Module

3

Selection of Manufacturing Processes

Lecture

5

Design for Machining

Instructional objectives

By the end of this lecture, the student will learn

(1) what are the different machining processes and their applications,
(2) advantages, disadvantages and design guidelines of parts for machining,
(3) concept and definition of machinability, and how to improve the same.

Introduction and Classification

Machining is the manufacturing process by which parts can be produced to the desired dimensions and surface finish from a blank by gradual removal of the excess material in the form of chips with the help of a sharp cutting tool. Almost 90% of the all engineering components are subjected to some kind of machining during manufacture. It is very important to design those parts in such a way that would lead to the increase in efficiency of the machining process, enhancement of the tool life and reduction of the overall cost of machining. To achieve these targets, a brief knowledge of various machining processes is required. *Figure 3.5.1* depicts a brief classification of various machining processes that are widely used in the manufacturing and fabrication industries of all kinds.

Overview of Major Machining Processes

Turning

Turning is the most important machining process and can produce a wide variety of parts. Primarily, *turning* is used to produce parts cylindrical in shape by a single point cutting tool on *lathes*. The cutting tool is fed either linearly in the direction parallel or perpendicular to the axis of rotation of the workpiece, or along a specified path to produce complex rotational shapes. The *primary* motion of cutting in turning is the rotation of the workpiece, and the *secondary* motion of cutting is the feed motion. *Figure 3.5.2* depicts a typical turning operation in *lathes*. Different types of *lathes* are available today from general purpose to specific job oriented special purpose machines. In general, *turning* refers to a class of processes carried out on a *lathe*. A brief outline of some the *sub-class of turning processes* are presented below.

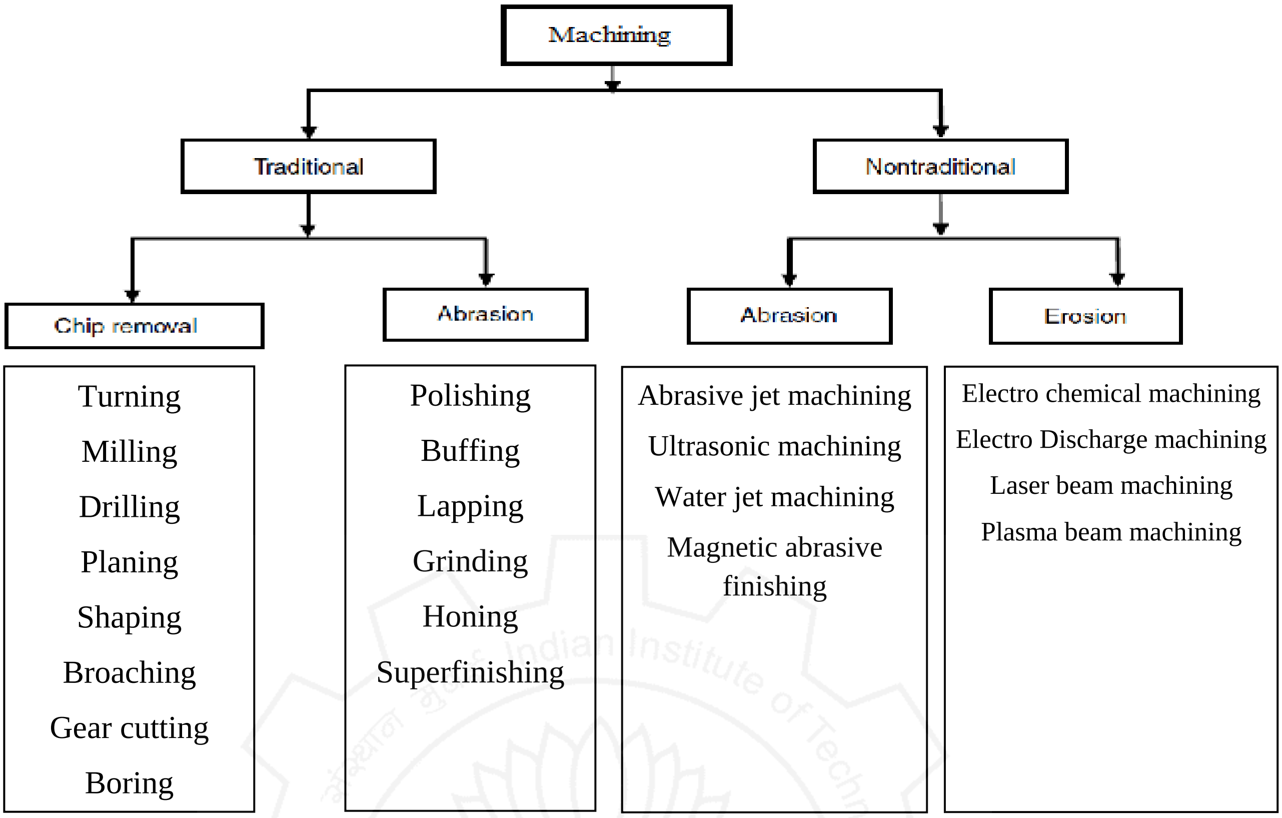


Figure 3.5.1 Classification of Machining Processes [5]

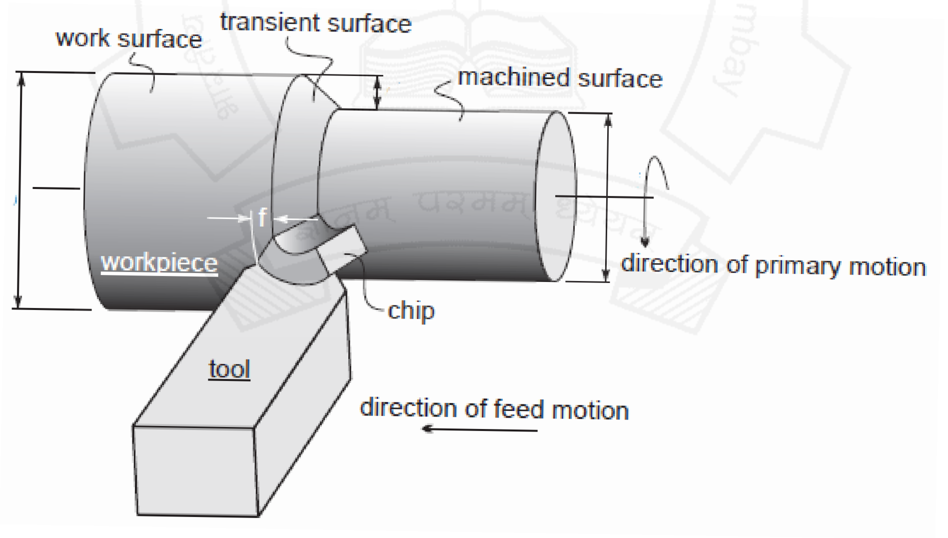


Figure 3.5.2 Schematic depiction of turning operation [4]

Straight turning is used to reduce the diameter of a part to a desired dimension (*Figure 3.5.3a*). The resulting machined surface is cylindrical. *Contour turning and Taper turning* (*Figure 3.5.3b*) are performed by employing a complex feed motion using special attachments to a *single point turning tool* thus creating a contoured shape on the workpiece.

Facing (*Figure 3.5.3c*) is done to create a smooth, flat face perpendicular to the axis of a cylindrical part. The tool is fed radially or axially to create a flat machined surface. *Thread cutting* (*Figure 3.5.3d*) is possible in *lathe* 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 tool point must be ground so that it has the same profile as the thread to be cut. Thread can be both external and internal types. In *form turning* (*Figure 3.5.3e*), the shape of the cutting tool is imparted to the workpiece by plunging the tool into the workpiece. In *form turning*, the cutting tool can be very complex and expensive but the feed will remain linear and will not require special machine tools or devices. *Boring* (*Figure 3.5.3f*) is similar to *straight turning* operation but differs in the fact that it can produce internal surface of revolution, which is often considered to be difficult due to overhanging condition of the tool.

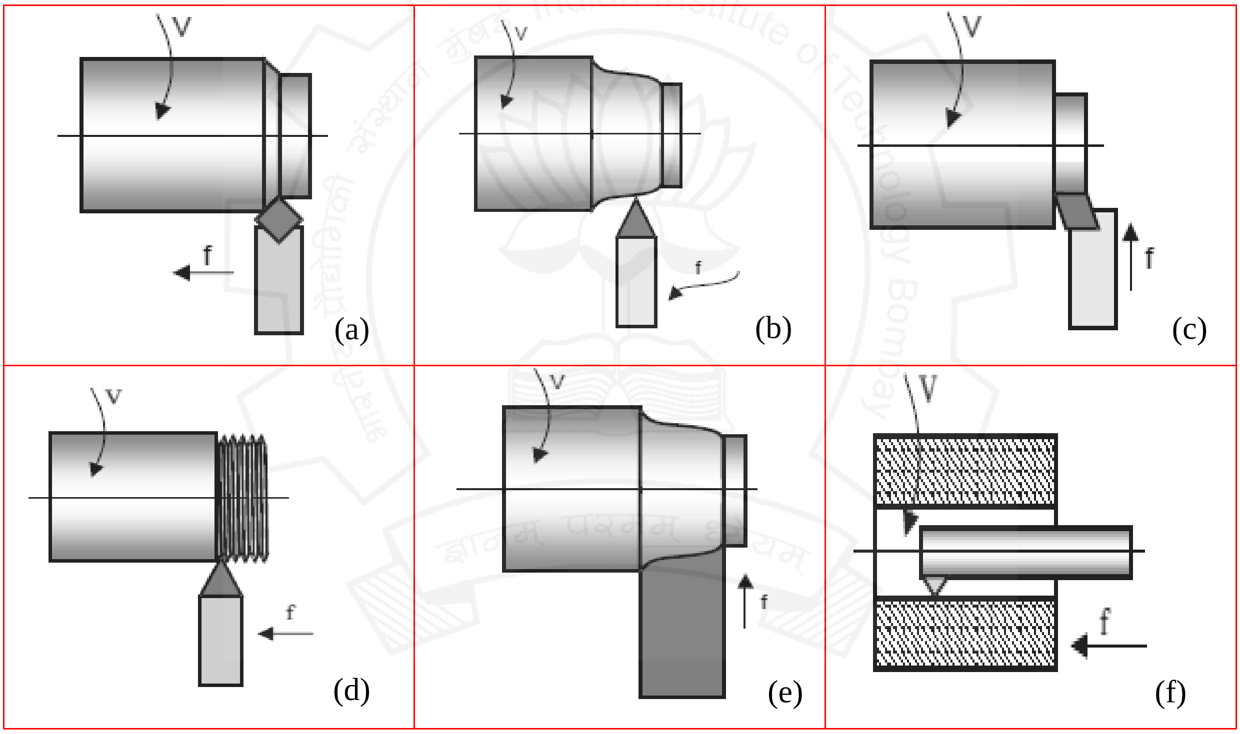
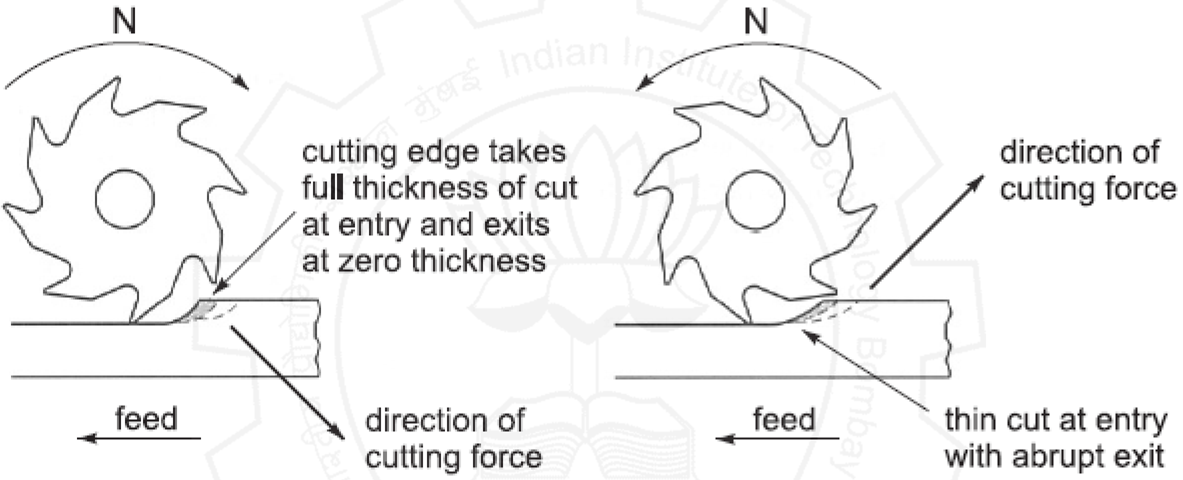


Figure 3.5.3 Different types of Turning Operations [5]

Milling

Milling is a process of producing flat and complex shapes with the use of multi-point (or multi-tooth) cutting tool. The axis of rotation of the cutting tool is perpendicular to the direction of feed, either parallel or perpendicular to the machined surface. Milling is usually an interrupted cutting operation since the teeth of the milling cutter enter and exit the workpiece 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. Figure 3.5.4 depicts two basic types of milling operations: *down milling*, when the cutter rotation is in the same direction as the motion of the workpiece being fed, and *up milling*, in which the workpiece is moving towards the cutter, opposing the cutter direction of rotation

In *down milling*, the cutting force is directed on to the work table, which allows thinner parts to be machined without susceptibility to breakage. Better surface finish is obtained in *down milling* but the stress load on the teeth is abrupt, which may damage the cutter. Backlash eliminator has to be used in this operation. In *up milling*, the cutting action tends to lift the workpiece and hence, proper fixture is required in this operation.



(a) (b)

Figure 3.5.4 Schematic depiction of down milling (a) and up milling (b) operations [5]

Depending on the orientation and geometry of the milling tool, several varieties of milling operations are possible. In *peripheral milling* (Figure 3.5.5a), also referred to as *plain milling*, the axis of the cutter is parallel to the surface being machined, and the operation is performed by the cutting edges on the outside periphery of the tool. The primary motion is the rotation of the tool. The feed is imparted to the workpiece. In *face milling (Figure 3.5.5b)*, the tool is perpendicular to the machined surface. The tool axis is vertical, and machining is performed by the teeth on both the end and the periphery of the face-milling tool. Also, up and down types of milling are available, depending on directions of the tool rotation and feed. *End milling* is used to produce pockets, key holes by using a tool referred to as the *end mill*, has a diameter less than the workpiece width. In *form milling (Figure 3.5.5c)*, the cutting edges of the peripheral tool (also referred to as *form cutter*) have a special profile that is imparted to the workpiece. Tools with various profiles are also available to cut different two-dimensional surfaces. One important application of form milling is in gear manufacturing. *Surface contouring (Figure 3.5.5d)*, is an operation performed by computer controlled milling machines in which a ball-end mill is fed back and forth across the workpiece along a curvilinear path at close intervals to produce complex three-dimensional surfaces.

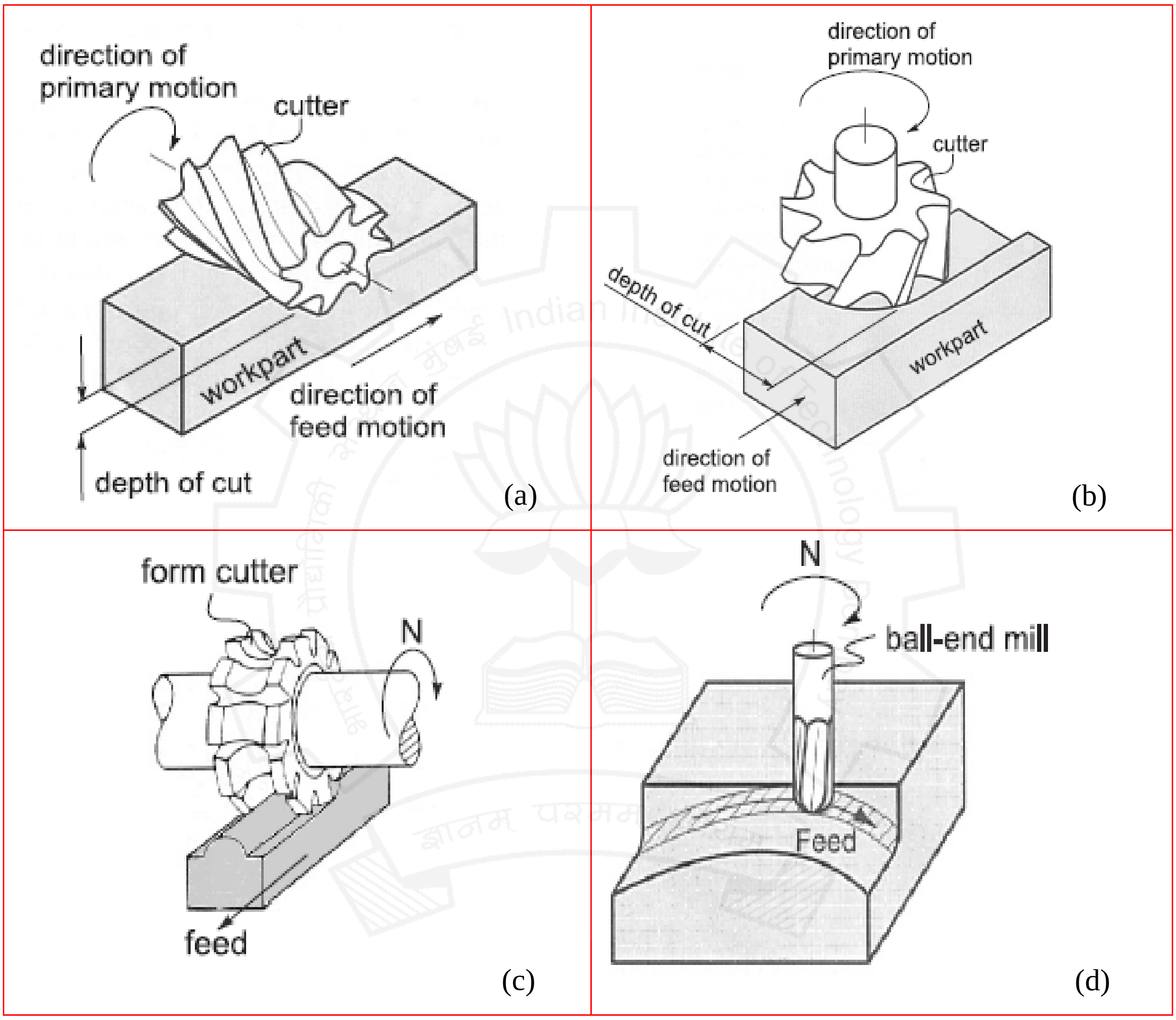


Figure 3.5.5 Different types of milling operations [4]

Drilling

Drilling is a process of producing round holes in a solid material or enlarging existing holes with the use of multi-point cutting tools called *drills* or *drill bits*. Various cutting tools are available for drilling, but the most common is the *twist drill*. A variety of drilling processes (*Figure 3.5.6*) are available to serve different purposes. *Drilling* is used to drill a round blind or through hole in a solid material. If the hole is larger than ~30 mm, a smaller pilot hole is drilled before *core drilling* the final one. For holes larger than ~50 mm, three-step drilling is recommended. *Core drilling* is used to increase the diameter of an existing hole. *Step drilling* is used to drill a stepped (multi-diameter) hole in a solid material. *Counter boring* provides a stepped hole again but with flat and perpendicular relative to hole axis face. The hole is used to seat internal hexagonal bolt heads. *Countersinking* is similar to counter boring, except that the step is conical for flat head screws.

Reaming operation is usually meant to slightly increase the size and to provide a better tolerance, surface finish and improved shape of an initially drilled hole. The tool is called *reamer*. *Center drilling* is used to drill a starting hole to precisely define the location for subsequent drilling operation and to provide centre support in lathe or turning centre. The tool is called *center drill* that has a thick shaft and very short flutes. *Gun drilling* is a specific operation to drill holes with very large *length-to-diameter* ratio up to 300. There are several modifications of this operation but in all cases cutting fluid is delivered directly to the cutting zone internally through the drill to cool and lubricate the cutting edges, and to remove the chips.

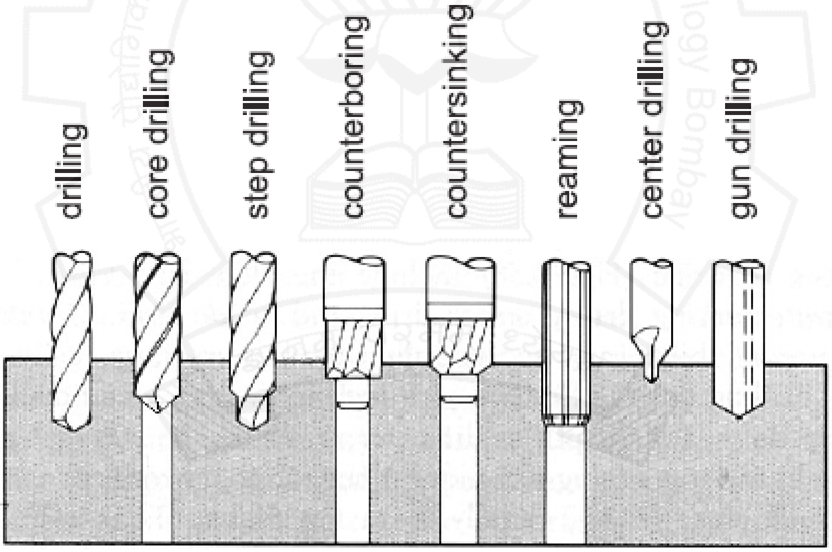


Figure 3.5.6 Different Types of Drilling Operations [3]

Planing, Shaping and Broaching

Planing and *shaping* (*Figure 3.5.7*) *are* similar operations, which differ only in the kinematics of the process. *Planing* is a machining operation in which the primary cutting motion is performed by the workpiece and feed motion is imparted to the cutting tool. In *shaping*, the primary motion is performed by the tool, and feed by the workpiece.

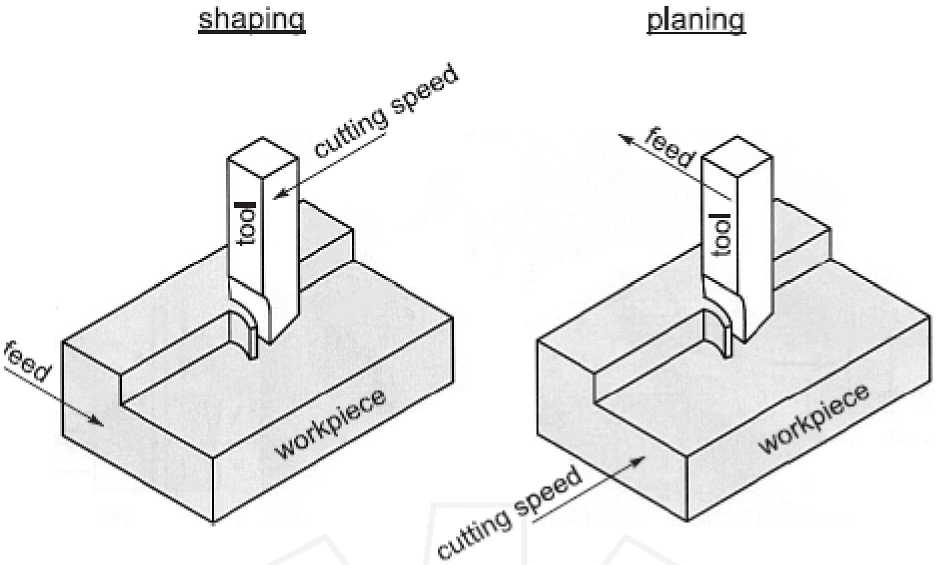


Figure 3.5.7 Kinematics of shaping and planning [4]

Broaching is a machining operation that involves the linear movement of a muti-point cutting tool (referred to as *broach*) relative to the workpiece in the direction of the tool axis. The shape of the machined surface is determined by the contour of the final cutting edges on the *broach*. *Broaching* is a highly productive method of machining with advantages like good surface finish, close tolerances, and the variety of possible machined surface shapes some of them can only be produced by *broaching*. Owing to the complicated geometry of the *broach*, the tooling is expensive. The broaching tools cannot be reground and have to be replaced when wear becomes excessive. *Broaching* is a typical mass production operation.

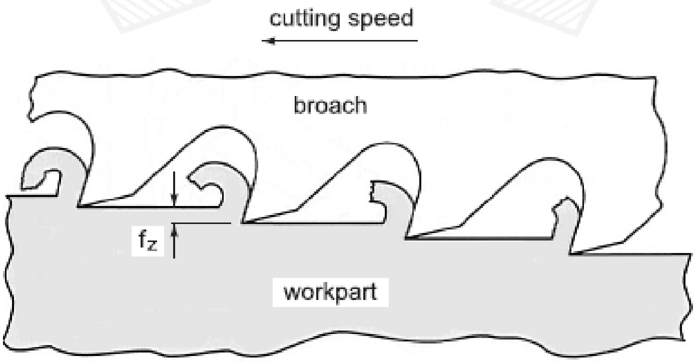


Figure 3.5.8 Schematic of broaching operation [1]

Grinding

Grinding (*Figure 3.5.9*) is the most popular form of abrasive machining. It involves an abrasive tools consisting of grain of hard materials which are forced to rub against the workpiece removing a very small amount of material. Due to the random orientation of grains and some uncontrollable cutting condition, the selection of proper parameters often becomes difficult. Grinding can be performed to produce flat as well as cylindrical (both external and internal) surface efficiently. Grinding is applied when the material is too hard to be machined economically or when tolerances required are very tight. *Grinding* can produce flatness tolerances of less than ±0.0025 mm on a 127 x 127 mm steel surface if the surface is adequately supported. In recent times, enormous amount of research work has made *grinding* process very economical and efficient for removing a large thickness of material also. Techniques like creep feed grinding, high efficiency deep feed grinding etc. is being used for bulk material removal. The major advantages of grinding process include dimensional accuracy, good surface finish, good form and locational accuracy applicable to both hardened and unhardened material.

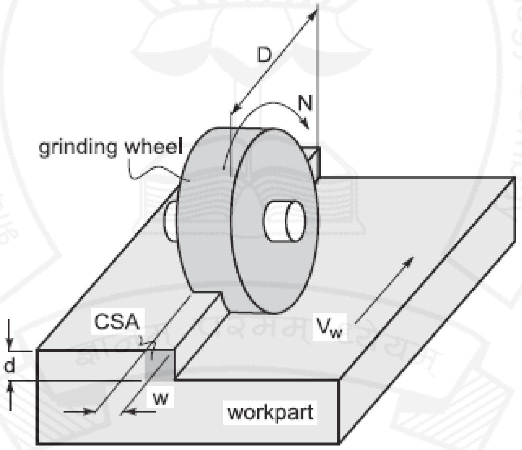


Figure 3.5.9 Schematic of grinding operation [1]

Abrasive Finishing

As the name indicates, these groups of operations are used to achieve superior surface finish up to mirror-like finishing and very close dimensional precision. The finishing operations are assigned as the last operations in typical single part production cycle usually after the conventional or abrasive machining operations. Honing, Lapping, Super finishing, Polishing process comes under this group. *Figure 3.5.10* depicts a comparison of surface roughness values for different processes.

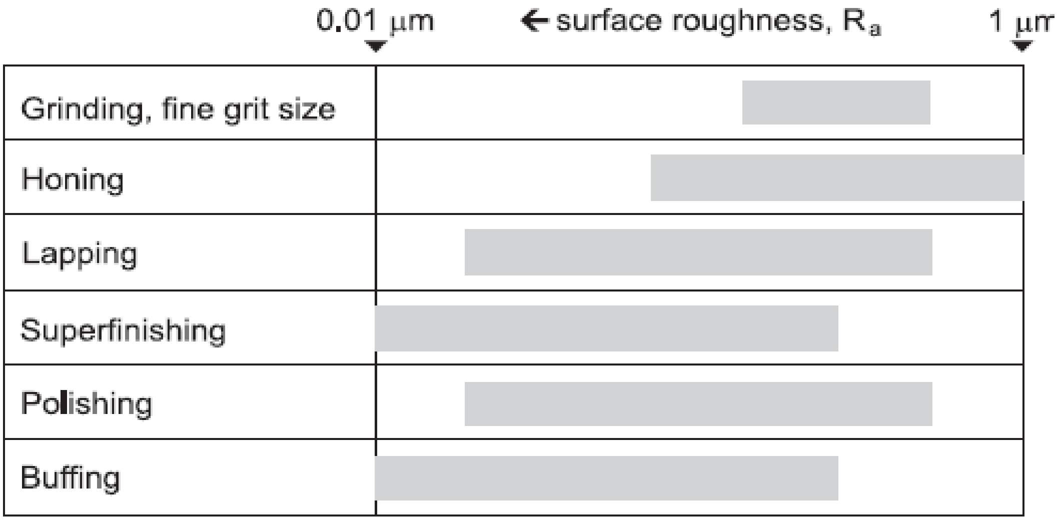


Figure 3.5.10 Comparison of surface roughness [4]

Non Traditional Machining Processes

To distinguish the non-traditional machining (NTM) processes from the traditional or conventional ones, it is necessary to understand the differences and the similar characteristics between conventional machining processes and NTM processes. The conventional processes generally involve a wedge shaped cutting tool to remove material in the form of chip by causing plastic deformation and shear failure. The cutting tool has to be harder than the work piece at room temperature as well as under machining conditions. However, the non-traditional processes commonly embody by the following characteristics:

(1) Material removal may occur with or without the conventional chip formation,

(2) A physical cutting tool may not always be present [e.g. a typical laser beam is used for machining in laser jet machiningprocess].

(3) The tool material needs not be harder than the workpiece material.

(4) Majority of the non-traditional machining processes do not necessarily use mechanical energy and rather different other forms of energy for material removal.

Some commonly used non-traditional machining processes are described below.

Abrasive Jet Machining

Abrasive jet machining (*Figure 3.5.11*) process involves impinging of fine abrasive particles on the work material at a very high velocity causing small fracture on the workpiece surface on impact. A gas stream carries both the abrasive particles and the fractured particles away. The jet velocity is in the range of 150-300 m/s and the applied pressure can range from two to ten times of atmospheric pressure. *Abrasive Jet Machining* (AJM) is used for deburring, etching, and cleaning of hard and brittle metals, alloys, and nonmetallic materials.

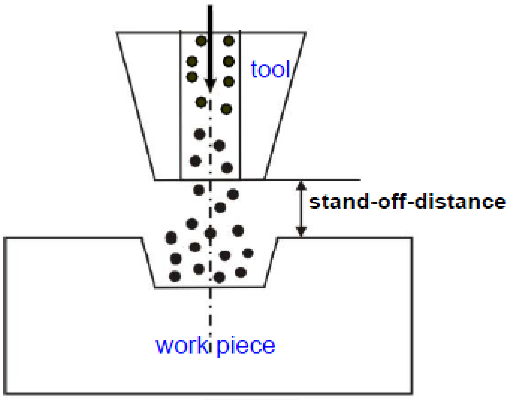


Figure 3.5.11 Schematic depiction of Abrasive Jet Machining [4]

Ultrasonic Machining

In *ultrasonic machining* (*Figure 3.5.12*), a tool of desired shape vibrates at an ultrasonic frequency (19 ~ 25 kHz) with an amplitude of around 15 – 50 μm over the workpiece. The tool is pressed downward with a feed force and the machining zone is flooded with hard abrasive particles generally in the form of water based slurry. As the tool vibrates at ultrasonic frequency, the abrasive particle removes material by indentation. This process can be used for very accurate machining of hard and brittle metallic alloys, semiconductors, glass, ceramics, carbides, wire drawing and punching dies, etc.

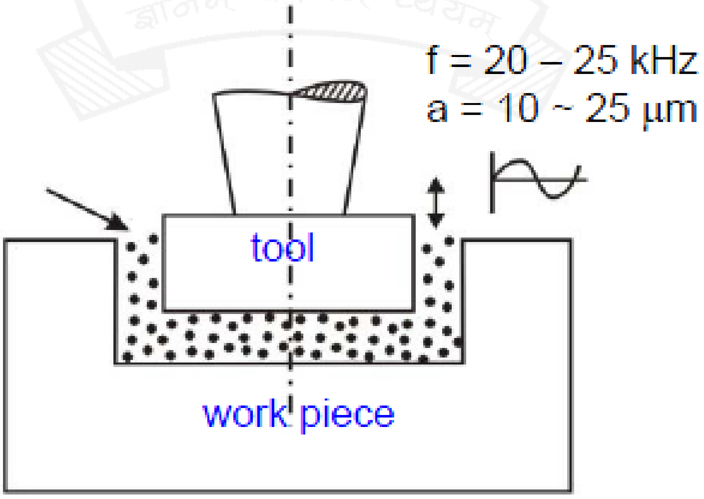


Figure 3.5.12 Schematic depiction of Ultrasonic Machining

Water Jet and Abrasive Water Jet Machining

Water Jet Machining uses a fine, high-pressure, high velocity (faster than the speed of sound) stream of water directed at the work surface to cause material removal. The cutting ability of water jet machining can be improved drastically by adding hard and sharp abrasive particles into the water jet and is termed as Abrasive Water Jet machining. This jet is sprayed over the work surface with very high pressure causing removal of material by the indentation action. Typical application of these processes includes paint removal, cleaning and cutting of sheets especially of softer materials, cutting of frozen meat, dismantling of nuclear plant parts, etc.

Electro Chemical Machining

Electro chemical machining (*Figure 3.5.13*) can be thought of a controlled anodic dissolution at atomic level of an electrically conductive workpiece due to the flow of high current at relatively low potential difference. The machining process is attained by a shaped tool. Both the workpiece and the tool are submerged into a suitable electrolyte which is often the water based neutral salt solution. In principle, it can be considered to be opposite of *electrochemical coating* process. As the tool does not contact the workpiece, there is no need to use expensive alloys to make the tool tougher or harder than the workpiece, which is a distinct advantage. There is less tool wear, and less heat and stresses are produced during this process. High tooling costs and risk of corrosion due to electrolyte are some disadvantages of this process.

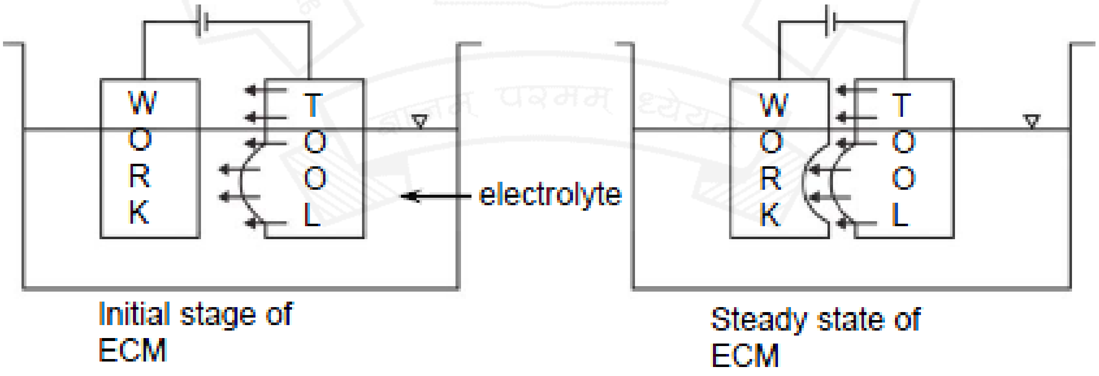


Figure 3.5.13 Schematic outline of Electro Chemical Machining [3]

Electro Discharge Machining

Electro Discharge Machining (EDM) (*Figure 3.5.14*) is an electro-thermal non-traditional machining process, where electrical energy is used to generate electrical spark between the tool and the workpiece. The material removal occurs primarily by vaporization of workpiece material due to high thermal energy of the spark. *Electro-discharge machining* is mainly used to machine difficult-to-machine materials and high strength and temperature resistant alloys. Difficult geometries in small batches or even on job-shop basis can be produced using this process. The only important point is that the workpiece material has to be electrically conductive. Some of the major advantages of this process are as follows:

- Complex shapes that are difficult to machine with conventional processes, can be done easily by *electrodischarge machining process,*
- Extremely hard material can be machined to close tolerances,
- Very small work pieces can be handled with sufficient ease, and
- A good surface finish can be obtained.

When the tool in *electrodischarge machining* process is replaced by a continuously moving small diameter electrically conducting wire, the same is referred to as *wire-electrodischarge machining* process that is widely used to cut a narrow kerf in the workpiece.

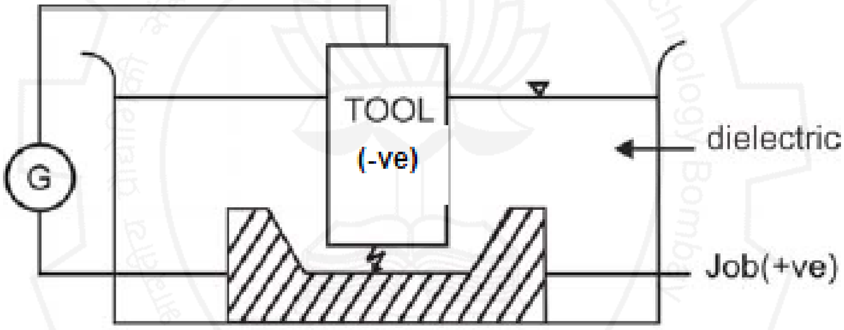


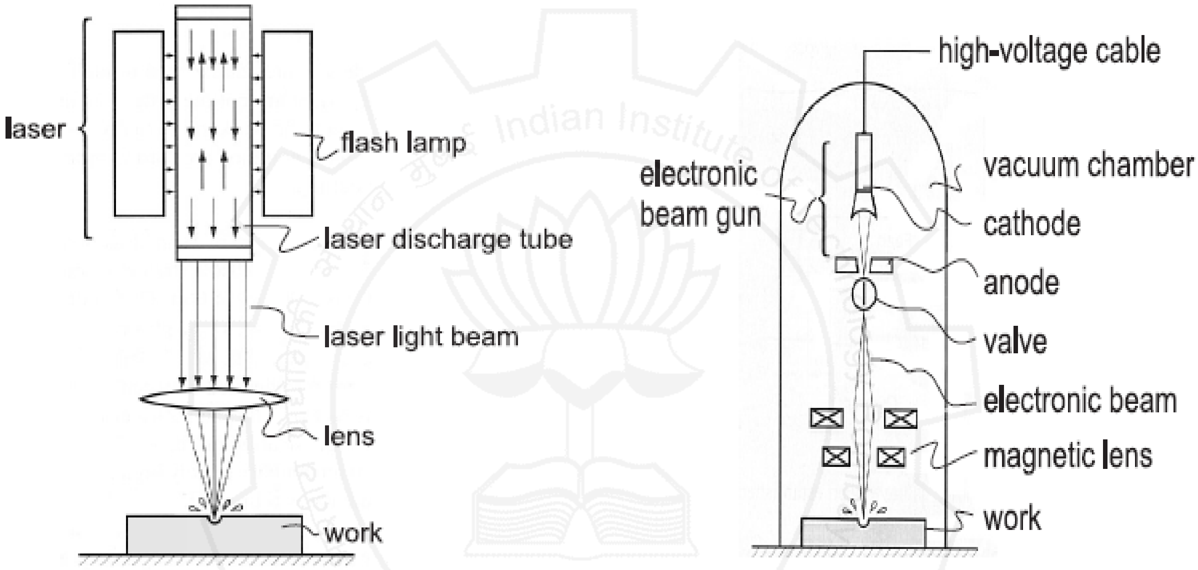
Figure 3.5.14 Schematic depiction of Electrodischarge Machining [3]

Laser and Electron Beam Machining

Laser beam machining (LBM) (*Figure 3.5.15a*) uses the light energy from a laser to remove material by vaporization and ablation whereas *electron beam machining* (EBM) uses a high-velocity stream of electrons focused on the work piece surface to remove material by melting and vaporization. The schematic of these processes are shown in the *Figure 3.5.15*.

The types of lasers used in *laser beam machining* process include carbon dioxide (CO2) gas lasers, solid lasers (Nd-YAG), fibre lasers and eximer lasers (especially for micro-level machining) although the CO2 based gas lasers are primarily used for machining. The light produced by the laser has significantly less power than a normal white light, but it can be focused optically to deliver a very high density source and when irradiated on a surface can result in melting and vaporization of workpiece material in a very localized area causing material removal.

In *electron beam machining* (*Figure 3.5.15b*) process, the electron beam gun generates a continuous stream of electrons that are focused through an electromagnetic lens on the work surface. The electrons are accelerated with voltages of approximately 1,50,000 V to create electron velocities over 200,000 km/s. On impinging the surface, the kinetic energy of the electrons is converted into thermal energy of extremely high density, which vaporizes the material in a much localized area. *Electron beam machining* must be carried out in a vacuum chamber to eliminate collision of the electrons with gas molecules.



(a) (b)

Figure 3.5.15 Schematic depiction of (a) Laser beam, and (b) Electron beam machining [3]

Design for Machining

Machinability

It is clear from the previous descriptions that there are a numbers of different machining processes available to meet the needs like dimensional accuracy, surface finish, ease of machining of a material etc. Depending of these factors, the proper process is chosen to meet the objective. It is always attempted to accomplish the machining effectively, efficiently and economically as far as possible by removing the excess material smoothly and speedily with lower power consumption, tool wear and surface deterioration. The term machinability is used for grading work material with respect to the machining characteristics. There is no proper definition of *machinability* and often it is referred to

- the ability of the work material to be machined,
- how easily and fast a material can be machined, and
- material response to machining.

A material is said to be more machinable if it results in lesser tool wear, greater tool life and provide better surface finish consuming lesser power. Attempts are made to measure or quantify the *machinability* in terms of (a) tool life which substantially influences productivity and economy in machining, (b) magnitude of cutting forces which affects power consumption and dimensional accuracy, and (c) surface finish, which plays role on performance and service life of the product. For example, cast iron is often considered more *machinable* than aluminium. Cast iron contains graphite flakes which causes failure easily by stress concentration. It also acts as a lubricant reducing the extent of heat generation and friction which finally leads to less tool wear. On the other hand, aluminium, being a ductile material, produces continuous chips and undergo sever plastic deformation prior to complete detachment. These not only create operational problems but also increase the cutting force. In practice it is not possible to quantify all the criteria that affect *machinability*. Application of cutting fluid also improve *machinability* by

- improving tool life by cooling and lubrication,
- reducing cutting forces and specific energy consumption, and
- Improving surface integrity by cooling, lubricating and cleaning at the cutting zone.

Selection of Machining Parameters

Selection of the process parameters is one of the major considerations during machining. A typical machining process depends on a numbers of factors. It is not possible to consider all factors together. Lots of research works have revealed the most important factors to be considered and controlled properly to achieve most efficient machining. Cutting speed, feed and depth of cut are the three most important factors to be considered to maximize production rate and minimize overall cost. To maximize the production rate, the total production time has to be minimized. The total time per unit product for operation is given by:

$$T_C = T_h + T_m + \frac{T_t}{n_p} \tag{1}$$

where T_h is part handling time, T_m is the machining time per part, $\frac{T_t}{n_p}$ is the tool change time per part , and n_p is the number of pieces cut in one tool life. Similarly, the cost per unit is given by

$$C_C = C_0 T_h + C_0 T_m + C_0 \frac{T_t}{n_p} + \frac{C_t}{n_p} \qquad (2)$$

Where C_t is the tool cost, C_o is the operation cost per unit time.

Optimizing Cutting Speed

Cutting speed is the major factor to be controlled during machining as it not only determines the production rate but also the tool life. Higher cutting speed leads to higher productivity but its upper value is limited by the tool life, given by the Taylor's tool life equation (eq. 3) as:

$$VT^n = C \qquad (3)$$

where V is the cutting speed in m/min, T is the tool life in min, and C and n are material constants. The term n is is also referred to as the *Taylor exponent*. The cutting speed has to be selected to achieve a balance between high metal removal rate and suitably longer tool life. Various mathematical formulations are available for optimal cutting speed. A typical variation of *machining cycle time* and *unit cost* with cutting speed is shown in the *Figure 3.5.16* and *3.5.17*, respectively.

Optimizing Depth of Cut and Feed

Depth of cut and *feed* also affect the machining efficiency to a lesser extent than the cutting speed. *Depth of cut* is often predetermined by the workpiece geometry and the operation sequences. In *roughing*, the *depth of cut* is made as large as possible to maximize the material removal rate, subject to limitations of available power, machine tool and setup rigidity, and strength of cutting tool In finishing, the *depth of cut* is set to achieve final part dimensions. The *feed rate* generally depends on the following factors:

(1) *Tooling* – harder tool materials require lower feeds

(2) *Roughing or finishing* - Roughing means high feeds, finishing means low feeds

(3) *Constraints on feed in roughing* - Limits imposed by cutting forces, setup rigidity, and sometimes machine power

(4) *Surface finish requirements in finishing* – select feed to produce desired finish

Equation (4) depicts the modified Taylor's tool life equation given as

$$V^{x} f^{y} t^{z} = \frac{C}{T} \tag{4}$$

where V is the cutting speed in m/min, T is the tool life in min, f is the feed in mm/rev, t is the depth of cut in mm, and C, x, y and z are material constants. The terms x, y, and z are also referred to as the *modified Taylor exponents*.

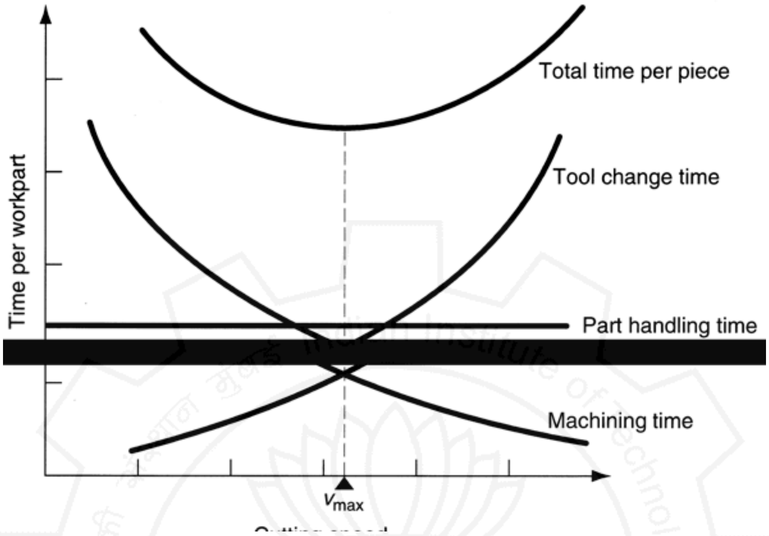


Figure 3.5.16 Machining cycle time vis-a-vis cutting speed [1]

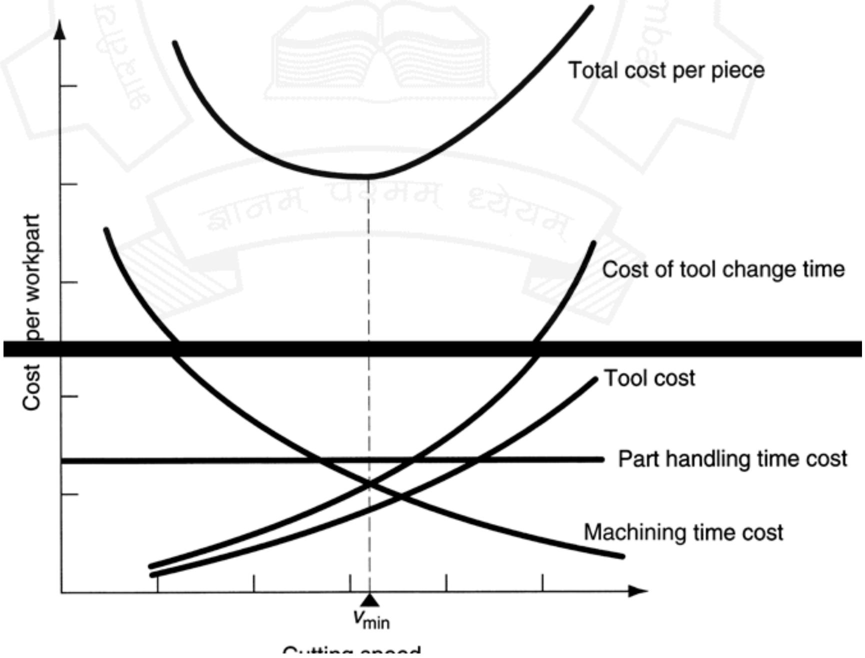


Figure 3.5.17 Unit cost vis-a-vis cutting speed [1]

Guide Lines for Designing Parts

(1) Machined features such as sharp corners, edges, and points should be avoided because they are difficult to machine, creates burrs and are dangerous to handle, causes stress concentration.

(2) Machined parts should be designed so they can be produced from standard stock sizes

(3) Select materials with good machinability

(4) Design machined parts with features that can be produced in a minimum number of setups (*Figure 3.5.17*).

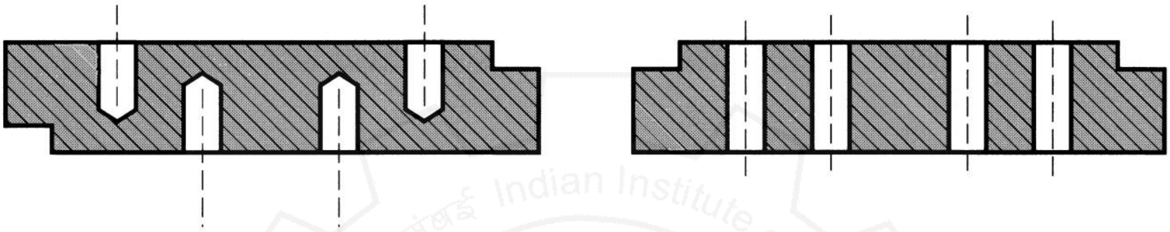


Figure 3.5.17 Through holes need less number of setup

(5) Machined parts should be designed with features that can be achieved with standard cutting tools.

(6) Avoid unusual hole sizes, threads, and features requiring special form tools.

(7) Design parts so that number of individual cutting tools needed is minimized.

(8) Reduce volume of material to be removed thus reducing machining time.

(9) Use large tolerances and surface roughness that will allow higher material removal rate or avoid finish cut.

(10) Reduce surface area to be machined.

(11) Reduce tool path length e.g. milling pockets larger radius allows larger diameter end mill and shorter path length. More rigid tool also allows higher feed rate in milling.

(12) Design the part in such a way that reduces setup, reorientation time thus reducing total operation time (*Figure 3.5.18*).

(13) Minimize the use of different machine for a single part. Use single machine as far as possible (*Figure 3.5.19*).

(14) Minimize the use of different machine for a single part. Use single machine as far as possible (Figure 3.5.19).

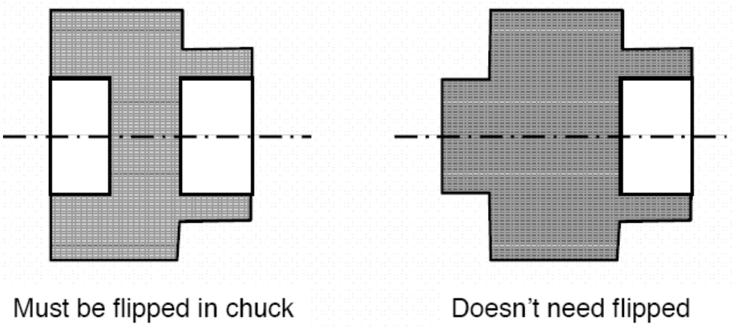


Figure 3.5.18 Avoid need to re-clamp

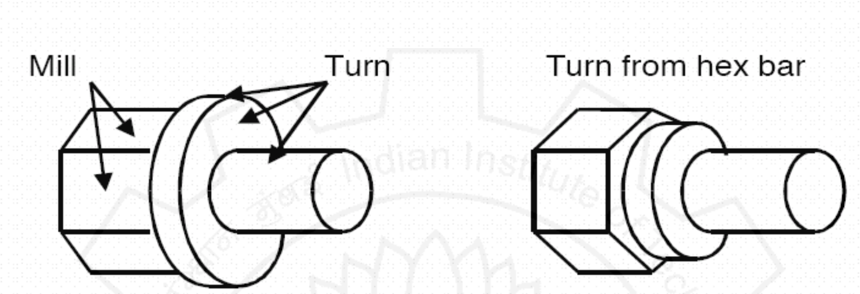


Figure 3.5.19 Using Single machine

Exercise

1. Machinability does not depends on
   (a) Micro structure of the work material, (b) Work-tool combination, (c) Cutting fluid, (d) Operator Skill

2. In electro discharge machining, the tool must be harder than the work piece. True or False?

3. MRR in ECM depends on

(a) Hardness of work material, (b) atomic weight of work material, (c) thermal conductivity of work material, (d) ductility of work material

Ans: 1. (d). 2. False 3. (d)

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Module

3

Machinability

Lesson

14

Failure of cutting tools and tool life

Instructional objectives

At the end of this lesson, the students will be able to

(i) State how the cutting tools fail
(ii) Illustrate the mechanisms and pattern of tool wear
(iii) Ascertain the essential properties of cutting tool materials
(iv) Define and assess tool life
(v) Develop and use tool life equation.

(i) Failure of cutting tools

Smooth, safe and economic machining necessitate

- prevention of premature and catastrophic failure of the cutting tools
- reduction of rate of wear of tool to prolong its life

To accomplish the aforesaid objectives one should first know why and how the cutting tools fail.

Cutting tools generally fail by :

i) Mechanical breakage due to excessive forces and shocks. Such kind of tool failure is random and catastrophic in nature and hence are extremely detrimental.
ii) Quick dulling by plastic deformation due to intensive stresses and temperature. This type of failure also occurs rapidly and are quite detrimental and unwanted.
iii) Gradual wear of the cutting tool at its flanks and rake surface.

The first two modes of tool failure are very harmful not only for the tool but also for the job and the machine tool. Hence these kinds of tool failure need to be prevented by using suitable tool materials and geometry depending upon the work material and cutting condition.

But failure by gradual wear, which is inevitable, cannot be prevented but can be slowed down only to enhance the service life of the tool.

The cutting tool is withdrawn immediately after it fails or, if possible, just before it totally fails. For that one must understand that the tool has failed or is going to fail shortly.

It is understood or considered that the tool has failed or about to fail by one or more of the following conditions :

(a) In R&D laboratories

- total breakage of the tool or tool tip(s)
- massive fracture at the cutting edge(s)
- excessive increase in cutting forces and/or vibration
- average wear (flank or crater) reaches its specified limit(s)

(b) In machining industries

- excessive (beyond limit) current or power consumption
- excessive vibration and/or abnormal sound (chatter)
- total breakage of the tool
- dimensional deviation beyond tolerance
- rapid worsening of surface finish
- adverse chip formation.

(ii) Mechanisms and pattern (geometry) of cutting tool wear

For the purpose of controlling tool wear one must understand the various mechanisms of wear, that the cutting tool undergoes under different conditions.
The common mechanisms of cutting tool wear are :

i) Mechanical wear
  - thermally insensitive type; like abrasion, chipping and delamination
  - thermally sensitive type; like adhesion, fracturing, flaking etc.

ii) Thermochemical wear
  - macro-diffusion by mass dissolution
  - micro-diffusion by atomic migration

iii) Chemical wear

iv) Galvanic wear

In diffusion wear the material from the tool at its rubbing surfaces, particularly at the rake surface gradually diffuses into the flowing chips either in bulk or atom by atom when the tool material has chemical affinity or solid solubility towards the work material. The rate of such tool wear increases with the increase in temperature at the cutting zone.
Diffusion wear becomes predominant when the cutting temperature becomes very high due to high cutting velocity and high strength of the work material.
Chemical wear, leading to damages like grooving wear may occur if the tool material is not enough chemically stable against the work material and/or the atmospheric gases.
Galvanic wear, based on electrochemical dissolution, seldom occurs when both the work tool materials are electrically conductive, cutting zone temperature is high and the cutting fluid acts as an electrolyte.
The usual pattern or geometry of wear of turning and face milling inserts are typically shown in Fig. 3.2.1 (a and b) and Fig. 3.2.2 respectively.

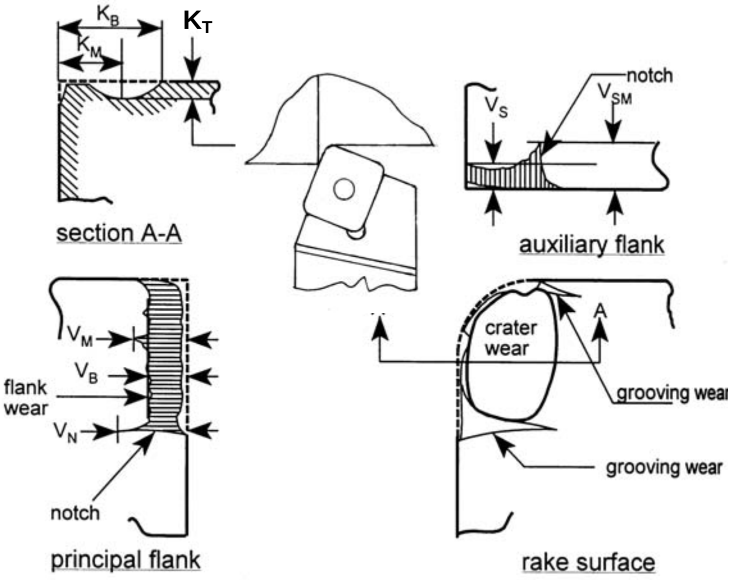


***Fig. 3.2.1 (a)** Geometry and major features of wear of turning tools*

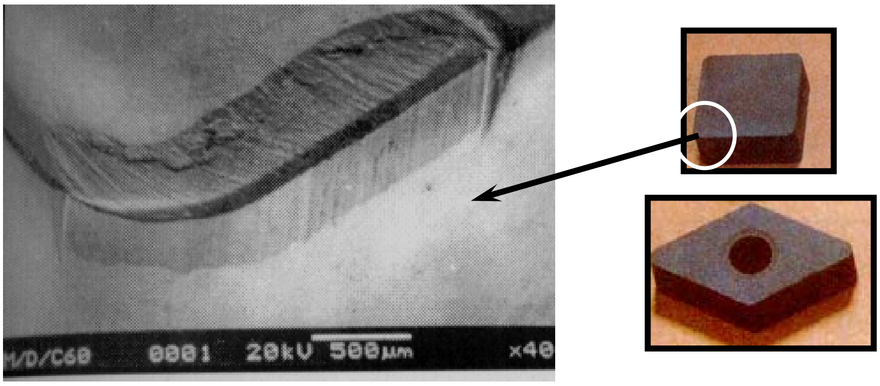
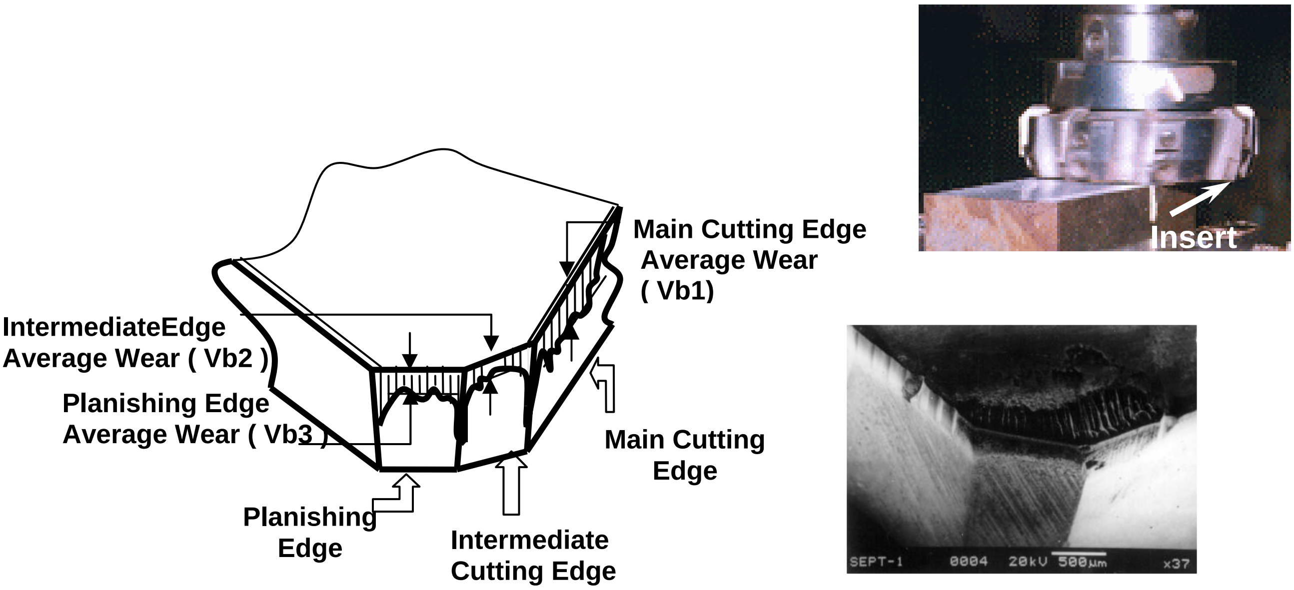


Fig. 3.2.1 (b) *Photographic view of the wear pattern of a turning tool insert*



(a) (b)

Fig. 3.2.2 *Schematic (a) and actual view (b) of wear pattern of face milling insert*

In addition to ultimate failure of the tool, the following effects are also caused by the growing tool-wear :

- increase in cutting forces and power consumption mainly due to the principal flank wear
- increase in dimensional deviation and surface roughness mainly due to wear of the tool-tips and auxiliary flank wear (V_s)
- odd sound and vibration
- worsening surface integrity
- mechanically weakening of the tool tip.

(iii) Essential properties for cutting tool materials

The cutting tools need to be capable to meet the growing demands for higher productivity and economy as well as to machine the exotic materials which are coming up with the rapid progress in science and technology.

The cutting tool material of the day and future essentially require the following properties to resist or retard the phenomena leading to random or early tool failure :

i) high mechanical strength; compressive, tensile, and TRA
ii) fracture toughness – high or at least adequate
iii) high hardness for abrasion resistance
iv) high hot hardness to resist plastic deformation and reduce wear rate at elevated temperature
v) chemical stability or inertness against work material, atmospheric gases and cutting fluids
vi) resistance to adhesion and diffusion
vii) thermal conductivity – low at the surface to resist incoming of heat and high at the core to quickly dissipate the heat entered
viii) high heat resistance and stiffness
ix) manufacturability, availability and low cost.

iv) Tool Life

Definition –

Tool life generally indicates, the amount of satisfactory performance or service rendered by a fresh tool or a cutting point till it is declared failed.

Tool life is defined in two ways :

(a) **In R & D :** Actual machining time (period) by which a fresh cutting tool (or point) satisfactorily works after which it needs replacement or reconditioning. The modern tools hardly fail prematurely or abruptly by mechanical breakage or rapid plastic deformation. Those fail mostly by wearing process which systematically grows slowly with machining time. In that case, **tool life means the span of actual machining time by which a fresh tool can work before attaining the specified limit of tool wear.** Mostly tool life is decided by the machining time till flank wear, V_B reaches 0.3 mm or crater wear, K_T reaches 0.15 mm.

(b) **In industries or shop floor :** The length of time of satisfactory service or amount of acceptable output provided by a fresh tool prior to it is required to replace or recondition.

Assessment of tool life

For R & D purposes, tool life is always assessed or expressed by span of machining time in minutes, whereas, in industries besides machining time in minutes some other means are also used to assess tool life, depending upon the situation, such as

- no. of pieces of work machined
- total volume of material removed
- total length of cut.

Measurement of tool wear

The various methods are :

i) by loss of tool material in volume or weight, in one life time – this method is crude and is generally applicable for critical tools like grinding wheels.
ii) by grooving and indentation method – in this approximate method wear depth is measured indirectly by the difference in length of the groove or the indentation outside and inside the worn area
iii) using optical microscope fitted with micrometer – very common and effective method
iv) using scanning electron microscope (SEM) – used generally, for detailed study; both qualitative and quantitative
v) Talysurf, specially for shallow crater wear.

(v) Taylor's tool life equation.

Wear and hence tool life of any tool for any work material is governed mainly by the level of the machining parameters i.e., cutting velocity, (V_C), feed, (s_o) and depth of cut (t). Cutting velocity affects maximum and depth of cut minimum.
The usual pattern of growth of cutting tool wear (mainly V_B), principle of assessing tool life and its dependence on cutting velocity are schematically shown in Fig.3.2.3.

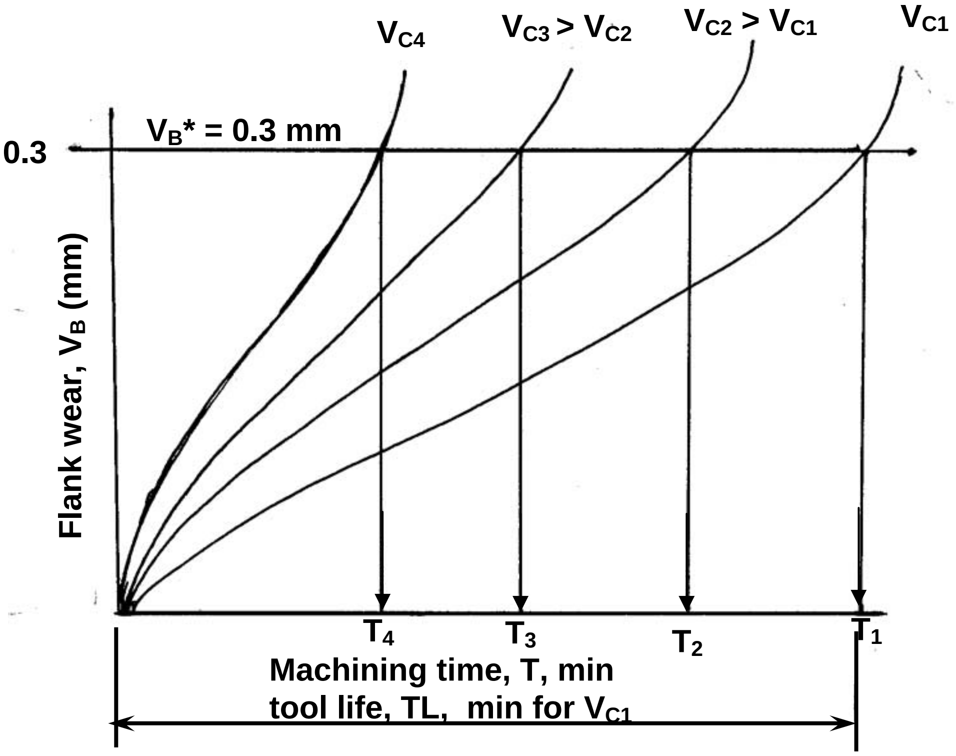


Fig. 3.2.3 *Growth of flank wear and assessment of tool life*

The tool life obviously decreases with the increase in cutting velocity keeping other conditions unaltered as indicated in Fig. 3.2.3.
If the tool lives, T_1, T_2, T_3, T_4 etc are plotted against the corresponding cutting velocities, V_1, V_2, V_3, V_4 etc as shown in Fig. 3.2.4, a smooth curve like a rectangular

hyperbola is found to appear. When F. W. Taylor plotted the same figure taking both V and T in log-scale, a more distinct linear relationship appeared as schematically shown in Fig. 3.2.5.

With the slope, n and intercept, c, Taylor derived the simple equation as

$$VT^n = C$$

where, n is called, Taylor's tool life exponent. The values of both 'n' and 'c' depend mainly upon the tool-work materials and the cutting environment (cutting fluid application). The value of C depends also on the limiting value of V_B undertaken (i.e., 0.3 mm, 0.4 mm, 0.6 mm etc.)

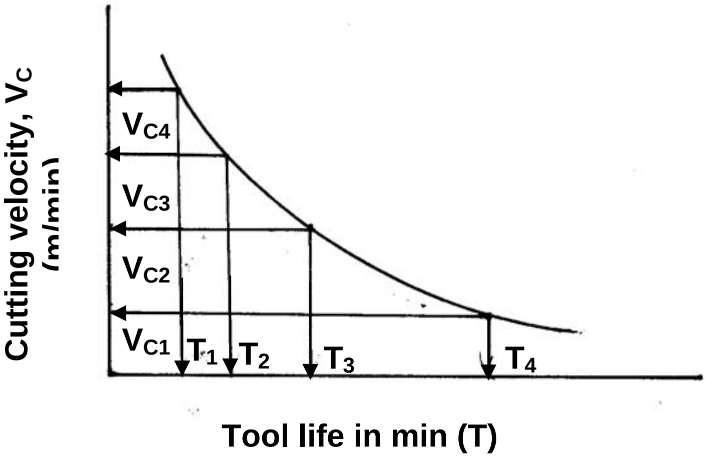


Fig. 3.2.4 Cutting velocity – tool life relationship

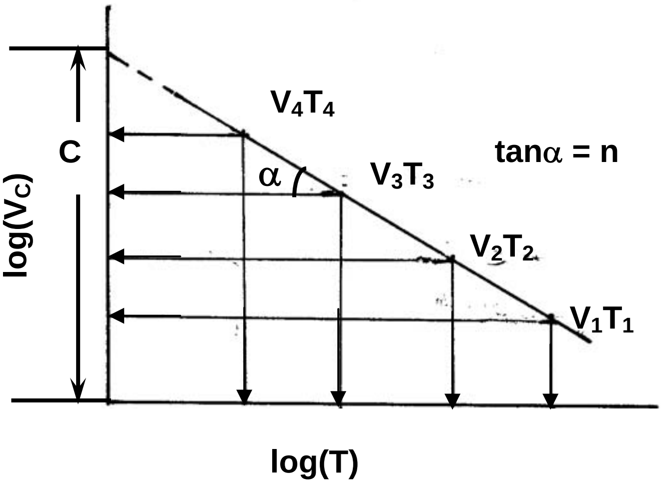


Fig. 3.2.5 Cutting velocity vs tool life on a log-log scale

Example of use of Taylor's tool life equation

Problem :

If in turning of a steel rod by a given cutting tool (material and geometry) at a given machining condition (s_o and t) under a given environment (cutting fluid application), the tool life decreases from 80 min to 20 min. due to increase in cutting velocity, V_C from 60 m/min to 120 m/min., then at what cutting velocity the life of that tool under the same condition and environment will be 40 min.?

Solution :

Assuming Taylor's tool life equation, $VT^n = C$

$V_1T_1 = V_2T_2 = V_3T_3 = ... = C$

Here, V_1 = 60 m/min; T_1 = 80 min.

V_2 = 120 m/min; T_2 = 20 min.

V_3 = ? (to be determined); T_3 = 40 min.

Taking,

$$V_1T_1^n = V_2T_2^n$$

i.e,
$$\left(\frac{T_1}{T_2}\right)^n = \left(\frac{V_2}{V_1}\right)$$

or
$$\left(\frac{80\min}{20\min}\right)^n = \left(\frac{120m/\min}{60m/\min}\right)$$

from which, n = 0.5

Again
$$V_3T_3^n = V_1T_1^n$$

i.e,
$$\left(\frac{V_3}{V_1}\right) = \left(\frac{T_1}{T_3}\right)^n$$

or
$$V_3 = \left(\frac{80}{40}\right)^{0.5} x60 = 84.84m/\min \qquad \textbf{\textit{Ans}}$$

Modified Taylor's Tool Life equation

In Taylor's tool life equation, only the effect of variation of cutting velocity, V_C on tool life has been considered. But practically, the variation in feed (s_o) and depth of cut (t) also play role on tool life to some extent.

Taking into account the effects of all those parameters, the Taylor's tool life equation has been modified as,

$$TL = \frac{C_T}{V_c^x s_o^y t^z}$$

where, TL = tool life in min

C_T — a constant depending mainly upon the tool – work materials and the limiting value of V_B undertaken.

x, y and z — exponents so called tool life exponents depending upon the tool – work materials and the machining environment.

Generally, x > y > z as V_C affects tool life maximum and t minimum.

The values of the constants, C_T, x, y and z are available in Machining Data Handbooks or can be evaluated by machining tests.

Exercise – 3.2

Quiz Test

Identify the correct answer from the given four options.

1. In high speed machining of steels the teeth of milling cutters may fail by
   (a) mechanical breakage
   (b) plastic deformation
   (c) wear
   (d) all of the above
2. Tool life in turning will decrease by maximum extent if we double the
   (a) depth of cut
   (b) feed
   (c) cutting velocity
   (d) tool rake angle
3. In cutting tools, crater wear develops at
   (a) the rake surface
   (b) the principal flank
   (c) the auxiliary flank
   (d) the tool nose
4. To prevent plastic deformation at the cutting edge, the tool material should possess
   (a) high fracture toughness
   (b) high hot hardness
   (c) chemical stability
   (d) adhesion resistance

Problems

Problem – 1

During turning a metallic rod at a given condition, the tool life was found to increase from 25 min to 50 min. when V_C was reduced from 100 m/min to 80 m/min. How much will be the life of that tool if machined at 90 m/min ?

Problem – 2

While drilling holes in steel plate by a 20 mm diameter HSS drill at a given feed, the tool life decreased from 40 min. to 24 min. when speed was raised from 250 rpm to 320 rpm. At what speed (rpm) the life of that drill under the same condition would be 30 min.?

Answers of the questions of Exercise – 3.2

Quiz Test

Q. 1 : (d)
Q. 2 : (c)
Q. 3 : (a)
Q. 4 : (b)

Solution to Problem 1.

Ans. 34.6 min

Solution to Problem 2

Ans. 287 rpm.

Module

1

Classification of Metal Removal Processes and Machine tools

Lesson
1

Introduction to Manufacturing and Machining

Instructional objectives

At the end of this lesson, the student would be able to :

(i) Identify the necessity of “manufacturing”
(ii) Define with examples the concept of “manufacturing”
(iii) List the main classifications of the manufacturing processes with examples
(iv) State the main purposes of “machining”
(v) Define with examples the concept of “machining”
(vi) State with example the principles of “machining”
(vii) State with examples the main requirements for “machining”
(viii) State with examples the main functions of “Machine tools”
(ix) Define the concept of “machine tools”

(i) Manufacturing – Need and concept

The progress and the prosperity of human civilization are governed and judged mainly by improvement and maintenance of standard of living through availability or production of ample and quality goods and services for men’s material welfare (MMW) in all respects covering housing, clothing, medicine, education, transport, communication and also entertainment. The successful creation of men’s material welfare (MMW) depends mainly on

- availability of natural resources (NR)
- exertion of human effort (HE); both physical and mental
- development and use of power tools and machines (Tools),

This can be depicted in a simple form,

$$MMW = NR(HE)^{TOOLS}$$

where, NR: refers to air, water, heat and light, plants and animals and solid and liquid minerals
TOOLS: refers to power plants, chemical plants, steel plants, machine tools etc. which magnify human capability.

This clearly indicates the important roles of the components; NR, HE and TOOLS on achieving MMW and progress of civilization.

Production or manufacturing can be simply defined as value addition processes by which raw materials of low utility and value due to its inadequate material properties and poor or irregular size, shape and finish are converted into high utility and valued products with definite dimensions, forms and finish imparting some functional ability. A typical example of manufacturing is schematically shown in Fig. 1.1.

A lump of mild steel of irregular shape, dimensions and surface, which had almost no use and value, has been converted into a useful and valuable product like bolt by a manufacturing process which imparted suitable features, dimensional accuracy and surface finish, required for fulfilling some functional requirements.

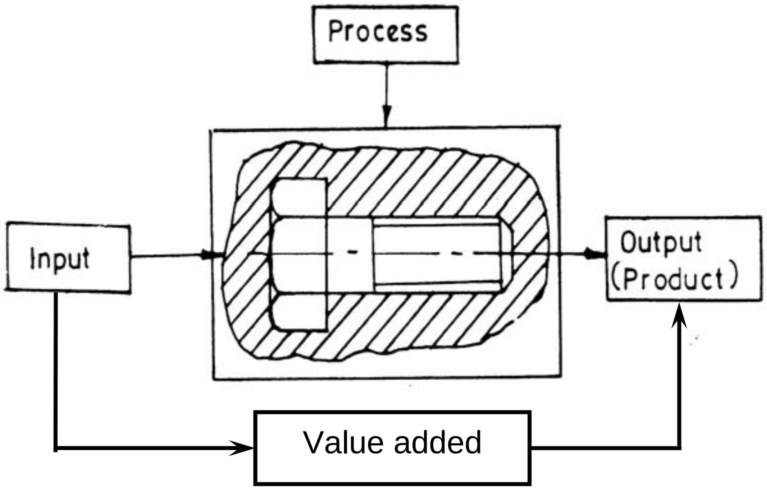


Fig. 1.1 *Value addition by manufacturing.*

Production Engineering covers two domains:
- (a) Production or Manufacturing Processes
- (b) Production Management

(a) Manufacturing Processes

This refers to science and technology of manufacturing products effectively, efficiently, economically and environment-friendly through

- Application of any existing manufacturing process and system
- Proper selection of input materials, tools, machines and environments.
- Improvement of the existing materials and processes
- Development of new materials, systems, processes and techniques

All such manufacturing processes, systems, techniques have to be

- Technologically acceptable
- Technically feasible
- Economically viable
- Eco-friendly

Manufacturing Science and technology are growing exponentially to meet the growing demands for;

- (i) Increase and maintenance of productivity, quality and economy specially in respect of liberalisation and global competitiveness

(ii) Making micro and ultra precision components for the modern electronics, computers and medical applications

(iii) Processing exotic materials, coming up with rapid and vast advent of science and technology like aerospace and nuclear engineering.

(b) Production Management

This is also equally important and essential in the manufacturing world. It mainly refers to planning, coordination and control of the entire manufacturing in most profitable way with maximum satisfaction to the customers by best utilization of the available resources like man, machine, materials and money. It may be possible to manufacture a product of given material and desired configuration by several processes or routes as schematically indicated in Fig. 1.2.

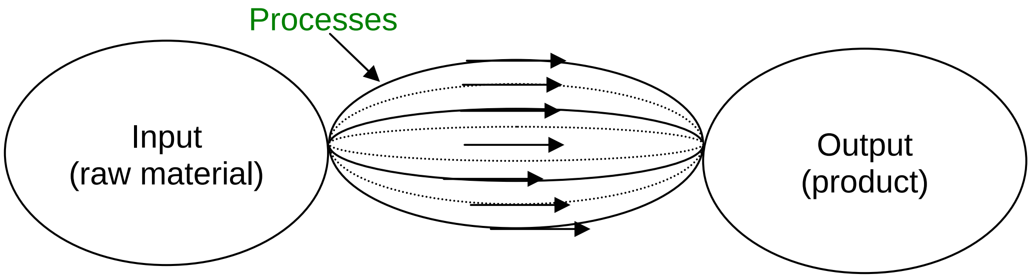


Fig. 1.2 Possibility of manufacturing in number of routes.

The various process routes may be different in respect of principle, technique, quality of products and time requirement and cost of manufacture. The best one is to be selected based on some criteria. Achieving the goal in manufacturing requires fulfillment of one or more of the following objectives:

- reduction of manufacturing time
- increase of productivity
- reduction of manufacturing cost
- increase in profit or profit rate

The most significant and ultimate objective, i.e., “Increase in Profit, P_r”, can be attained by

(i) reducing the overall manufacturing cost, C_m

(ii) increase in revenue, R by increasing quality and reliability of the products

(iii) enhancement of saleable production

As has been indicated in Fig. 1.3

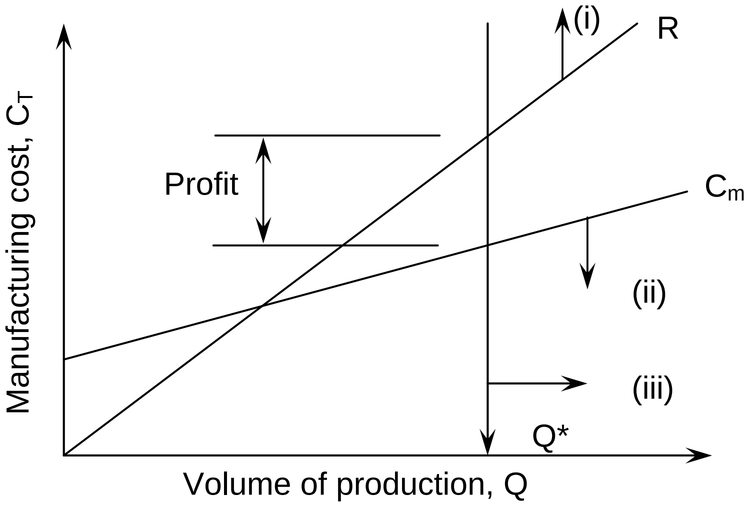


Fig. 1.3 *Strategies of increasing profit.*

Production management integrates and accomplishes all such essential activities leading to maximum benefits by best utilization of the resources and strategies.

(ii) Broad classification of Engineering Manufacturing Processes.

It is extremely difficult to tell the exact number of various manufacturing processes existing and are being practiced presently because a spectacularly large number of processes have been developed till now and the number is still increasing exponentially with the growing demands and rapid progress in science and technology. However, all such manufacturing processes can be broadly classified in four major groups as follows:

(a) Shaping or **forming**
Manufacturing a solid product of definite size and shape from a given material taken in three possible states:

- in solid state – e.g., forging rolling, extrusion, drawing etc.
- in liquid or semi-liquid state – e.g., casting, injection moulding etc.
- in powder form – e.g., powder metallurgical process.

(b) Joining process
Welding, brazing, soldering etc.

(c) Removal process
Machining (Traditional or Non-traditional), Grinding etc.

(d) Regenerative manufacturing

Production of solid products in layer by layer from raw materials in different form:

- liquid – e.g., stereo lithography
- powder – e.g., selective sintering
- sheet – e.g., LOM (laminated object manufacturing)
- wire – e.g., FDM. (Fused Deposition Modelling)

Out of the aforesaid groups, Regenerative Manufacturing is the latest one which is generally accomplished very rapidly and quite accurately using CAD and CAM for Rapid Prototyping and Tooling.

(iii) Machining – Purpose, Principle and Definition

(a) Purpose of Machining

Most of the engineering components such as gears, bearings, clutches, tools, screws and nuts etc. need dimensional and form accuracy and good surface finish for serving their purposes. Preforming like casting, forging etc. generally cannot provide the desired accuracy and finish. For that such preformed parts, called blanks, need semi-finishing and finishing and it is done by machining and grinding. Grinding is also basically a machining process.

Machining to high accuracy and finish essentially enables a product

- fulfill its functional requirements
- improve its performance
- prolong its service

(b) Principle of Machining

The basic principle of machining is typically illustrated in Fig. 1.4.

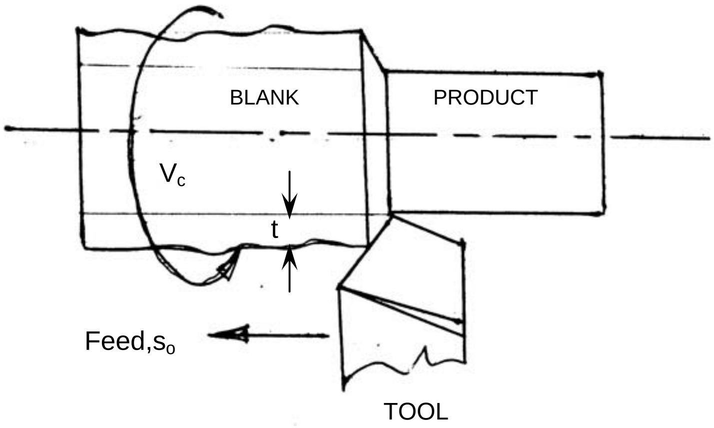


Fig. 1.4 *Principle of machining (turning)*

A metal rod of irregular shape, size and surface is converted into a finished rod of desired dimension and surface by machining by proper relative motions of the tool-work pair.

(c) Definition of Machining: Machining is an essential process of finishing by which jobs are produced to the desired dimensions and surface finish by gradually removing the excess material from the preformed blank in the form of chips with the help of cutting tool(s) moved past the work surface(s).

(iv) Machining requirements

The essential basic requirements for machining work are schematically illustrated in Fig. 1.5

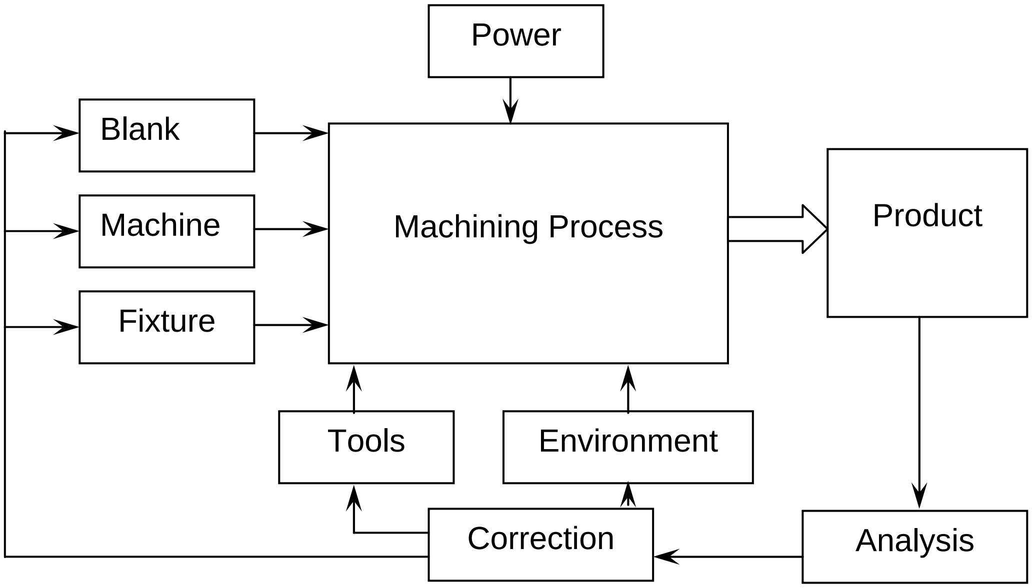


Fig. 1.5 *Requirements for machining*

The blank and the cutting tool are properly mounted (in fixtures) and moved in a powerful device called machine tool enabling gradual removal of layer of material from the work surface resulting in its desired dimensions and surface finish. Additionally some environment called cutting fluid is generally used to ease machining by cooling and lubrication.

(v) Basic functions of Machine Tools

Machine Tools basically produce geometrical surfaces like flat, cylindrical or any contour on the preformed blanks by machining work with the help of cutting tools. The physical functions of a Machine Tool in machining are:

- firmly holding the blank and the tool
- transmit motions to the tool and the blank

- provide power to the tool-work pair for the machining action.
- control of the machining parameters, i.e., speed, feed and depth of cut.

(vi) Machine Tool - definition

A machine tool is a non-portable power operated and reasonably valued device or system of devices in which energy is expended to produce jobs of desired size, shape and surface finish by removing excess material from the preformed blanks in the form of chips with the help of cutting tools moved past the work surface(s).

A. Quiz Test:

Select the correct answer from the given four possible answers: -

1. Machining is a
   (a) shaping process
   (b) removal process
   (c) regenerative process
   (d) joining process.

2. An object is machined to
   (a) fulfill its functional requirement
   (b) provide desirably good performance
   (c) render longer service life
   (d) all of the above.

3. Feed rate is expressed in turning operation by
   (a) mm/revolution
   (b) mm/stroke
   (c) mm per min
   (d) none of the above.

4. Rapid prototyping is a
   (a) joining process
   (b) removal process
   (c) regenerative manufacturing process
   (d) finishing process.

B. Exercises:

1. What should be the aims and objectives in manufacturing of any product?

2. Justify “Machining is a value addition process”.

3. Why even a battery operated pencil sharpener cannot be accepted as a machine tool?

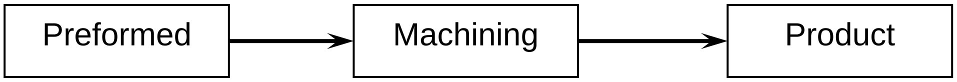
4. Why is making profit must for any industry ?

Answers of the given questions.

A. 1. – (b)
2. – (d)
3. – (a)
4. – (c)

B.
Ans. 1 Aim – enhance profit rate and job opportunity
Objectives –
- reduce manufacturing time
- increase rate of production
- reduce cost of manufacturing
- raise profit and profit rate

Ans.2



Preformed:
- Poor quality
- Less utility
- Less value

Machining:
- Dimensional accuracy
- Good finish

Product:
- High quality
- High utility
- High value

Ans. 3 Inspite of having all other major features of machine tools, the sharpener is of low value.

Ans. 4 For
- Maintenance, repair & replacement
- Modernisation
- Increase salary / incentive
- Expansion

Module

3

Machinability

Lesson

13

Concept of Machinability and its Improvement

Instructional objectives

At the end of this lesson, the students would be able to

(i) Conceptualise machinability and state its
- Definition
- Criteria of judgement

(ii) Illustrate how machinability is governed or influenced by several factors,
- Chemical and physical properties of work material
- Processing parameters
- Cutting tool parameters
- Environmental factors

(iii) Suggest various methods of improvement of machinability

(i) Concept, Definition And Criteria Of Judgement Of Machinability

It is already known that preformed components are essentially machined to impart dimensional accuracy and surface finish for desired performance and longer service life of the product. It is obviously attempted to accomplish machining effectively, efficiently and economically as far as possible by removing the excess material smoothly and speedily with lower power consumption, tool wear and surface deterioration. But this may not be always and equally possible for all the work materials and under all the conditions. The machining characteristics of the work materials widely vary and also largely depend on the conditions of machining. A term; ‘Machinability’ has been introduced for gradation of work materials w.r.t. machining characteristics.

But truly speaking, there is no unique or clear meaning of the term machinability. People tried to describe “Machinability” in several ways such as:
- It is generally applied to the machining properties of work material
- It refers to material (work) response to machining
- It is the ability of the work material to be machined
- It indicates how easily and fast a material can be machined.

But it has been agreed, in general, that it is difficult to clearly define and quantify Machinability. For instance, saying ‘material A is more machinable than material B’ may mean that compared to ‘B’,
- ‘A’ causes lesser tool wear or longer tool life
- ‘A’ requires lesser cutting forces and power
- ‘A’ provides better surface finish

where, surface finish and tool life are generally considered more important in finish machining and cutting forces or power in bulk machining.

Machining is so complex and dependant on so many factors that the order of placing the work material in a group, w.r.t. favourable behaviour in machining, will change if the consideration is changed from tool life to cutting power or surface quality of the product and vice versa. For instance, the machining behaviour of work materials are so affected by the cutting tool; both material and geometry, that often machinability is expressed as “operational characteristics of the work-tool combination”. Attempts were made to measure or quantify machinability and it was done mostly in terms of :

- tool life which substantially influences productivity and economy in machining
- magnitude of cutting forces which affects power consumption and dimensional accuracy
- surface finish which plays role on performance and service life of the product.

Often cutting temperature and chip form are also considered for assessing machinability.

But practically it is not possible to use all those criteria together for expressing machinability quantitatively. In a group of work materials a particular one may appear best in respect of, say, tool life but may be much poor in respect of cutting forces and surface finish and so on. Besides that, the machining responses of any work material in terms of tool life, cutting forces, surface finish etc. are more or less significantly affected by the variation; known or unknown, of almost all the parameters or factors associated with machining process. Machining response of a material may also change with the processes, i.e. turning, drilling, milling etc. therefore, there cannot be as such any unique value to express machinability of any material, and machinability, if to be used at all, has to be done for qualitative assessment.

However, earlier, the relative machining response of the work materials compared to that of a standard metal was tried to be evaluated quantitatively only based on tool life ($V_B^* = 0.33$ mm) by an index,

Machinability rating (MR)

$$= \frac{\text{speed (fpm) of machining the work giving 60 min tool life}}{\text{speed (fpm) of machining the standard metal giving 60 min tool life}} \text{x}100$$

Fig. 3.1.1 shows such scheme of evaluating Machinability rating (MR) of any work material.

The free cutting steel, AISI – 1112, when machined (turned) at 100 fpm, provided 60 min of tool life. If the work material to be tested provides 60 min of tool life at cutting velocity of 60 fpm (say), as indicated in Fig. 3.1.1, under the same set of machining condition, then machinability (rating) of that material would be,

$\text{MR} = \frac{60}{100}\text{x}100 = 60\%$ or simply 60 (based on 100% for the standard material)

or, simply the value of the cutting velocity expressed in fpm at which a work material provides 60 min tool life was directly considered as the MR of that work material. In this way the MR of some materials, for instance, were evaluated as,

Metal	MR
Ni	200
Br	300
Al	200
CI	70
Inconel	30

But usefulness and reliability of such practice faced several genuine doubts and questions :

- tool life cannot or should not be considered as the only criteria for judging machinability
- under a given condition a material can yield different tool life even at a fixed speed (cutting velocity); exact composition, microstructure, treatments etc. of that material may cause significant difference in tool life
- the tool life - speed relationship of any material may substantially change with the variation in
  - material and geometry of the cutting tool
  - level of process parameters (V_c, s_o, t)
  - machining environment (cutting fluid application)
  - machine tool condition

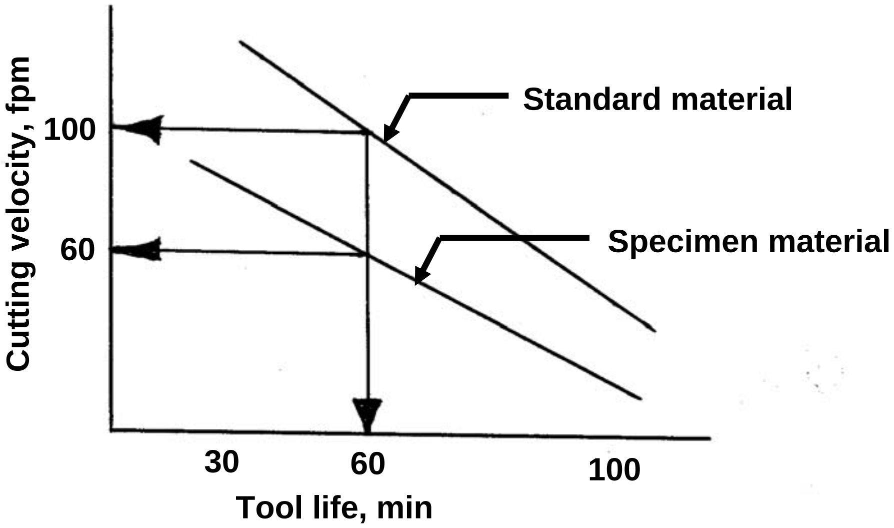


Fig. 3.1.1 *Machinability rating in terms of cutting velocity giving 60 min tool life.*

Keeping all such factors and limitations in view, Machinability can be tentatively defined as "ability of being machined" and more reasonably as " ease of machining".
Such ease of machining or machinability characteristics of any tool-work pair is to be judged by :

- magnitude of the cutting forces
- tool wear or tool life
- surface finish
- magnitude of cutting temperature
- chip forms

Machinability will be considered desirably high when cutting forces, temperature, surface roughness and tool wear are less, tool life is long and chips are ideally uniform and short enabling short chip-tool contact length and less friction.

(ii) Role Of Variation Of The Different Machining Parameters Or Factors On Machinability Of Work Materials.

The machinability characteristics and their criteria, i.e., the magnitude of cutting forces and temperature, tool life and surface finish are governed or influenced more or less by all the variables and factors involved in machining such as,

(a) properties of the work material
(b) cutting tool; material and geometry
(c) levels of the process parameters
(d) machining environments (cutting fluid application etc)

Machinability characteristics of any work – tool pair may also be further affected by,

- strength, rigidity and stability of the machine
- kind of machining operations done in a given machine tool
- functional aspects of the special techniques, if employed.

(a) Role of the properties of the work material on machinability.

The work material properties that generally govern machinability in varying extent are:

- the basic nature – brittleness or ductility etc.
- microstructure
- mechanical strength – fracture or yield
- hardness
- hot strength and hot hardness
- work hardenability
- thermal conductivity
- chemical reactivity
- stickiness / self lubricity.

- **Machining of brittle and ductile materials**

In general, brittle materials are relatively more easily machinable for :

- the chip separation is effected by brittle fracture requiring lesser energy of chip formation
- shorter chips causing lesser frictional force and heating at the rake surface

For instance, compared to even mild steel, grey cast iron jobs produce much lesser cutting forces and temperature. Smooth and continuous chip formation is likely to enable mild steel produce better surface finish but BUE, if formed, may worsen the surface finish.

For machining, like turning of ductile metals, the expression

$$P_Z = ts_o\tau_s f \qquad (3.1.1)$$

Indicates that cutting forces increase with the increase in yield shear strength, τ_s of the work material. The actual value of τ_s of any material, again, changes with the condition of machining and also on the ductility of the work material as,

$$\tau_s = 0.74\sigma_U\varepsilon^{0.6\Delta} \qquad (3.1.2)$$

where,

σ_u = ultimate tensile strength which is a classical property of the material

Δ = percentage elongation indicating ductility of the work material

ε = cutting strain

Role of microstructure

The value of τ_s of a given material depends sizeably on its microstructure. Coarse microstructure leads to lesser value of τ_s. Therefore, τ_s can be desirably reduced by

- proper heat treatment like annealing of steels
- controlled addition of materials like sulphur (S), lead (Pb), Tellerium etc leading to free cutting of soft ductile metals and alloys.

Free Cutting steels

Addition of lead in low carbon steels and also in aluminium, copper and their alloys help reduce their τ_s. The dispersed lead particles act as discontinuity and solid lubricants and thus improve machinability by reducing friction, cutting forces and temperature, tool wear and BUE formation. Addition of sulphur also enhances machinability of low carbon steels by enabling its free cutting. The added sulphur reacts with Mn present in the steels and forms MnS inclusions which being very soft act almost as voids and reduce friction at the tool – work interfaces resulting reduction of cutting forces and temperature and their consequences. The degree of ease of machining of such free cutting steels depend upon the morphology of the MnS inclusions which can be made more favourable by addition of trace of Tellurium.

Effects of hardness, hot strength and hot hardness and work hardening of work materials.

Harder materials are obviously more difficult to machine for increased cutting forces and tool damage.
Usually, with the increase in cutting velocity the cutting forces decrease to some extent making machining easier through reduction in τ_s and also chip thickness. τ_s decreases due to softening of the work material at the shear zone due to elevated temperature. Such benefits of increased temperature and cutting velocity are not attained when the work materials are hot strong and hard like Ti and Ni based superalloys and work hardenable like high manganese steel, Ni- hard, Hadfield steel etc.
Sticking of the materials (like pure copper, aluminium and their alloys) and formation of BUE at the tool rake surface also hamper machinability by increasing friction, cutting forces, temperature and surface roughness. Lower thermal conductivity of the work material affects their machinability by raising the cutting zone temperature and thus reducing tool life.
Sticking of the materials (like pure copper, aluminium and their alloys) and formation of BUE at the tool rake surface also hamper machinability by increasing friction, cutting forces, temperature and surface roughness.

(b) Role of cutting tool material and geometry on machinability of any work material.

- **Role of tool materials**

In machining a given material, the tool life is governed mainly by the tool material which also influences cutting forces and temperature as well as accuracy and finish of the machined surface. The composition, microstructure, strength, hardness, toughness, wear resistance, chemical stability and thermal conductivity of the tool material play significant roles on the machinability characteristics though in different degree depending upon the properties of the work material.
Fig. 3.1.2 schematically shows how in turning materials like steels, the tool materials affect tool life at varying cutting velocity.
High wear resistance and chemical stability of the cutting tools like coated carbides, ceramics, cubic Boron nitride (cBN) etc also help in providing better surface integrity of the product by reducing friction, cutting temperature and BUE formation in high speed machining of steels. Very soft, sticky and chemically reactive material like pure aluminium attains highest machinability when machined by diamond tools.

- **Role of the geometry of cutting tools on machinability.**

The geometrical parameters of cutting tools (say turning tool) that significantly affect the machinability of a given work material (say mild steel) under given machining conditions in terms of specific energy requirement, tool life, surface finish etc. are:

- tool rake angles (γ)
- clearance angle (α)
- cutting angles (ϕ and ϕ_1)

- nose radius (r)

The other geometrical (tool) parameters that also influence machinability to some extent directly and indirectly are:

— inclination angle (λ)
— edge bevelling or rounding (r′)
— depth, width and form of integrated chip breaker

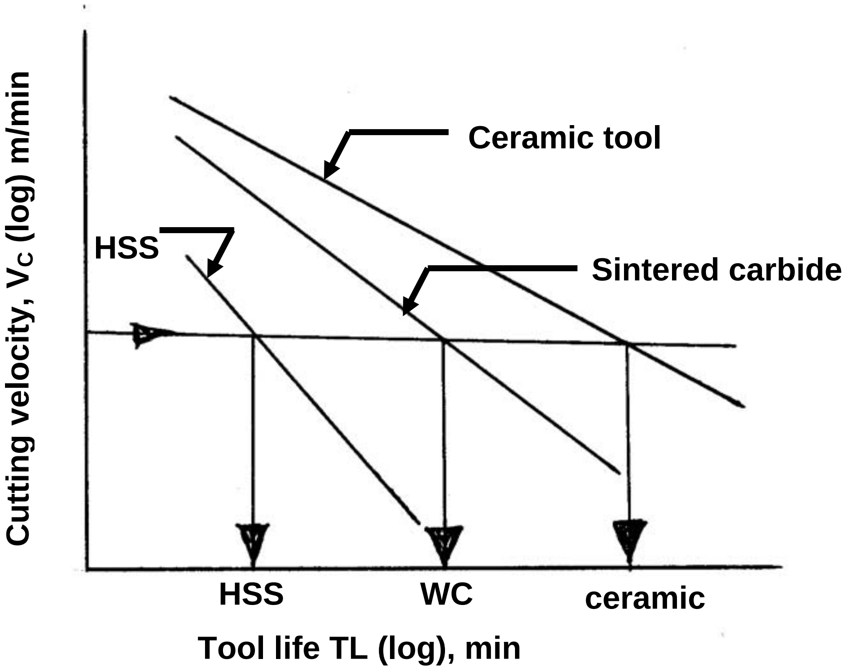


Fig. 3.1.2 *Role of cutting tool material on machinability (tool life)*

Effects of tool rake angle(s) on machinability

In machining like turning ductile material, the main cutting force, P_Z decreases as typically shown in Fig. 3.1.3 mainly due to,

$$P_Z = ts_o\tau_s f \tag{3.1.3}$$

where, $f = \zeta - \tan\gamma + 1$

$$\zeta = e^{\mu(\pi/2-\gamma)}$$

$$\tau_s = 0.74\sigma_U\varepsilon^{0.6\Delta}$$

$$\varepsilon \cong \zeta - \tan\gamma$$

The expressions clearly show that increase in γ reduces P_Z through reduction in cutting strain (ε), chip reduction coefficient (ζ) and hence τ_s and the form factor, f.

With P_Z, P_{XY} also decreases proportionally.

But too much increase in rake weakens the cutting edge both mechanically and thermally and may cause premature failure of the tool.

Presence of inclination angle, λ enhances effective rake angle and thus helps in further reduction of the cutting forces.

However, the tool rake angle does not affect surface finish that significantly.

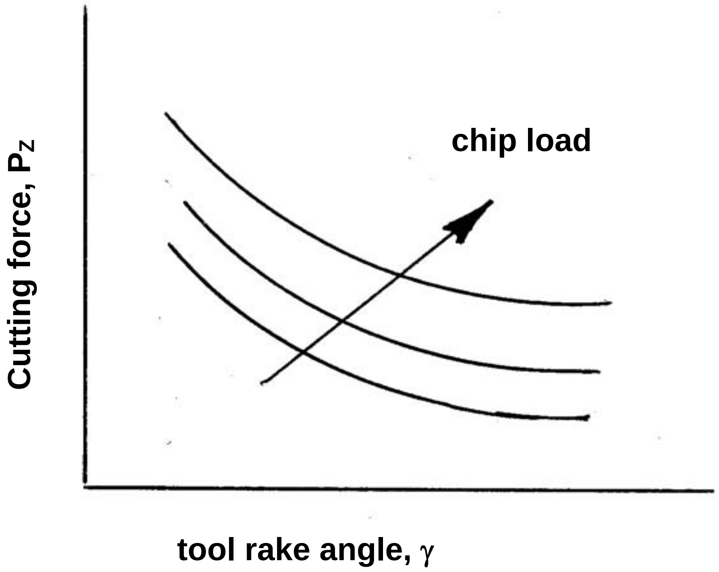


Fig. 3.1.3 *Effect of tool rake angle on machinability (cutting force, P_Z)*

Role of cutting angles (φ and ϕ_1) on machinability

The variation in the principal cutting edge angle, φ does not affect P_Z or specific energy requirement but influences P_Y and the cutting temperature (θ_C) quite significantly as indicated in Fig. 3.1.4 mainly for,

$$P_Y = P_{XY}\cos\phi \quad \text{i.e.,} \ \alpha \ P_Z\cos\phi \qquad (3.1.4)$$

$$\text{and} \quad \theta_C \ \alpha \ \sqrt{V_C s_o \sin\phi} \qquad (3.1.5)$$

The force, P_Y, if large, may impair the product quality by dimensional deviation and roughening the surface due to vibration.

Reduction in both φ and ϕ_1 improves surface finish sizeably in continuous chip formation, as

$$h_{max} = \frac{s_o}{\cot\phi + \cot\phi_1} \qquad (3.1.6)$$

where h_{max} (define h_{max} ?) is the maximum surface roughness due to feed marks alone.

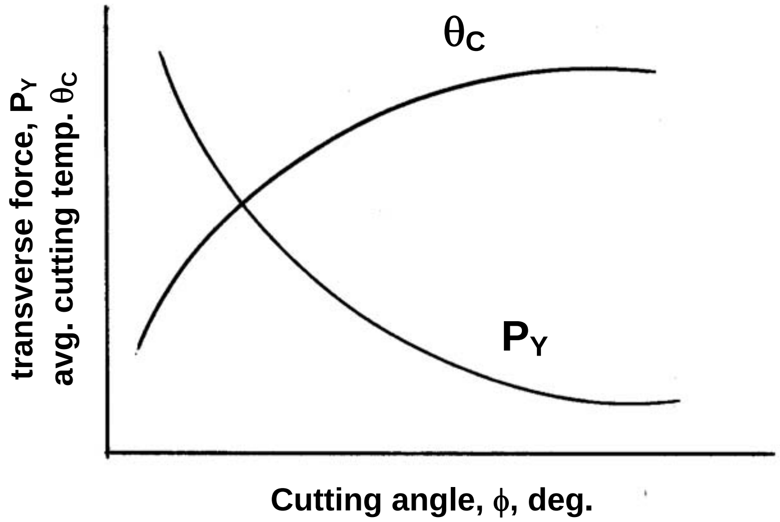


Fig. 3.1.4 *Effects of variation in cutting angle on machinability (θ_C and P_y)*

Effects of clearance angle (α)

Fig. 3.1.5 schematically shows how clearance angle, α affects tool life.

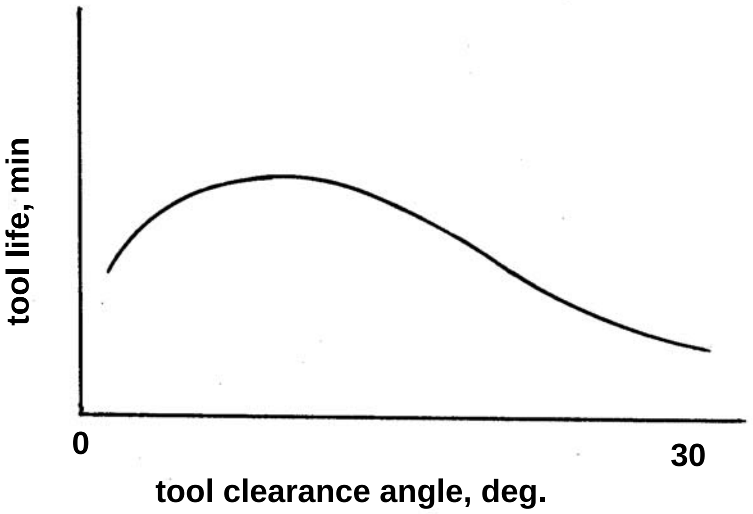


Fig. 3.1.5 *Influence of tool clearance angle on tool life.*

Inadequate clearance angle reduces tool life and surface finish by tool - work rubbing, and again too large clearance reduces the tool strength and hence tool life.

Role of tool nose radius (r) on machinability

Proper tool nose radiusing improves machinability to some extent through

- increase in tool life by increasing mechanical strength and reducing temperature at the tool tip
- reduction of surface roughness, h_{max}

  as $h_{max} = \frac{(s_o)^2}{8r}$ (3.1.7)

Proper edge radiusing (r′) also often enhances strength and life of the cutting edge without much increase in cutting forces

(c) Role of the process parameters on machinability

Proper selection of the levels of the process parameters (V_C, s_o and t) can provide better machinability characteristics of a given work – tool pair even without sacrificing productivity or MRR.

Amongst the process parameters, depth of cut, t plays least significant role and is almost invariable. Compared to feed (s_o) variation of cutting velocity (V_C) governs machinability more predominantly. Increase in V_C, in general, reduces tool life but it also reduces cutting forces or specific energy requirement and improves surface finish through favourable chip-tool interaction. Some cutting tools, specially ceramic tools perform better and last longer at higher V_C within limits. Increase in feed raises cutting forces proportionally but reduces specific energy requirement to some extent. Cutting temperature is also lesser susceptible to increase in s_o than V_C. But increase in s_o, unlike V_C raises surface roughness. Therefore, proper increase in V_C, even at the expense of s_o often can improve machinability quite significantly.

(d) Effects of machining environment (cutting fluids) on machinability

The basic purpose of employing cutting fluid is to improve machinability characteristics of any work – tool pair through :

- improving tool life by cooling and lubrication
- reducing cutting forces and specific energy consumption
- improving surface integrity by cooling, lubricating and cleaning at the cutting zone

The favourable roles of cutting fluid application depend not only on its proper selection based on the work and tool materials and the type of the machining process but also on its rate of flow, direction and location of application.

(iii) Possible Ways Of Improving Machinability Of Work Materials

The machinability of the work materials can be more or less improved, without sacrificing productivity, by the following ways :

- Favourable change in composition, microstructure and mechanical properties by mixing suitable type and amount of additive(s) in the work material and appropriate heat treatment
- Proper selection and use of cutting tool material and geometry depending upon the work material and the significant machinability criteria under consideration
- Optimum selection of V_C and s_o based on the tool – work materials and the primary objectives.
- Proper selection and appropriate method of application of cutting fluid depending upon the tool – work materials, desired levels of productivity i.e., V_C and s_o and also on the primary objectives of the machining work undertaken
- Proper selection and application of special techniques like dynamic machining, hot machining, cryogenic machining etc, if feasible, economically viable and eco-friendly.

Module

2

Mechanics of Machining

Lesson

8

Machining forces and Merchant's Circle Diagram (MCD)

Instructional Objectives

At the end of this lesson, the student would be able to

(i) Ascertain the benefits and state the purposes of determining cutting forces
(ii) Identify the cutting force components and conceive their significance and role
(iii) Develop Merchant's Circle Diagram and show the forces and their relations
(iv) Illustrate advantageous use of Merchant's Circle Diagram

(i) Benefit of knowing and purpose of determining cutting forces.

The aspects of the cutting forces concerned :

- Magnitude of the cutting forces and their components
- Directions and locations of action of those forces
- Pattern of the forces : static and / or dynamic.

Knowing or determination of the cutting forces facilitate or are required for :

- Estimation of cutting power consumption, which also enables selection of the power source(s) during design of the machine tools
- Structural design of the machine – fixture – tool system
- Evaluation of role of the various machining parameters (process – V_C, s_o, t, tool – material and geometry, environment – cutting fluid) on cutting forces
- Study of behaviour and machinability characterisation of the work materials
- Condition monitoring of the cutting tools and machine tools.

(ii) Cutting force components and their significances

The single point cutting tools being used for turning, shaping, planing, slotting, boring etc. are characterised by having only one cutting force during machining. But that force is resolved into two or three components for ease of analysis and exploitation. Fig. 8.1 visualises how the single cutting force in turning is resolved into three components along the three orthogonal directions; X, Y and Z.

The resolution of the force components in turning can be more conveniently understood from their display in 2-D as shown in Fig. 8.2.

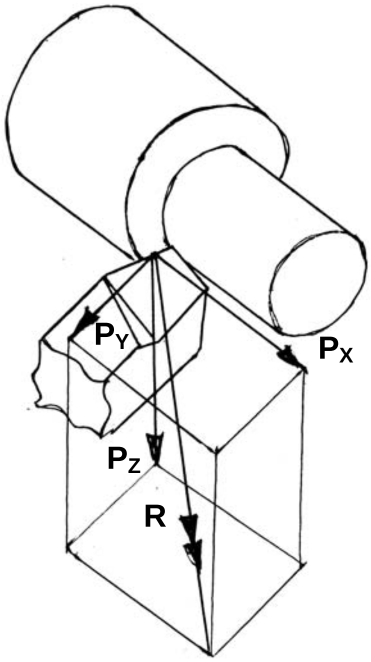


Fig. 8.1 *Cutting force R resolved into P_X, P_Y and P_Z*

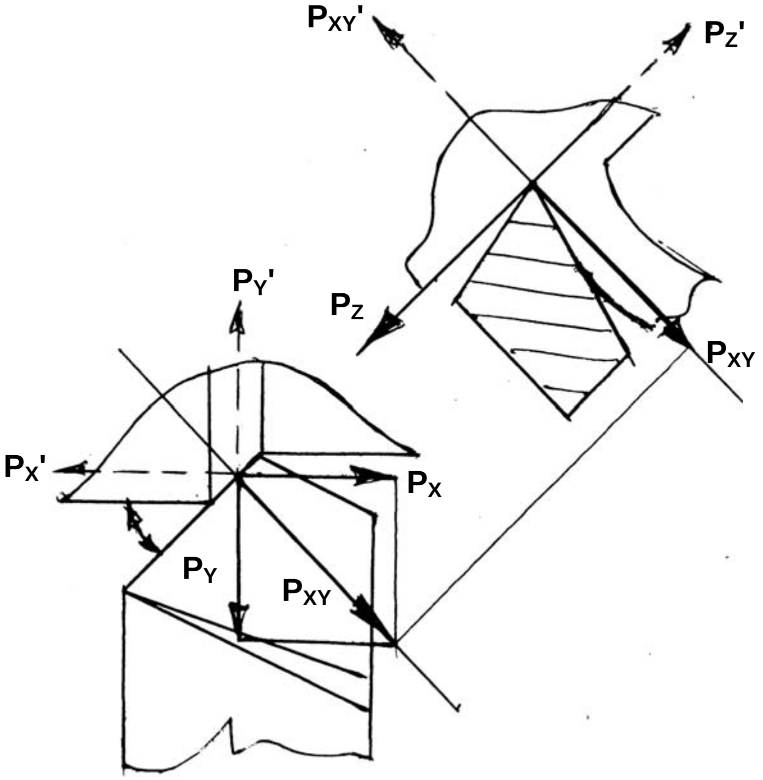


Fig. 8.2 *Turning force resolved into P_Z, P_X and P_Y*

The resultant cutting force, R is resolved as,

$$\overline{R} = \overline{P_Z} + \overline{P}_{XY} \qquad (8.1)$$

and $$\overline{P}_{XY} = \overline{P}_X + \overline{P}_Y \qquad (8.2)$$

where, $P_X = P_{XY}\sin\phi$ and $P_Y = P_{XY}\cos\phi$ (8.3)

where, P_Z = tangential component taken in the direction of Z_m axis
P_X = axial component taken in the direction of longitudinal feed or X_m axis
P_Y = radial or transverse component taken along Y_m axis.

In Fig. 8.1 and Fig. 8.2 the force components are shown to be acting on the tool. A similar set of forces also act on the job at the cutting point but in opposite directions as indicated by P_Z', P_{XY}', P_X' and P_Y' in Fig. 8.2

Significance of P_Z, P_X and P_Y

P_Z : called the main or major component as it is the largest in magnitude. It is also called power component as it being acting along and being multiplied by V_C decides cutting power ($P_Z.V_C$) consumption.
P_y : may not be that large in magnitude but is responsible for causing dimensional inaccuracy and vibration.
P_X : It, even if larger than P_Y, is least harmful and hence least significant.

Cutting forces in drilling

In a drill there are two main cutting edges and a small chisel edge at the centre as shown in Fig. 8.3.
The force components that develop (Fig. 8.3) during drilling operation are :

- a pair of tangential forces, P_{T1} and P_{T2} (equivalent to P_Z in turning) at the main cutting edges
- axial forces P_{X1} and P_{X2} acting in the same direction
- a pair of identical radial force components, P_{Y1} and P_{Y2}
- one additional axial force, P_{Xe} at the chisel edge which also removes material at the centre and under more stringent condition.

P_{T1} and P_{T2} produce the torque, T and causes power consumption P_C as,

$$T = P_T \times \tfrac{1}{2}(D) \qquad (8.3)$$

and $$P_C = 2\pi TN \qquad (8.4)$$

where, D = diameter of the drill
and N = speed of the drill in rpm.
The total axial force P_{XT} which is normally very large in drilling, is provided by

$$P_{XT} = P_{X1} + P_{X2} + P_{Xe} \qquad (8.5)$$

But there is no radial or transverse force as P_{Y1} and P_{Y2}, being in opposite direction, nullify each other if the tool geometry is perfectly symmetrical.

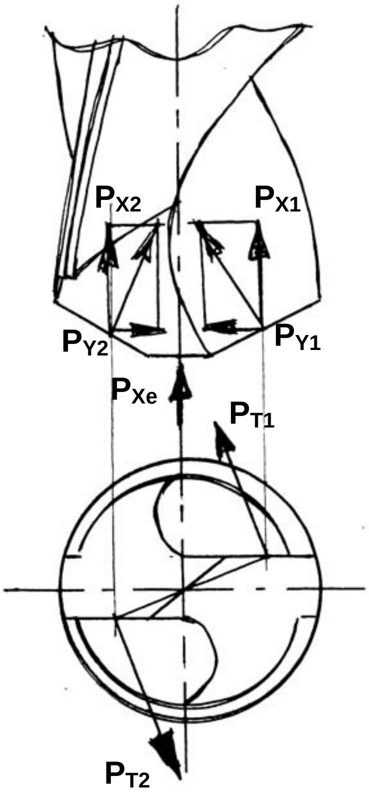


Fig. 8.3 *Cutting forces in drilling.*

Cutting forces in milling

The cutting forces (components) developed in milling with straight fluted slab milling cutter under single tooth engagement are shown in Fig. 8.4.
The forces provided by a single tooth at its angular position, ψ_I are :

- Tangential force P_{Ti} (equivalent to P_Z in turning)
- Radial or transverse force, P_{Ri} (equivalent to P_{XY} in turning)
- R is the resultant of P_T and P_R
- R is again resolved into P_Z and P_Y as indicated in Fig. 8.4 when Z and Y are the major axes of the milling machine.

Those forces have the following significance:

o P_T governs the torque, T on the cutter or the milling arbour as

$$T = P_T \times D/2 \qquad (8.5)$$

and also the power consumption, P_C as

$$P_C = 2\pi TN \qquad (8.6)$$

where, N = rpm of the cutter.

The other forces, P_R, P_Z, P_Y etc are useful for design of the Machine – Fixture – Tool system.

In case of multitooth engagement;

Total torque will be $D/2.\sum P_{Ti}$ and total force in Z and Y direction will be $\sum P_Z$ and $\sum P_Y$ respectively.

One additional force i.e. axial force will also develop while milling by helical fluted cutter

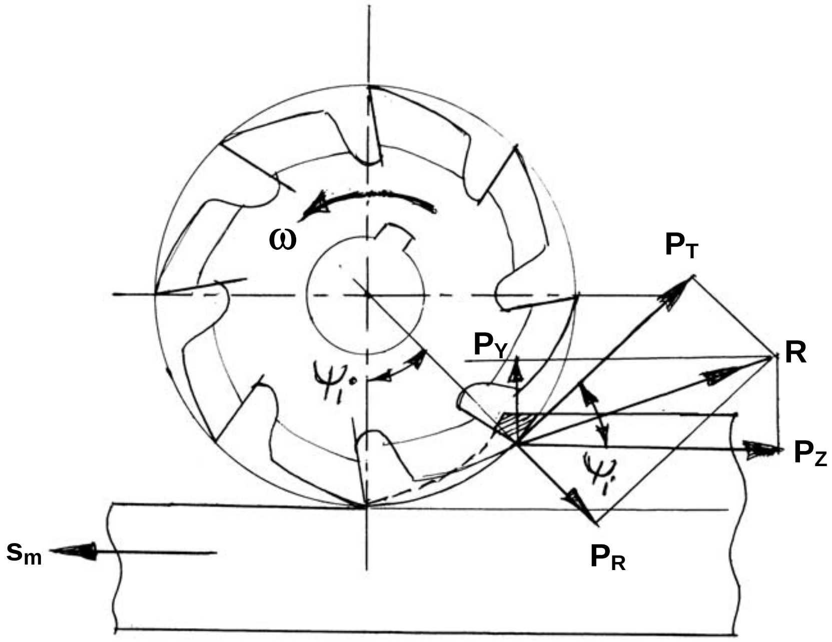


Fig. 8.4 *Cutting forces developed in plain milling (with single tooth engagement)*

(iii) Merchant's Circle Diagram and its use

In orthogonal cutting when the chip flows along the orthogonal plane, π_O, the cutting force (resultant) and its components P_Z and P_{XY} remain in the orthogonal plane. Fig. 8.5 is schematically showing the forces acting on a piece of continuous chip coming out from the shear zone at a constant speed. That chip is apparently in a state of equilibrium.

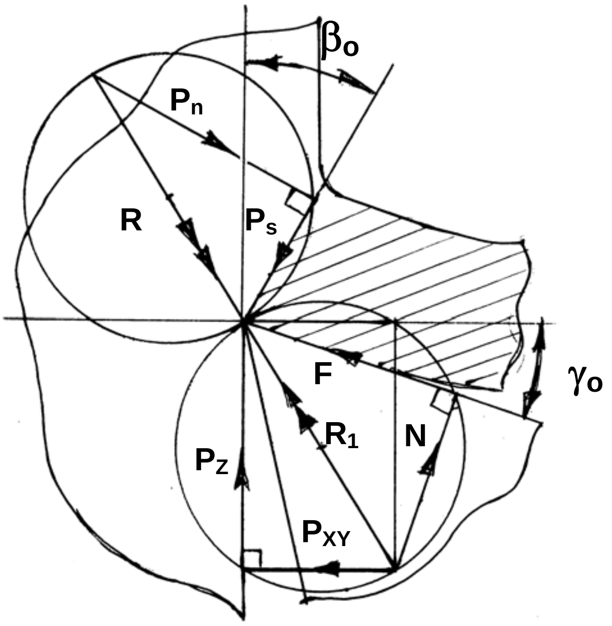


Fig. 8.5 *Development of Merchants Circle Diagram.*

The forces in the chip segment are :

- From job-side :
  - P_S – shear force and
  - P_n – force normal to the shear force

  where, $\overline{P_s} + \overline{P_n} = \overline{R}$ (resultant)
- From tool side :
  - $\overline{R_1} = \overline{R}$ (in state of equilibrium)
  - where $\overline{R_1} = \overline{F} + \overline{N}$
  - N = force normal to rake face
  - F = friction force at chip tool interface.

The resulting cutting force R or R_1 can be resolved further as

$$\overline{R_1} = \overline{P_Z} + \overline{P_{XY}}$$

where, P_Z = force along the velocity vector

and P_{XY} = force along orthogonal plane.

The circle(s) drawn taking R or R_1 as diameter is called Merchant's circle which contains all the force components concerned as intercepts. The two circles with their forces are combined into one circle having all the forces contained in that as shown by the diagram called Merchant's Circle Diagram (MCD) in Fig. 8.6

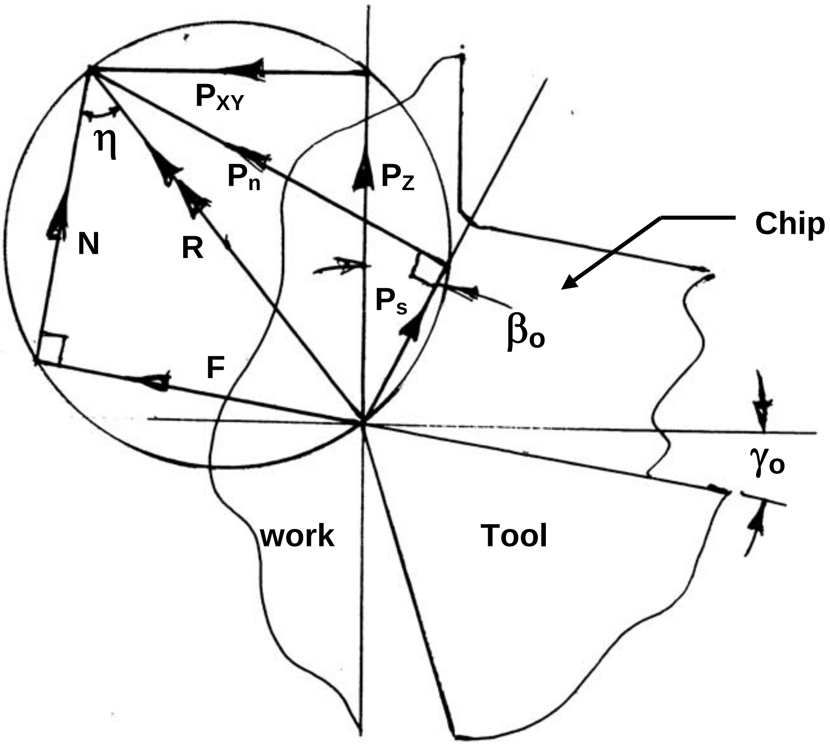


Fig. 8.6 Merchant' s Circle Diagram with cutting forces.

The significance of the forces displayed in the Merchant's Circle Diagram are :

P_S – the shear force essentially required to produce or separate the chip from the parent body by shear

P_n – inherently exists along with P_S

F – friction force at the chip tool interface

N – force acting normal to the rake surface

P_Z – main force or power component acting in the direction of cutting velocity

P_{XY} – $\overline{P}_X + \overline{P}_Y$

The magnitude of P_S provides the yield shear strength of the work material under the cutting condition.

The values of F and the ratio of F and N indicate the nature and degree of interaction like friction at the chip-tool interface. The force components P_X, P_Y, P_Z are generally obtained by direct measurement. Again P_Z helps in determining cutting power and specific energy requirement. The force components are also required to design the cutting tool and the machine tool.

(iv) Advantageous use of Merchant's Circle Diagram (MCD)

Proper use of MCD enables the followings :

- Easy, quick and reasonably accurate determination of several other forces from a few known forces involved in machining
- Friction at chip-tool interface and dynamic yield shear strength can be easily determined
- Equations relating the different forces are easily developed.

Some limitations of use of MCD

- Merchant's Circle Diagram(MCD) is valid only for orthogonal cutting
- by the ratio, F/N, the MCD gives apparent (not actual) coefficient of friction
- It is based on single shear plane theory.

The advantages of constructing and using MCD has been illustrated as by an example as follows ;

Suppose, in a simple straight turning under orthogonal cutting condition with given speed, feed, depth of cut and tool geometry, the only two force components P_Z and P_X are known by experiment i.e., direct measurement, then how can one determine the other relevant forces and machining characteristics easily and quickly without going into much equations and calculations but simply constructing a circle-diagram. This can be done by taking the following sequential steps :

- Determine P_{XY} from $P_X = P_{XY}\sin\phi$, where P_X and ϕ are known.
- Draw the tool and the chip in orthogonal plane with the given value of γ_o as shown in Fig. 8.4
- Choose a suitable scale (e.g. 100 N = 1 cm) for presenting P_Z and P_{XY} in cm
- Draw P_Z and P_{XY} along and normal to $\overline{V_C}$ as indicated in Fig. 8.6
- Draw the cutting force R as the resultant of P_Z and P_{XY}
- Draw the circle (Merchant's circle) taking R as diameter

- Get F and N as intercepts in the circle by extending the tool rake surface and joining tips of F and R
- Divide the intercepts of F and N by the scale and get the values of F and N
- For determining P_s (and P_n) the value of the shear angle β_o has to be evaluated from

  $$\tan\beta_o = \frac{\cos\gamma_o}{\zeta - \sin\gamma_o}$$

  where γ_o is known and ζ has to be obtained from

  $$\zeta = \frac{a_2}{a_1} \text{ where } a_1 = s_o \sin\phi$$

  s_o and ϕ are known and a_2 is either known, if not, it has to be measured by micrometer or slide calliper
- Draw the shear plane with the value of β_o and then P_s and P_n as intercepts shown in Fig. 8.6.
- Get the values of P_s and P_n by dividing their corresponding lengths by the scale
- Get the value of apparent coefficient of friction, μ_a at the chip tool interface simply from the ratio, $\mu_a = \frac{F}{N}$
- Get the friction angle, η, if desired, either from $\tan\eta = \mu_a$ or directly from the MCD drawn as indicated in Fig. 8.6.
- Determine dynamic yield shear strength (τ_s) of the work material under the cutting condition using the simple expression

  $$\tau_s = \frac{P_s}{A_s}$$

  where, A_s = shear area as indicated in Fig. 8.7

  $$= \frac{a_1 b_1}{\sin\beta_o} = \frac{t s_o}{\sin\beta_o}$$

  t = depth of cut (known)

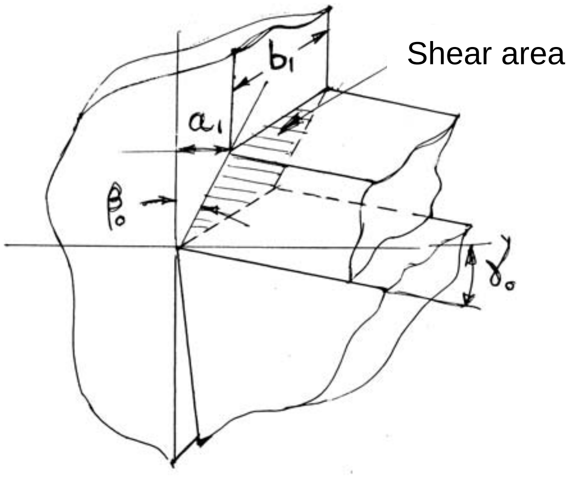


Fig. 8.7 Shear area in orthogonal turning

Evaluation of cutting power consumption and specific energy requirement

Cutting power consumption is a quite important issue and it should always be tried to be reduced but without sacrificing MRR.

Cutting power consumption, P_C can be determined from,

$$P_C = P_Z.V_C + P_X.V_f \qquad (8.4)$$

where, V_f = feed velocity

$= Ns_o/1000$ m/min [N=rpm]

Since both P_X and V_f, specially V_f are very small, $P_X.V_f$ can be neglected and then $P_C \cong P_Z.V_C$

Specific energy requirement, which means amount of energy required to remove unit volume of material, is an important machinability characteristics of the work material. Specific energy requirement, U_s, which should be tried to be reduced as far as possible, depends not only on the work material but also the process of the machining, such as turning, drilling, grinding etc. and the machining condition, i.e., V_C, s_o, tool material and geometry and cutting fluid application.

Compared to turning, drilling requires higher specific energy for the same work-tool materials and grinding requires very large amount of specific energy for adverse cutting edge geometry (large negative rake).

Specific energy, U_s is determined from

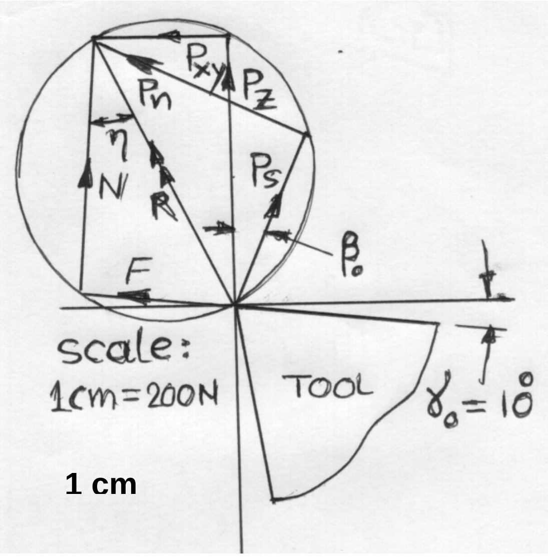
$$U_s = \frac{P_Z.V_C}{MRR} = \frac{P_Z}{ts_o}$$

Exercise - 8
Solution of some Problems

Problem 1

During turning a ductile alloy by a tool of $\gamma_o = 10^o$, it was found P_Z= 1000 N, P_X= 400 N, P_Y= 300 N and $\zeta = 2.5$. Evaluate, using MCD, the values of F, N and μ as well as P_s and P_n for the above machining.

Solution :



- force, $P_{XY} = \sqrt{P_X^2 + P_Y^2}$ = $\sqrt{(400)^2 + (300)^2}$ = 500 N
- Select a scale: 1 cm=200N
- Draw the tool tip with γ_o =10^o
  In scale, P_Z=1000/200= 5 cm and P_{XY}=500/200=2.5cm

- Draw P_Z and P_{XY} in the diagram
- Draw R and then the MCD
- Extend the rake surface and have F and N as shown
- Determine shear angle, β_o

  $\tan \beta_o = \cos\gamma_o / (\zeta - \sin\gamma_o)$

  $= \cos 10^o/(2.5 – \sin 10^o) = 0.42$

  $\beta_o = \tan^{-1}(0.42) = 23^o$
- Draw P_S and P_n in the MCD
- From the MCD, find F = 3x200 = 600 N; N = 4.6x200 = 920 N;

  μ = F/N = 600/920 = 0.67

  P_S = 3.4x200 = 680; P_n= 4.3x200 = 860 N

Problem 2

During turning a steel rod of diameter 160 mm at speed 560 rpm, feed 0.32 mm/rev. and depth of cut 4.0 mm by a ceramic insert of geometry

0^o, —10^o, 6^o, 6^o, 15^o, 75^o, 0 (mm)

The followings were observed :

P_Z =1600 N, P_X=800 N and chip thickness=1mm. Determine with the help of MCD the possible values of F, N, m_a, P_S, P_n, cutting power and specific energy consumption.

Solution

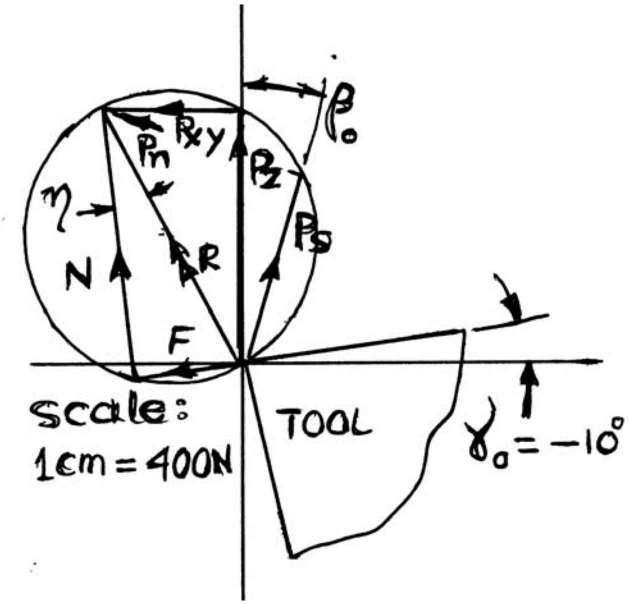
- $P_{XY}=P_X/\sin\phi$ = 800/sin75^o = 828 N
- Select a scale: 1cm = 400N
- Draw the tool tip with $\gamma_o = -10^o$
- Draw P_Z and P_{XY} in scale as shown
- Draw resultant and MCD

  shear angle, β_o

  $\tan \beta_o = \cos\gamma_o / (\zeta - \sin \gamma_o)$

  where, $\zeta = a_2/a_1 = a_2/(s_o \sin\phi) = 3.2$

  $\beta_o = \tan^{-1}(\cos(-10^o))/\{(3.2 - \sin(-10^o))\}= 16.27^o$



- Draw P_S and P_n as shown
- Using the scale and intercepts determine
  F = 1.75xscale = 700 N
  N = 4.40xscale = 1760 N
  μ_a = F/N = 700/1760 = 0.43
  P_S = 3.0 x scale = 1200 N
  P_n = 3.3 x scale = 1320 N
- Cutting Power, P_C $P_C = P_Z.V_C$ where
  $V_C = \pi DN/1000 = \pi \times 160 \times 560/1000 = 281.5$ m/min
  So, P_C = 8 KW.
- Specific energy = $P_Z/(ts_o)$ = 1600/(4 x 0.32)= 1250 N-mm/mm^3

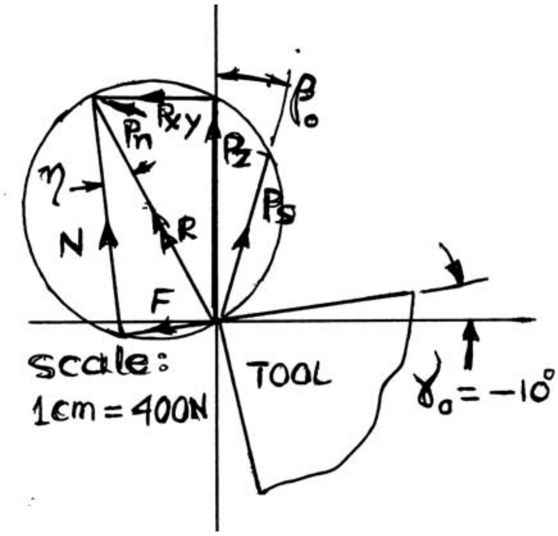
Problem 3

For turning a given steel rod by a tool of given geometry if shear force P_S, frictional force F and shear angle γ_o could be estimated to be 400N and 300N respectively, then what would be the possible values of P_X P_Y and P_Z? [use MCD]

Solution:

- tool geometry is known. Let rake angle be γ_o and principal cutting edge angle be ϕ.
- Draw the tool tip with the given value of γ_o as shown.
- Draw shear plane using the essential value of β_o
- using a scale (let 1cm=400N) draw shear force P_S and friction force F in the respective directions.
- Draw normals on P_S and F at their tips as shown and let the normals meet at a point.
- Join that meeting point with tool tip to get the resultant force

- Based on resultant force R draw the MCD and get intercepts for P_Z and P_{xy}
- Determine P_Z and P_{xy} from the MCD
- P_Z= __ x scale = ____
- P_{xy} = __ x scale = ___
- P_Y= P_{XY} cosϕ
- P_X= P_{XY} sinϕ



Problem - 4

During shaping like single point machining/turning) a steel plate at feed, 0.20 mm/stroke and depth 4 mm by a tool of $\lambda = \gamma = 0^o$ and $\phi = 90^o$ P_Z and P_X were found (measured by dynamometer) to be 800 N and 400 N respectively, chip thickness, a_2 is 0.4 mm. From the aforesaid conditions and using Merchant's Circle Diagram determine the yield shear strength of the work material in the machining condition?

Solution

- It is orthogonal (λ= 0^o) cutting \ MCD is valid
- draw tool with $\gamma_o = 0^o$ as shown
- P_{XY}= P_X/sinϕ = 400/sin90^o = 400 N
- Select a scale : 1 cm= 200N
- Draw P_Z and P_{XY} using that scale

  P_Z = 800/200 = 4 cm,

  P_{XY} = 400/200 = 2 cm
- Get R and draw the MCD
- Determine shear angle, β_o from

$$\tan\beta_o = \cos\gamma_o/(\zeta - \sin\gamma_o),\quad \gamma_o= 0^o \text{ and}$$

$$\zeta = a_2/a_1 \quad a_1 = (s_o\sin\phi) = 0.2 \times \sin 90^o = 0.2$$

$$\beta_o = \tan^{-1}(0.2/0.4) = 26^o$$

- Draw P_S along the shear plane and find P_S= 2.5 x 200 = 500 N
- Now, $\tau_S = P_S/A_S$;

$A_S = (ts_O)/\sin\beta_o = 4 \times 0.2/\sin 26^0 = 1.82\ \text{mm}^2$

or, $\tau_S = 500/1.82$

$= 274.7\ \text{N/mm}^2$