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.

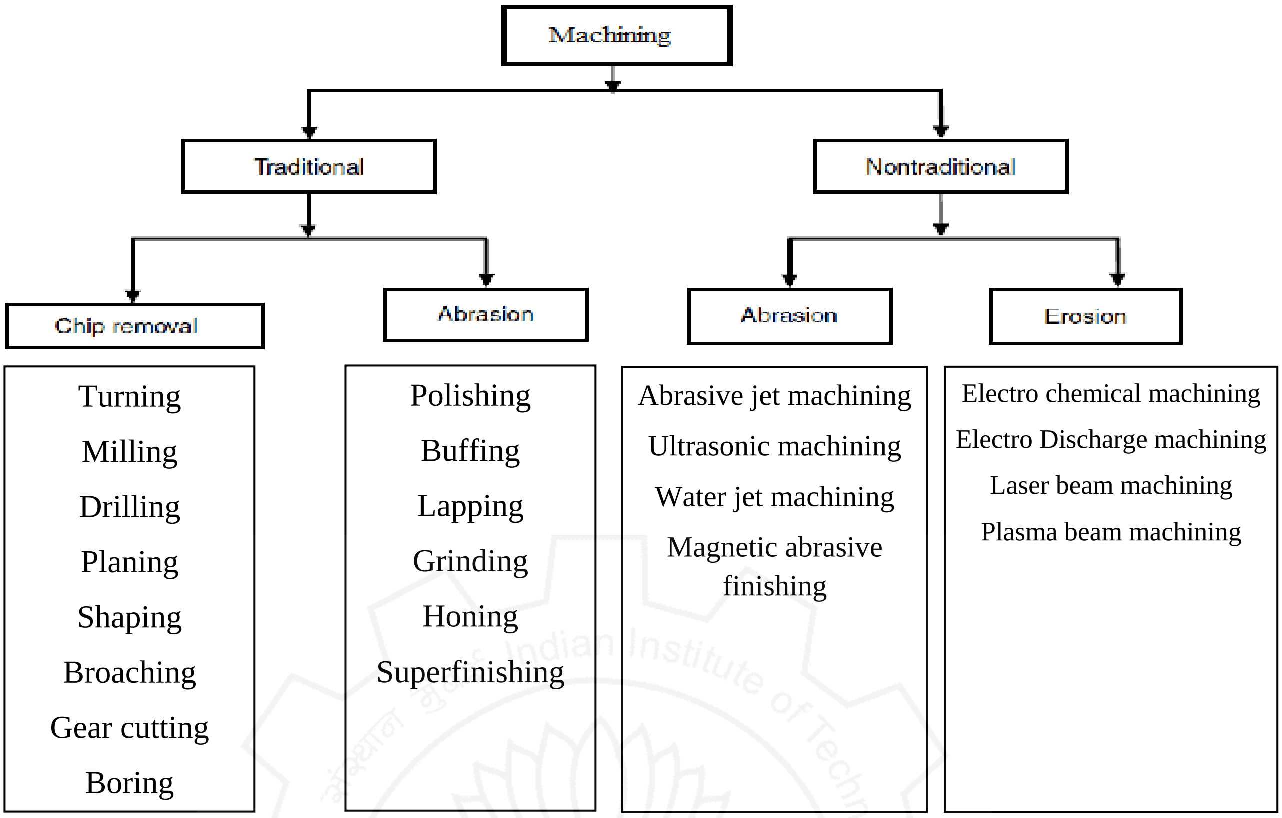


Figure 3.5.1 Classification of Machining Processes [5]

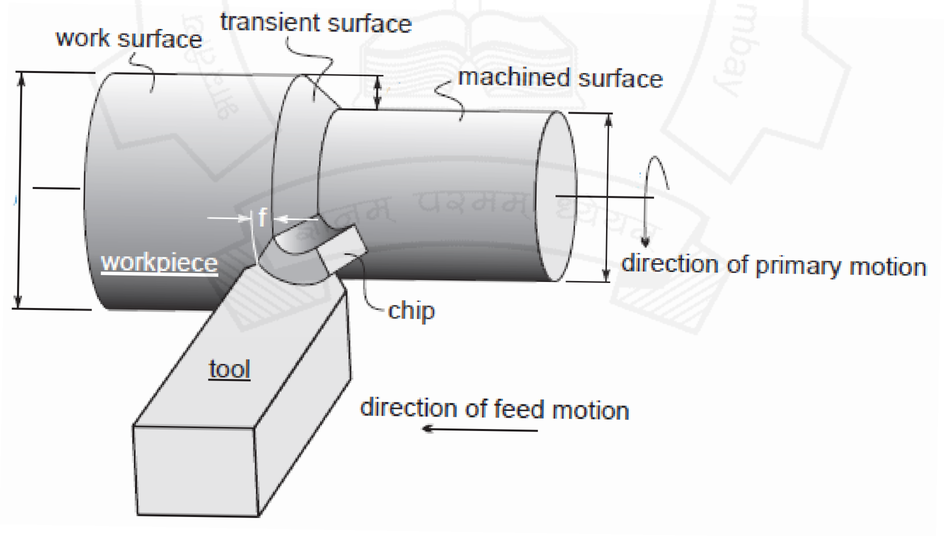


Figure 3.5.2 Schematic depiction of turning operation [4]

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.

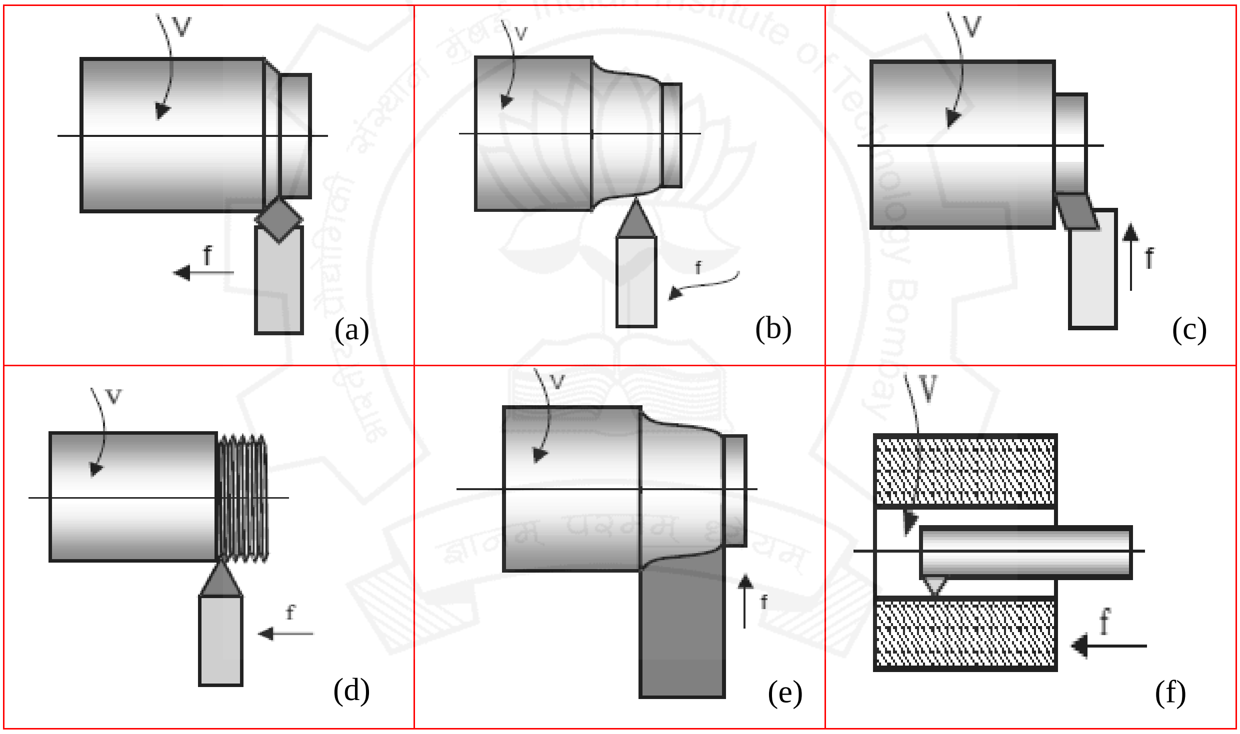
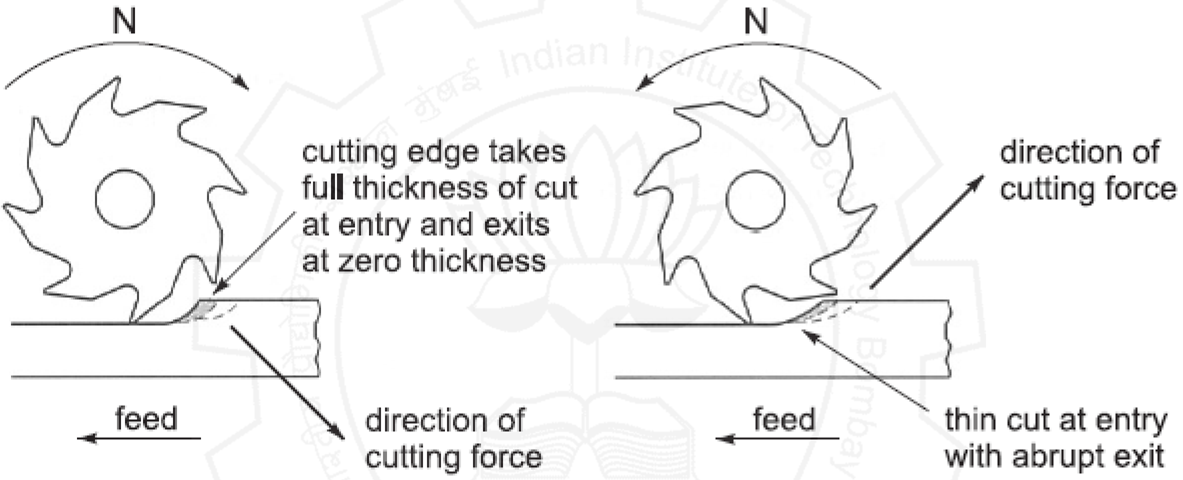


Figure 3.5.3 Different types of Turning Operations [5]

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.

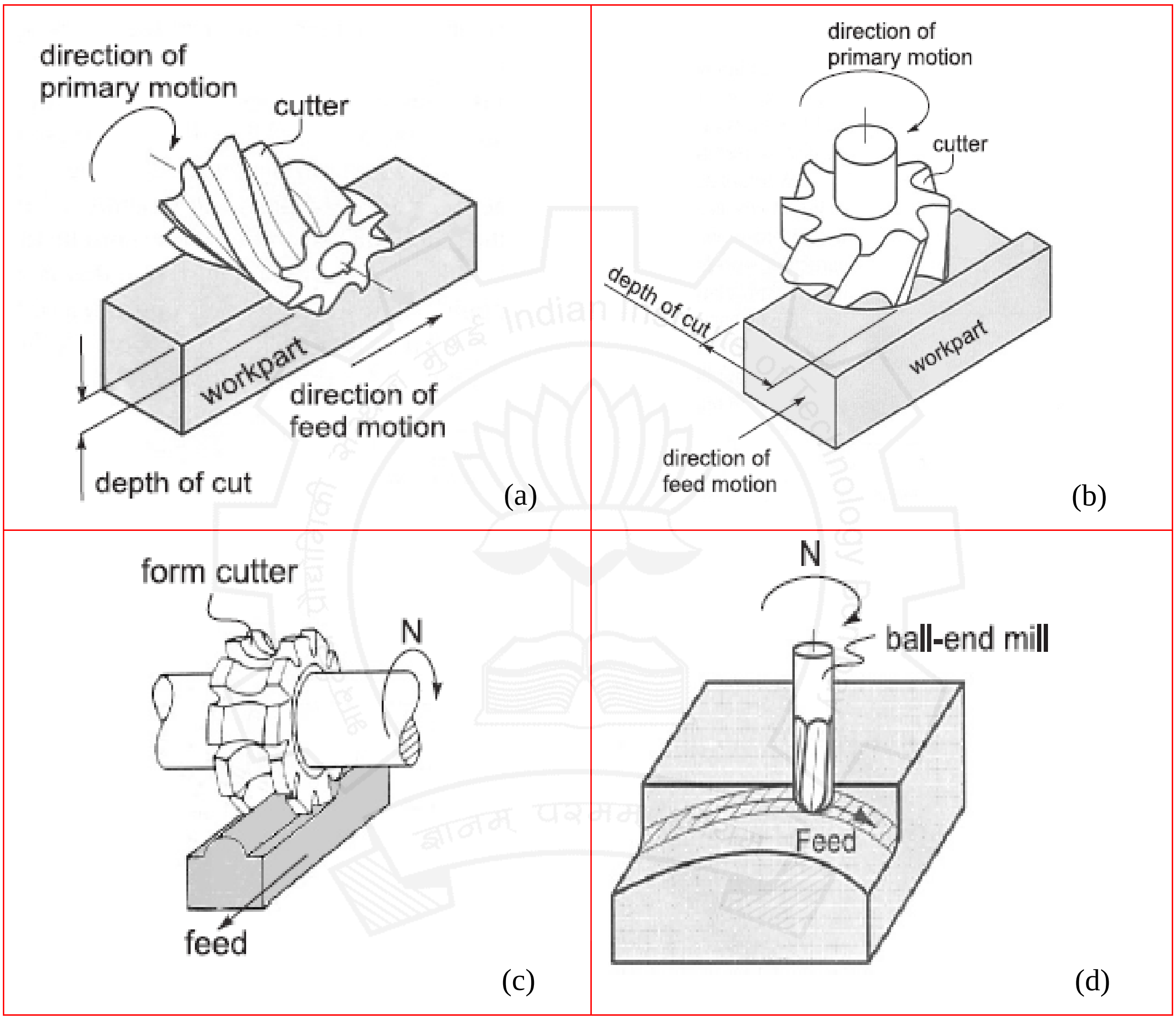


Figure 3.5.5 Different types of milling operations [4]

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.

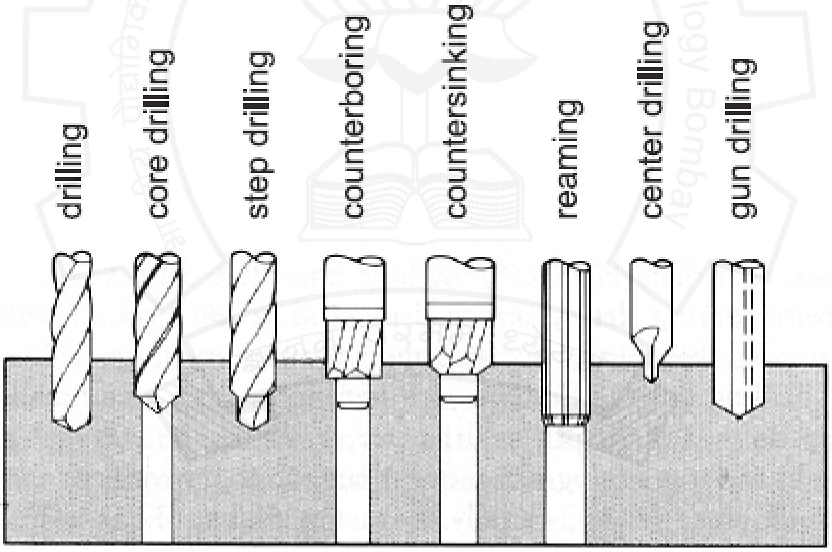


Figure 3.5.6 Different Types of Drilling Operations [3]

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.

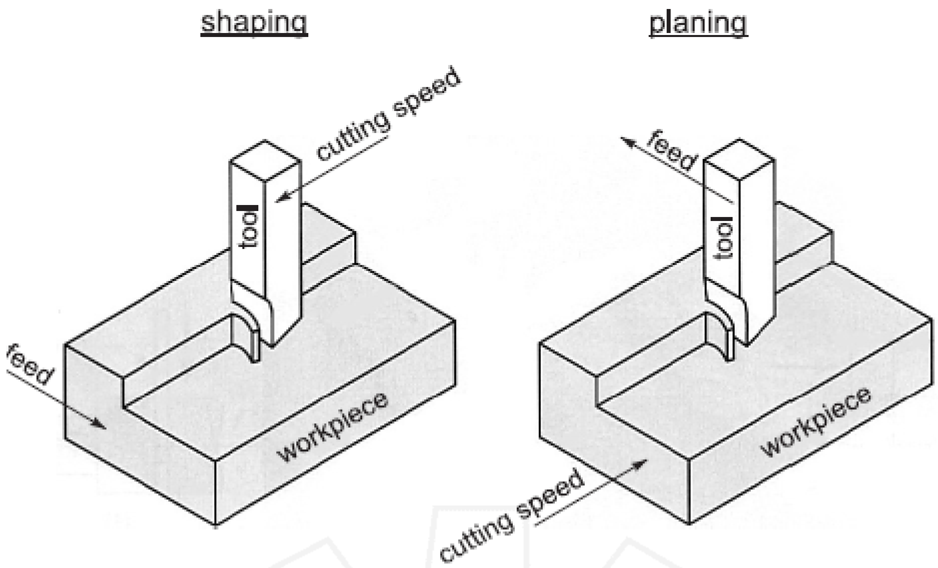


Figure 3.5.7 Kinematics of shaping and planning [4]

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.

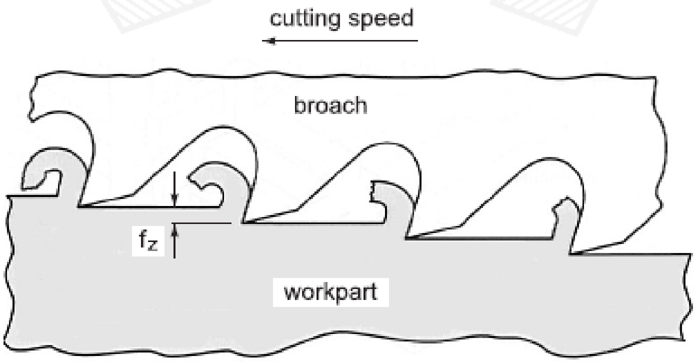


Figure 3.5.8 Schematic of broaching operation [1]

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.

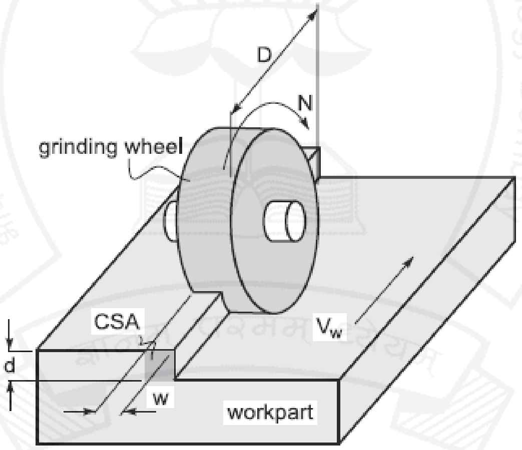


Figure 3.5.9 Schematic of grinding operation [1]

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.

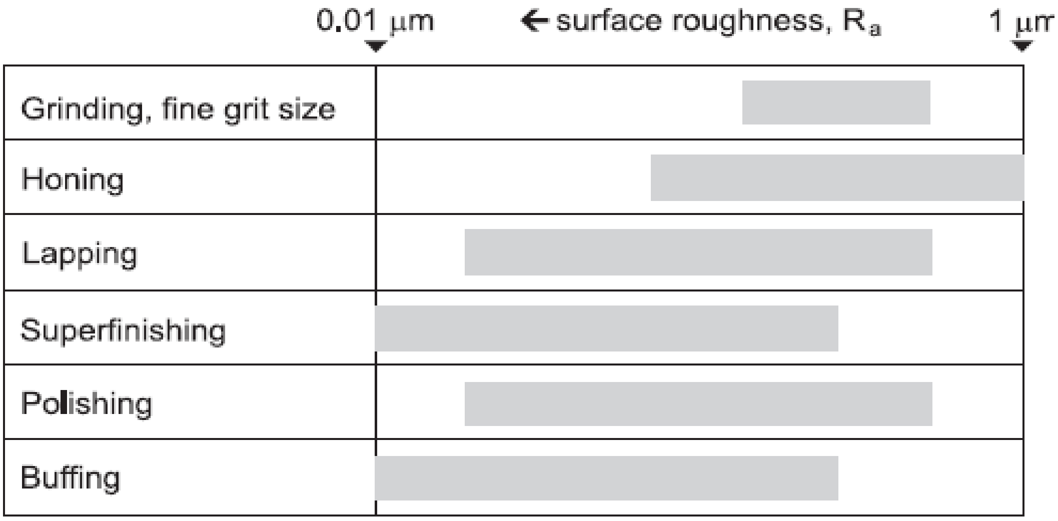


Figure 3.5.10 Comparison of surface roughness [4]

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.

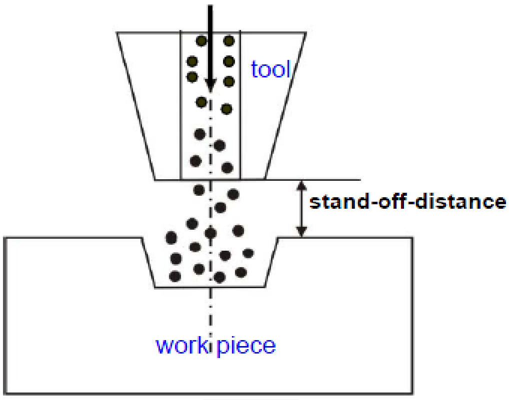


Figure 3.5.11 Schematic depiction of Abrasive Jet Machining [4]

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.

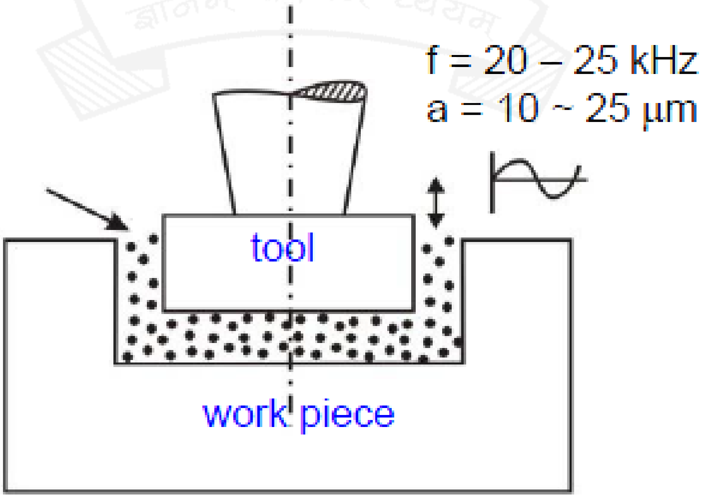


Figure 3.5.12 Schematic depiction of Ultrasonic Machining

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.

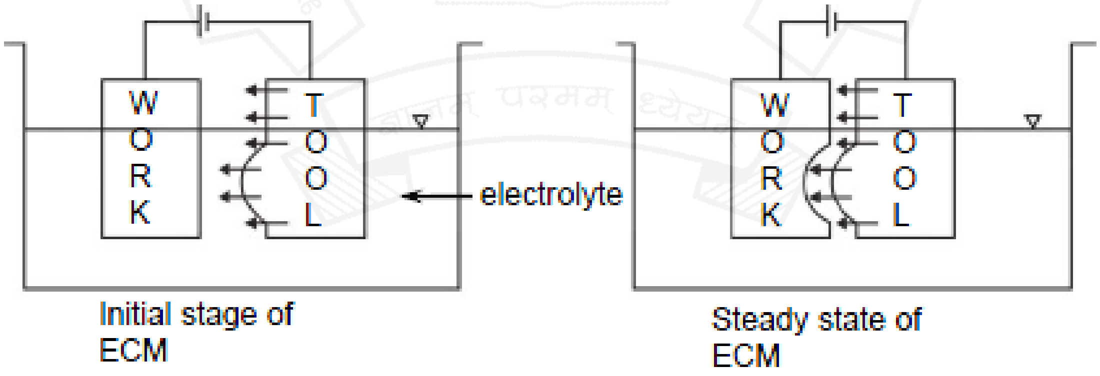


Figure 3.5.13 Schematic outline of Electro Chemical Machining [3]

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.

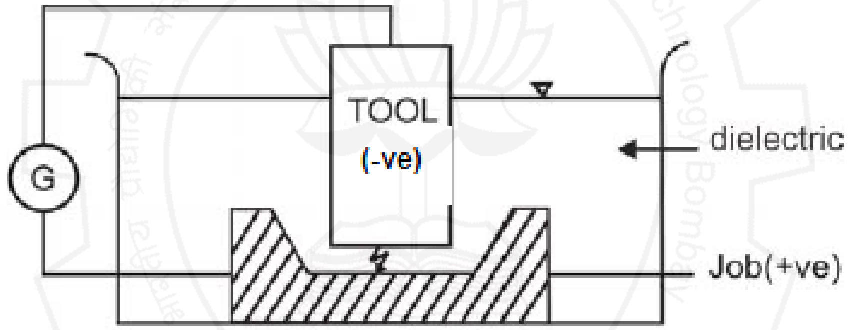


Figure 3.5.14 Schematic depiction of Electrodischarge Machining [3]

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.

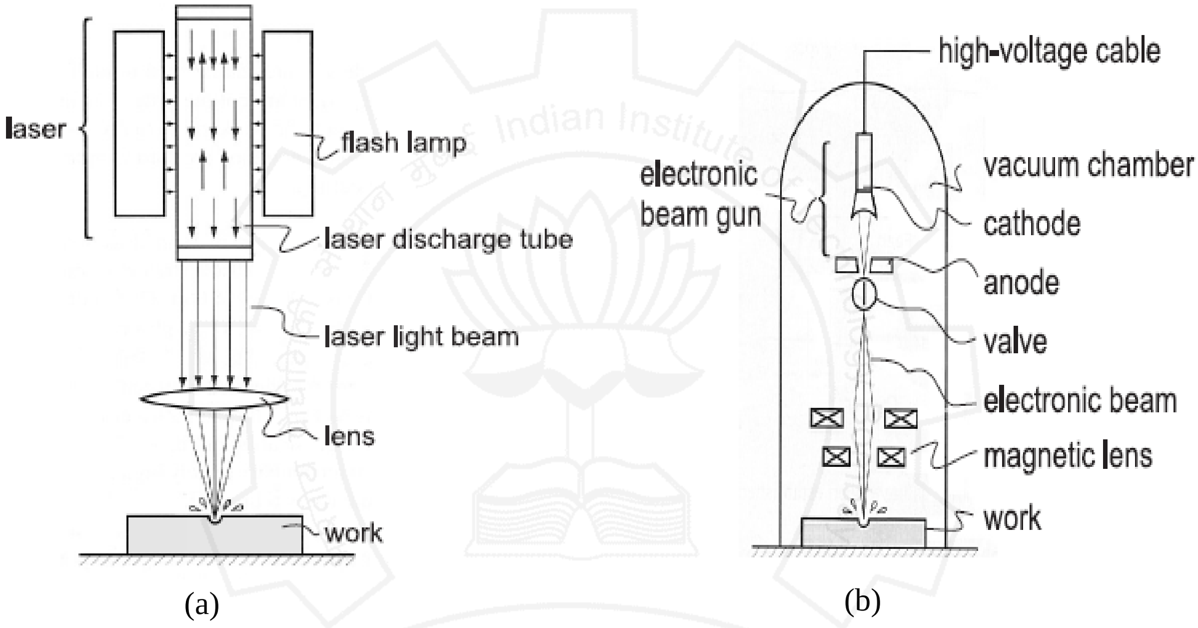


Figure 3.5.15 Schematic depiction of (a) Laser beam, and (b) Electron beam machining [3]

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:

$$T_C = T_h + T_m + \frac{T_t}{n_p} \qquad (1)$$

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*.

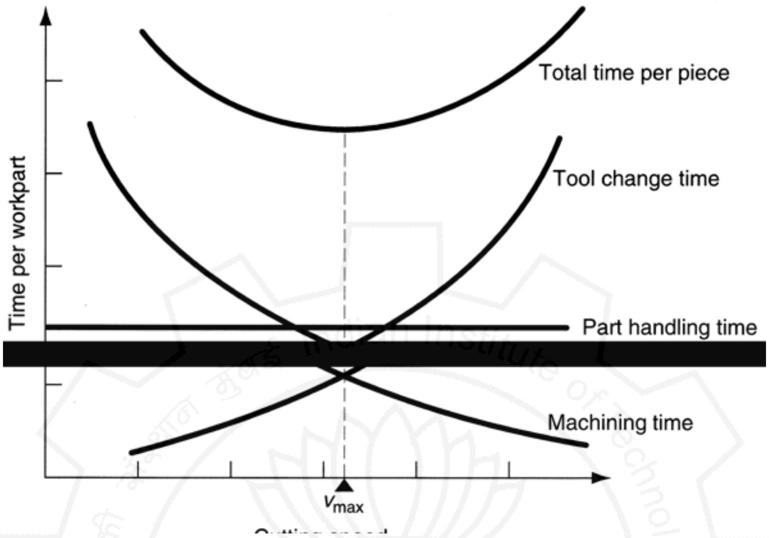


Figure 3.5.16 Machining cycle time vis-a-vis cutting speed [1]

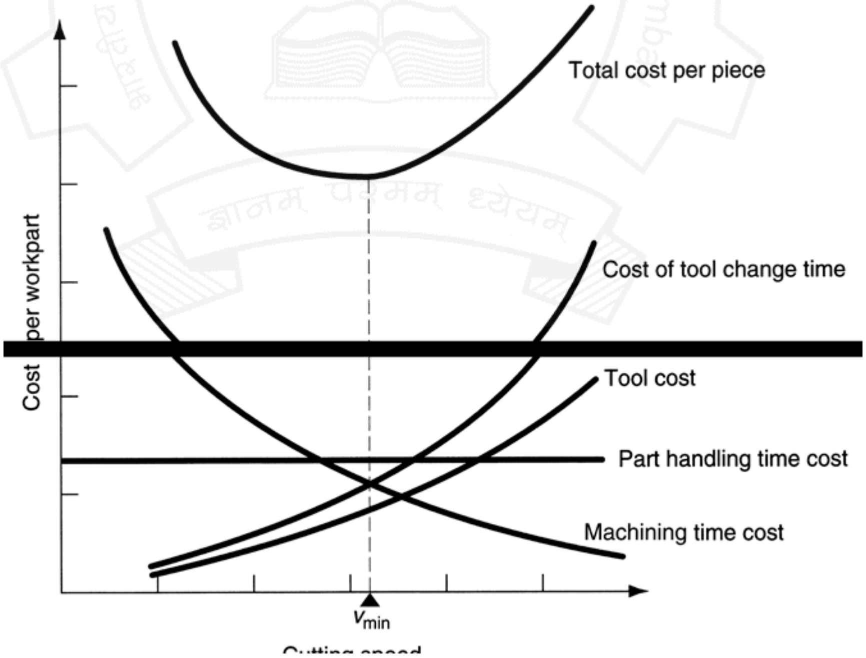


Figure 3.5.17 Unit cost vis-a-vis cutting speed [1]

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*).

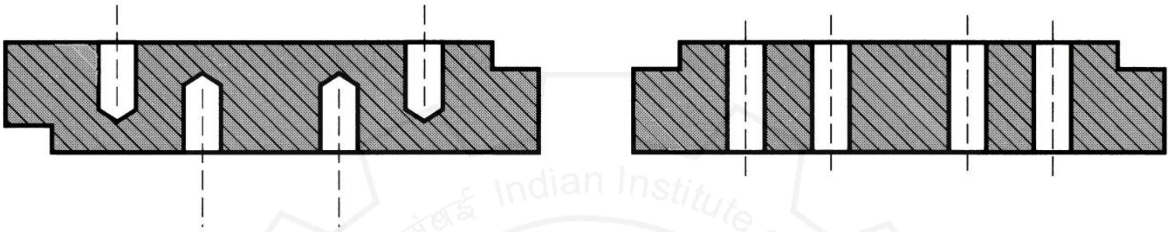


Figure 3.5.17 Through holes need less number of setup

(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).

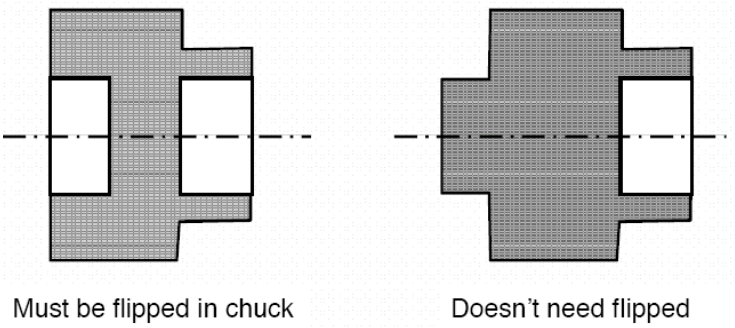


Figure 3.5.18 Avoid need to re-clamp

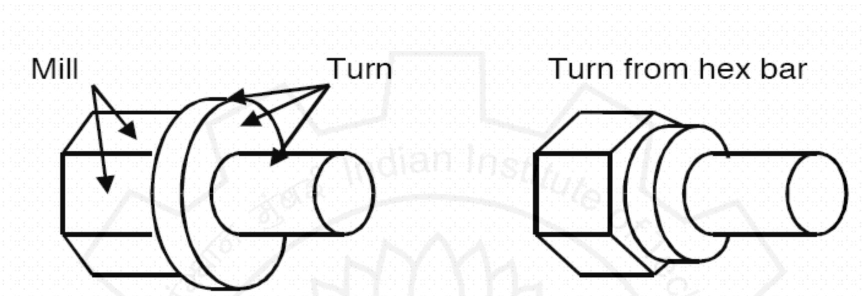


Figure 3.5.19 Using Single machine

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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