedure, including controlled heating and cooling operations, conducted for the purpose of changing the alloy microstructure and resulting in achieving required properties.

Heat treatment is a process utilized to change certain characteristics of metals and alloys in order to make them more suitable for a particular kind of application. In general, heat treatment is the term for any process employed which changes the physical properties of a metal by either heating or cooling. When properly performed, heat treatment can greatly influence mechanical properties such as strength, hardness, ductility, toughness, and wear resistance.
Most carbon steels and carbon alloy steels can be heat treated for improving mechanical properties such as tensile and yield strength. This is accomplished due to the heat treatment fundamentally altering the microstructure of the steel.
The various types of heat-treating processes are similar because they all involve the heating and cooling of metals; they differ in the heating temperatures, the cooling rates used, and the results. The usual methods of heat-treating ferrous metals (metals with iron) are annealing, normalizing, hardening, and tempering. Most nonferrous metals can be annealed, but never tempered, normalized, or case-hardened.

6.1 Stages of Heat Treatment
Heat treatment is accomplished in three major stages:

Stage l—Heating the metal slowly to ensure a uniform temperature
Stage 2—Soaking (holding) the metal at a given temperature for a given time and cooling the metal to room temperature
Stage 3—Cooling the metal to room temperature

6.2 Types of Heat Treatment
The four basic types of heat treatment are annealing, normalizing, hardening, and tempering.
anneal metals to relieve internal stresses, soften them, make them more ductile, and refine their grain structures.

Annealing
Annealing consists of heating a metal to a specific temperature, holding it at that temperature for a set length of time, and then cooling the metal to room temperature. The cooling method depends on the metal and the properties desired. Some metals are furnace-cooled, and others are cooled by burying them in ashes, lime, or other insulating materials. Welding produces areas that have molten metal next to other areas that are at room temperature. As the weld cools, internal stresses occur along with hard spots and brittleness. Welding can actually weaken the metal. Annealing is just one of the methods for correcting these problems.
Annealing results in relief of internal stresses, softening, chemical homogenizing and transformation of the grain structure into more stable state. To produce the maximum softness in steel, the metal is heated to its proper temperature (usually the annealing temperature of metals is between one-third to one-half of the freezing point measured in Kelvin (absolute) temperature scale) , soak it, and then let it cool very slowly. The cooling is done by burying the hot part in an insulating material or by shutting off the furnace and allowing the furnace and the part to cool together. The soaking period depends on both the mass of the part and the type of metal. Steel with an extremely low-carbon content requires the highest annealing temperature. As the carbon content increases, the annealing temperatures decrease.
Nonferrous metal like copper that becomes hard and brittle when mechanically worked can be made soft again by annealing. The annealing temperature for copper is between 700°F and 900°F. Copper

maybe cooled rapidly or slowly since the cooling rate has no effect on the heat treatment. The one drawback experienced in annealing copper is the phenomenon called “hot shortness.” At about 900°F, copper loses its tensile strength, and if not properly supported, it could fracture. Aluminium reacts similar to copper when heat treated. It also has the characteristic of “hot shortness.” A number of aluminium alloys exist and each requires special heat treatment to produce their best properties.

Normalizing

Normalizing is a type of heat treatment applicable to ferrous metals only. It differs from annealing in that the metal is heated to a higher temperature and then removed from the furnace for air cooling. The purpose of normalizing is to remove the internal stresses induced by heat treating, welding, casting, forging, forming, or machining. Stress, if not controlled, leads to metal failure; therefore, before hardening steel, you should normalize it first to ensure the maximum desired results. Usually, low-carbon steels do not require normalizing; however, if these steels are normalized, no harmful effects result. Castings are usually annealed, rather than normalized; however, some castings require the normalizing treatment. Soaking time varies with the thickness of the metal. Normalized steels are harder and stronger than annealed steels. In the normalized condition, steel is much tougher than in any other structural condition. Parts subjected to impact and those that require maximum toughness with resistance to external stress are usually normalized. In normalizing, the mass of metal has an influence on the cooling rate and on the resulting structure. Thin pieces cool faster and are harder after normalizing than thick ones. In annealing (furnace cooling), the hardness of the two are about the same.

Hardening

The hardening treatment for most steels consists of heating the steel to a set temperature and then cooling it rapidly by plunging it into oil, water, or brine. Most steels require rapid cooling (quenching) for hardening but a few can be air-cooled with the same results. Hardening increases the hardness and strength of the steel, but makes it less ductile. Generally, the harder the steel, the more brittle it becomes. To remove some of the brittleness, you should temper the steel after hardening.

Many nonferrous metals can be hardened and their strength increased by controlled heating and rapid cooling. In this case, the process is called heat treatment, rather than hardening.

To harden steel, you cool the metal rapidly after thoroughly soaking it at a temperature slightly above its upper critical point. The addition of alloys to steel decreases the cooling rate required to produce hardness. A decrease in the cooling rate is an advantage, since it lessens the danger of cracking and warping. Pure iron, wrought iron, and extremely low-carbon steels have very little hardening properties and are difficult to harden by heat treatment. Cast iron has limited capabilities for hardening. When cast iron is cooled rapidly, it forms white iron, which is hard and brittle. And when it is cooled slowly, it forms gray iron, which is soft but brittle under impact. In plain carbon steel, the maximum hardness obtained by heat treatment depends almost entirely on the carbon content of the steel. As the carbon content increases, the hardening ability of the steel increases; however, this capability of hardening with an increase in carbon content continues only to a certain point. In practice, 0.80 percent carbon is required for maximum hardness. When the carbon content is increased beyond 0.80 percent, there is no increase in hardness, but there is an increase in wear resistance. This increase in wear resistance is due to the formation of a substance called hard cementite. When alloy steel is heated to increase its hardness, the alloys make the carbon more effective in increasing hardness and strength. Because of this, the carbon content required to produce maximum hardness is lower than it is for plain carbon steels. Usually, alloy steels are superior to carbon steels. Carbon steels are usually quenched in brine or water, and alloy steels are generally quenched in oil. When hardening carbon steel, the steel must be cooled to below 1000°F in less than 1 second. When alloys are added to steel, the time limit for the temperature to drop below 1000°F increases above the l-second limit, and a slower quenching medium can produce the desired hardness. Quenching produces extremely high internal stresses in steel, and to relieve them, there is the need to temper the steel just before it becomes cold. The part is removed from the quenching bath at a temperature of about 200°F and allowed to air-cool. The temperature range from 200°F down to room temperature is called the "cracking range" and the steel must not pass through it.

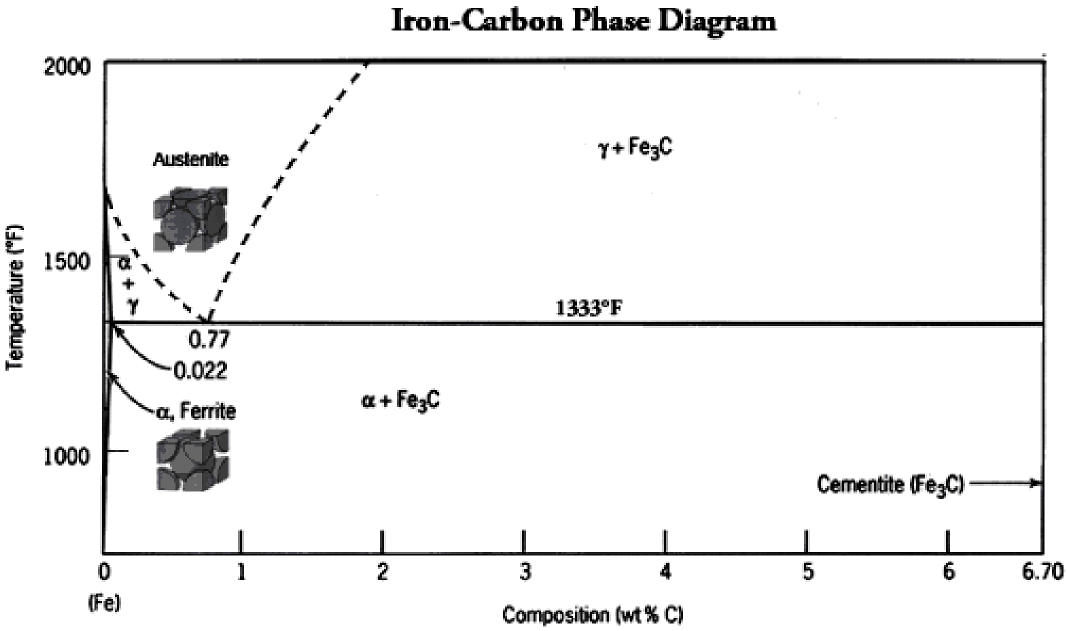


Figure 6.1: Iron-Carbon Phase Diagram

The Y-axis (vertical) is a measurement of temperature while the X-axis (horizontal) is a measurement of the carbon content of the steel. The far left hand side of the X-axis represents the ferrite phase of steel (low carbon content) while the far right hand side represents the cementite phase of steel (high carbon content), which is also known as iron carbide. The austenite phase is located between the dashed phase lines and occurs only above 1333 °F. When ferrite (low carbon steel) is at room temperature, it has a body-centered -cubic structure, which can only absorb a low amount of carbon. Because ferrite can only absorb a very low amount of carbon at room temperature, the un-absorbed carbon separates out of the body-centered-cubic structure to form carbides which join together to create small pockets of an extremely hard crystal structure within the ferrite called cementite.
However, when ferrite is heated to a temperature above the transformation line (horizontal line at 1333 ºF) the body-centered-cubic structure changes to a face-centered-cubic structure known as austenite, thus allowing for absorption of the carbon into the crystal structure. Once the steel enters the austenitic phase, all of the cementite dissolves into austenite. If the steel is allowed to cool slowly, the carbon will separate out of the ferrite as the cubic-structure reverts from face-centered back to body-centered. The islands of cementite will reform within the ferrite, and the steel will have the same properties that it did before it was heated. However, when the steel is rapidly cooled, or quenched, in a quenching medium (such as oil, water, or cold air) the carbon does not have time to exit the cubic structure of the ferrite and it becomes trapped within it. This leads to the formation of martensite; the microstructure that produces the most sought after mechanical properties in steel fasteners. During quenching it is impossible to cool the specimen at a uniform rate throughout. The surface will always cool more rapidly than the interior of the specimen. Therefore, the austenite will transform over a range of temperatures, yielding a possible variation of microstructure and properties depending on the position within the material. The successful heat treatment of steels to produce a predominantly martensitic microstructure throughout the cross section depends mainly on three factors:

1. The composition of the alloy
2. The type and character of the quenching medium
3. The size and shape of the specimen

Hardenability is the ability of a steel to transform into martensite with a particular quenching treatment. This is directly affected by the alloy composition of the steel. For every different steel alloy there is a specific relationship between its mechanical properties and its cooling rate. Hardenability is not "hardness" which is a resistance to indentation; rather, hardness measurements are utilized to determine the extent of a martensitic transformation in the interior of the material. A steel alloy that has a high hardenability is one that hardens, or forms martensite, not only at the surface but also to a large degree throughout the entire interior. In other words, hardenability is a measure of the degree to which a specific alloy may be hardened.

The newly formed martensite is considered a grain structure (or microstructure), not a phase and is very hard and brittle. Due to the brittleness inherent in martensite, steel that has been quenched from austenitizing temperatures will require tempering before it can be placed into service. Tempering involves heating the steel to a specific temperature below that of the transformation line and allowing it to cool slowly. This causes the crystal structure to relax, thereby increasing the ductility and decreasing the hardness to specified levels. The specific tempering temperature will vary based on the desired results for the steel.

Process annealing is a heat treatment that is used to negate the effects of cold work that is to soften and increase the ductility of a previously strain-hardened metal.

Stress relieving is an annealing process that is utilized when internal residual stresses develop in metal pieces in response to such things as cold working. Failure to remove these internal stresses may result in distortion and warping. The internal stresses are relieved by bond relaxation as a result of heating. A stress relief is carried out by heating the piece to a recommended temperature (approximately 165 °F below the transformation temperature for carbon steels), holding the work piece at temperature long enough to attain a uniform temperature throughout the part, and finally cooling to room temperature in air. Stress relieving can eliminate some internal stresses without significantly altering the structure of the material. Steels that have been plastically deformed (e.g.: by a rolling operation) consist of grains of pearlite, which are irregularly shaped and relatively large, but vary substantially in size. Normalizing is an annealing heat treatment used to refine the grains and produce a more uniform and desirable size distribution. Normalizing is accomplished by heating the material to a temperature above its upper critical temperature (e.g.: just above 1333°F for most fastener-related steels). After sufficient time has been allowed for the alloy to completely transform to austenite, the metal is allowed to cool in the air.

Medium and high carbon steels having a microstructure containing coarse pearlite may still be too hard to conveniently machine or plastically deform. These steels (and in fact, any steel) may be annealed to develop the spheroidite structure. Spheroidized steels have a maximum softness and ductility and are easily machined or deformed.

Case Hardening

Case hardening produces a hard, wear-resistant surface or case over a strong, tough core. The principal forms of casehardening are carburizing, cyaniding, and nitriding. Only ferrous metals are case hardened. Case hardening is ideal for parts that require a wear-resistant surface and must be tough enough internally to withstand heavy loading. The steels best suited for case hardening are the low-carbon and low-alloy series. When high-carbon steels are case-hardened, the hardness penetrates the core and causes brittleness. In case hardening, you change the surface of the metal chemically by introducing a high carbide or nitride content. The core remains chemically unaffected. When heat-treated, the high-carbon surface responds to hardening, and the core toughens.

Carburizing

Carburizing is a case-hardening process by which carbon is added to the surface of low-carbon steel. This results in a carburized steel that has a high-carbon surface and a low-carbon interior. When the carburized steel is heat-treated, the case becomes hardened and the core remains soft and tough. Two methods are used for carburizing steel. One method consists of heating the steel in a furnace containing a carbon monoxide atmosphere. The other method has the steel placed in a container packed with charcoal or some other carbon-rich material and then heated in a furnace. To cool the parts, you can leave the container in the furnace to cool or remove it and let it air cool. In both cases, the parts become annealed during the slow cooling. The depth of the carbon penetration depends on the length of the soaking period. With today's methods, gas atmospheres almost exclusively do carburizing.

Cyaniding

This process is a type of case hardening that is fast and efficient. Preheated steel is dipped into a heated cyanide bath and allowed to soak. Upon removal, it is quenched and then rinsed to remove any residual cyanide. This process produces a thin, hard shell that is harder than the one produced by carburizing and can be completed in 20 to 30 minutes vice several hours. The major drawback is that cyanide salts are a deadly poison.

Nitriding

This case-hardening method produces the hardest surface of any of the hardening processes. It differs from the other methods in that the individual parts have been heat-treated and tempered before nitriding. The parts are then heated in a furnace that has an ammonia gas atmosphere. No quenching is required so there is no worry about warping or other types of distortion. This process is used to case harden items, such as gears, cylinder sleeves, camshafts and other engine parts, that need to be wear resistant and operate in high-heat areas.

Flame Hardening

Flame hardening is another procedure that is used to harden the surface of metal parts. When you use an oxyacetylene flame, a thin layer at the surface of the part is rapidly heated to its critical temperature and then immediately quenched by a combination of a water spray and the cold base metal. This process produces a thin, hardened surface, and at the same time, the internal parts retain their original properties. Whether the process is manual or mechanical, a close watch must be maintained, since the torches heat the metal rapidly and the temperatures are usually determined visually. Flame hardening may be either manual or automatic. Automatic equipment produces uniform results and is more desirable. Most automatic machines have variable travel speeds and can be adapted to parts of various sizes and shapes. The size and shape of the torch depends on the part. The torch consists of a mixing head, straight extension tube, 90-degree extension head, an adjustable yoke, and a water-cooled tip.

7.0 TOOLS FOR WOOD WORKING

Below are top 10 hand tools for nearly any woodworking project:

1. Claw Hammer (Finish Head)

Figure 7.1: Claw Hammer
Everyone has used a hammer at some point in their lives. While there are many types, the most versatile is the claw hammer with a smooth, slightly rounded finish head.

2. 6" Layout Square
A Layout Square is an invaluable woodworking tool. Not only is it probably the quickest and easiest tool for marking a square line for an end cut, but can be used to quickly mark any angle up to 45-degrees or measure up to six inches.

3. 25' Retractable Tape Measure
A Retractable Tape Measure is another tool that is an absolute must for any woodworker. A quality tape measure should have both Standard and Metric markings, a locking mechanism and a slightly loose hook on the end of the tape. The hook is loose on it's rivets by design so the user will get accurate results whether the tape is used to take internal or external measurements.

4. Utility Knife
A Utility Knife with a locking mechanism that uses disposable razor blades is another requirement for the woodworker. This versatile cutting device can be used for scribing a mark in a piece of stock, cleaning up a hinge mortise or any of a hundred other times when a knife is needed.

5. Chisels
The Chisel is another essential woodworking tool. A finely-sharpened chisel is perfect for cleaning out waste from joints and mortises. I like to keep one each of 1/4", 1/2", 3/4" and 1" width bevel-edged chisels within easy reach.

6. Level
When you need to know if a piece of stock is perfectly horizontal (level) or vertical (plumb), you need a level. I like to keep two levels available: one relatively long level (I use a 28" or 36") and a short, 6" Torpedo Level.

7. Screwdrivers
Like the claw hammer, everybody has used a screwdriver at least once or twice in their lives. I keep a few versions in my shop: #1, 2 and 3 sizes of both Phillips and Flathead varieties, as well as a couple of square head, Torx and star drivers.

8. Sliding Bevel
A Sliding Bevel is very similar to a square, except that it can be adjusted to any angle and locked in place using a locking mechanism. This is very handy when an angle needs to be duplicated.

9. Nail Sets
A nail set looks somewhat like a small, round chisel, but is used to sink nail heads flush or just beneath the wood's surface. I keep three different sizes in my pouch.

10. Block Plane
The last absolute necessity every woodworker should have is a small block plane. This device is used for shaving thin amounts of wood away from the stock, and is invaluable for cleaning up edges during assembly.

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