LECTURE NOTES

ON

UNCONVENTIONAL MACHINING PROCESS

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UNIT I - INTRODUCTION

Unconventional manufacturing processes is defined as a group of processes that remove excess material by various techniques involving mechanical, thermal, electrical or chemical energy or combinations of these energies but do not use a sharp cutting tools as it needs to be used for traditional manufacturing processes.

Extremely hard and brittle materials are difficult to machine by traditional machining processes such as turning, drilling, shaping and milling. Nontraditional machining processes, also called advanced manufacturing processes, are employed where traditional machining processes are not feasible, satisfactory or economical due to special reasons as outlined below.

a) Very hard fragile materials difficult to clamp for traditional machining
b) When the workpiece is too flexible or slender
c) When the shape of the part is too complex

Several types of non-traditional machining processes have been developed to meet extra required machining conditions. When these processes are employed properly, they offer many advantages over non-traditional machining processes. The common non- traditional machining processes are described in this section.

Manufacturing processes can be broadly divided into two groups:

a) primary manufacturing processes : Provide basic shape and size

b) secondary manufacturing processes : Provide final shape and size with tighter control on dimension, surface characteristics

Material removal processes once again can be divided into two groups

a) Conventional Machining Processes

b) Non-Traditional Manufacturing Processes or Unconventional Machining processes

Conventional Machining Processes mostly remove material in the form of chips by applying forces on the work material with a wedge shaped cutting tool that is harder than the work material under machining condition.

The major characteristics of conventional machining are:

a) Generally macroscopic chip formation by shear deformation

b) Material removal takes place due to application of cutting forces – energy domain can be classified as mechanical cutting tool is harder than work piece at room temperature.

Non-conventional manufacturing processes is defined as a group of processes that remove excess material by various techniques involving mechanical, thermal, electrical or chemical energy or combinations of these energies but do not use a sharp cutting tools as it needs to be used for traditional manufacturing processes.

Material removal may occur with chip formation or even no chip formation may take place. For example in AJM, chips are of microscopic size and in case of Electrochemical machining material removal occurs due to electrochemical dissolution at atomic level.

CLASSIFICATION OF UCM PROCESSES:

1. Mechanical Processes
    a) Abrasive Jet Machining(AJM)
    b) Ultrasonic Machining(USM)
    c) Water Jet Machining(WJM)
2. Abrasive Water Jet Machining(AWJM)
3. Electro chemical Processes
    a) Electrochemical Machining(ECM)
    b) Electrochemical Grinding(ECG)
    c) Electro Jet Drilling(EJD)

4. Electro-Thermal Processes
    a) Electro-discharge machining(EDM)
    b) Laser Jet Machining(LJM)
    c) Electron Beam Machining(EBM)

5. Chemical Processes
    a) Chemical Milling(CHM)
    b) Photochemical Milling(PCM)

NEED FOR UNCONVENTIONAL MACHINING PROCESSES

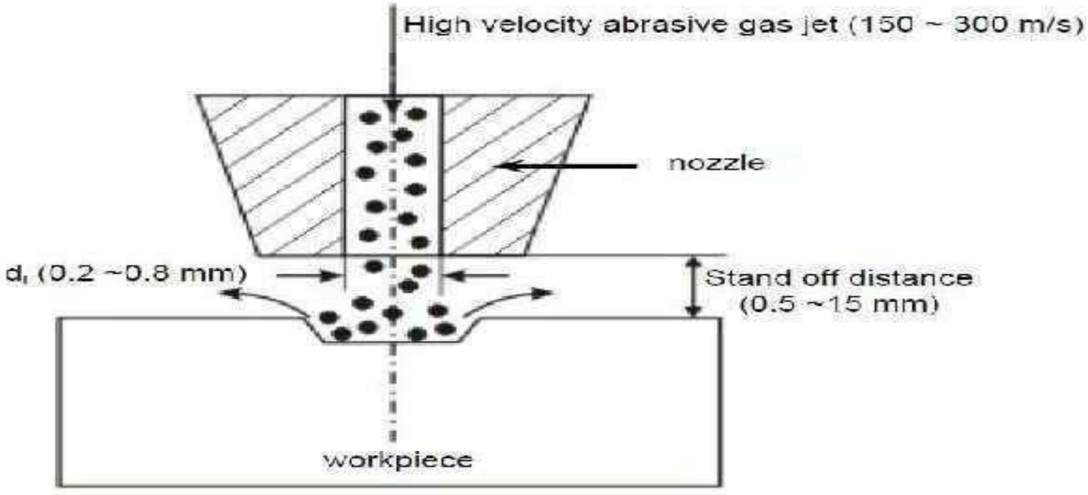
a) Extremely hard and brittle materials or Difficult to machine material are difficult to machine by traditional machining processes.
b) When the workpiece is too flexible or slender to support the cutting or grinding forces
c) When the shape of the part is too complex.

UNIT II – MECHANICAL ENERGY BASED MACHINING

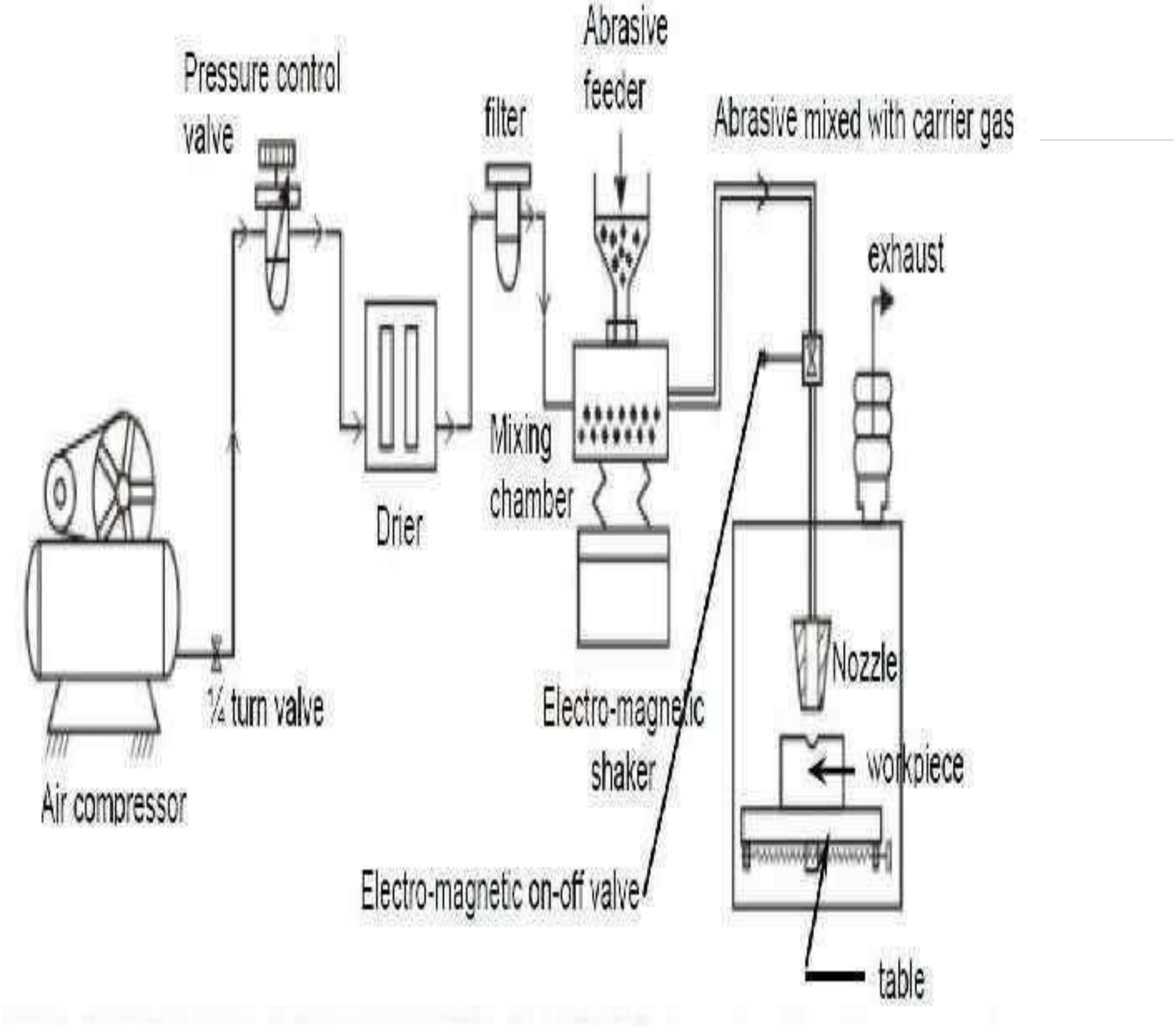
ABRASIVE JET MACHINING (AJM)

In Abrasive Jet Machining (AJM), abrasive particles are made to impinge on the work material at a high velocity. The high velocity abrasive particles remove the material by micro-cutting action as well as brittle fracture of the work material.

In AJM, generally, the abrasive particles of around 50 µm grit size would impinge on the work material at velocity of 200 m/s from a nozzle of I.D. of 0.5 mm with a standoff distance of around 2 mm. The kinetic energy of the abrasive particles would be sufficient to provide material removal due to brittle fracture of the work piece or even micro cutting by the abrasives.



AJM



SCHEMATIC ARRANGEMENT OF AJM

Process Parameters and Machining Characteristics

Abrasive: Material – Al_2O_3 / SiC / glass beads

Shape – irregular / spherical

Size – 10 ~ 50 μm

Mass flow rate – 2 ~ 20 gm/min

Carrier gas : Composition – Air, CO_2, N_2 Density – Air ~

1.3kg/m3

Velocity – 500 ~ 700m/s

Pressure – 2 ~ 10 bar Flow rate – 5 ~ 30 lpm

Abrasive Jet : Velocity – 100 ~ 300 m/s

Mixing ratio – mass flow ratio of abrasive to gas Stand-off distance –

0.5 ~ 5 mm

Impingement Angle – 60^0 ~ 90^0 Nozzle : Material – WC

Diameter –(Internal) 0.2 ~ 0.8 mm

Life–10~300hours Modelling of material removal

Material removal in AJM takes place due to brittle fracture of the work material due to impact of high velocity abrasive particles.

Modeling has been done with the following assumptions:

a) Abrasives are spherical in shape and rigid. The particles are characterized by the mean grit diameter
b) The kinetic energy of the abrasives are fully utilized in removing material
c) Brittle materials are considered to fail due to brittle fracture and the fracture volume is considered to be hemispherical with diameter equal to choral length of the indentation

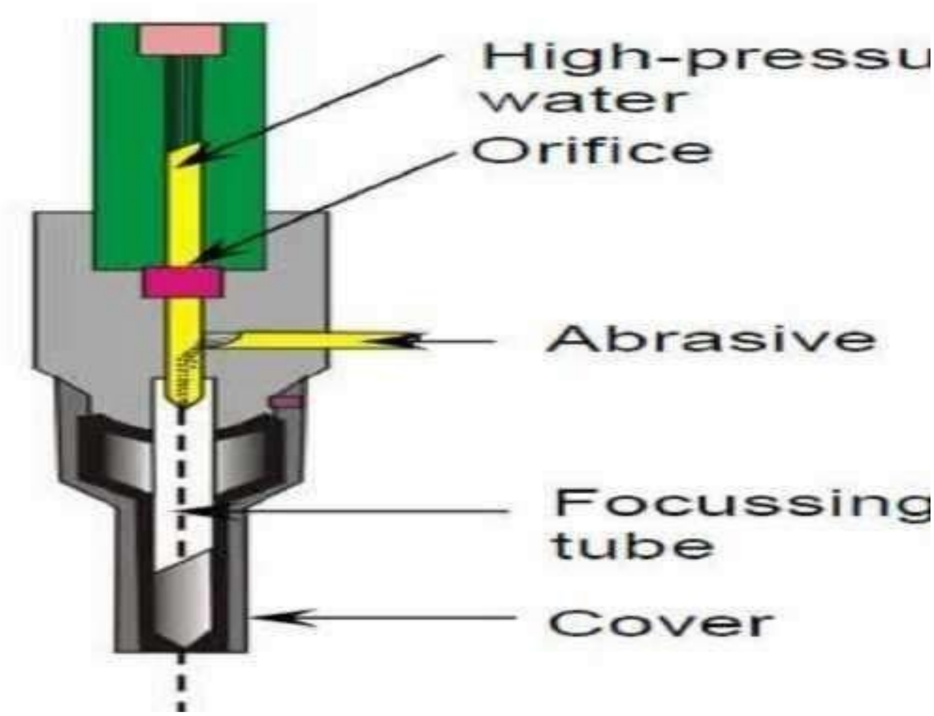
For ductile material, removal volume is assumed to be equal to the indentation volume due to particulate impact.

Water Jet Machining (WJM)

Introduction

Water jet cutting can reduce the costs and speed up the processes by eliminating or reducing expensive secondary machining process. Since no heat is applied on the materials, cut edges are clean with minimal burr. Problems such as cracked edge defects, crystalisation, hardening, reduced wealdability and machinability are reduced in this process.

Water jet technology uses the principle of pressurizing water to extremely high pressures, and allowing the water to escape through a very small opening called “orifice” or “jewel”. Water jet cutting uses the beam of water exiting the orifice to cut soft materials. This method is not suitable for cutting hard materials. The inlet water is typically pressurized between 1300 – 4000 bars. This high pressure is forced through a tiny hole in which is typically to 0.4 mm in diameter. A picture of water jet machiningprocess



Applications

Water jet cutting is mostly used to cut lower strength materials such as wood, plastics and aluminum. When abrasives are added, (abrasive water jet cutting) stronger materials such as steel and tool steel.

Advantages of water jet cutting

a) There is no heat generated in water jet cutting; which is especially useful for cutting tool steel and other metals where excessive heat may change the properties of the material.
b) Unlike machining or grinding, water jet cutting does not produce any dust or particles that are harmful if inhaled.
c) Other advantages are similar to abrasive water jet cutting

Disadvantages of water jet cutting

a) One of the main disadvantages of water jet cutting is that a limited number of materials can be cut economically.
b) Thick parts cannot be cut by this process economically and accurately
c) Taper is also a problem with water jet cutting in very thick materials. Taper is when the jet exits the part at different angle than it enters the part, and cause dimensional inaccuracy.

ABRASIVE WATER-JETMACHINING (AWJM)

Introduction

Abrasive water jet cutting is an extended version of water jet cutting; in which the water jet contains abrasive particles such as silicon carbide or aluminum oxide in order to increase the material removal rate above that of water jet machining. Almost any type of material ranging from hard brittle materials such as ceramics, metals and glass to extremely soft materials such as foam and rubbers can be cut by abrasive water jet cutting. The narrow cutting stream and computer controlled movement enables this process to produce parts accurately and efficiently. This machining process is especially ideal for cutting materials that cannot be cut by laser or thermal cut. Metallic, non-metallic and advanced composite materials of various thicknesses can be cut by this process. This process is particularly suitable for heat sensitive materials that cannot be machined by processes that produce heat while machining.

The schematic of abrasive water jet cutting is shown in Figure 15 which is similar to water jet cutting apart from some more features underneath the jewel; namely abrasive, guard and mixing tube. In this process, high velocity water exiting the jewel creates a vacuum which sucks abrasive from the abrasive line, which mixes with the water in the mixing tube to form a high velocity beam of abrasives.

Applications

Abrasive water jet cutting is highly used in aerospace, automotive and electronics industries. In aerospace industries, parts such as titanium bodies for military aircrafts, engine components (aluminium, titanium, and heat resistant alloys), aluminium body parts and interior cabin parts are made using abrasive water jet cutting.

In automotive industries, parts like interior trim (head liners, trunk liners, door panels) and fibre glass body components and bumpers are made by this process. Similarly, in electronics industries, circuit boards and cable stripping are made by abrasive water jet cutting.

Advantages of abrasive water jet cutting

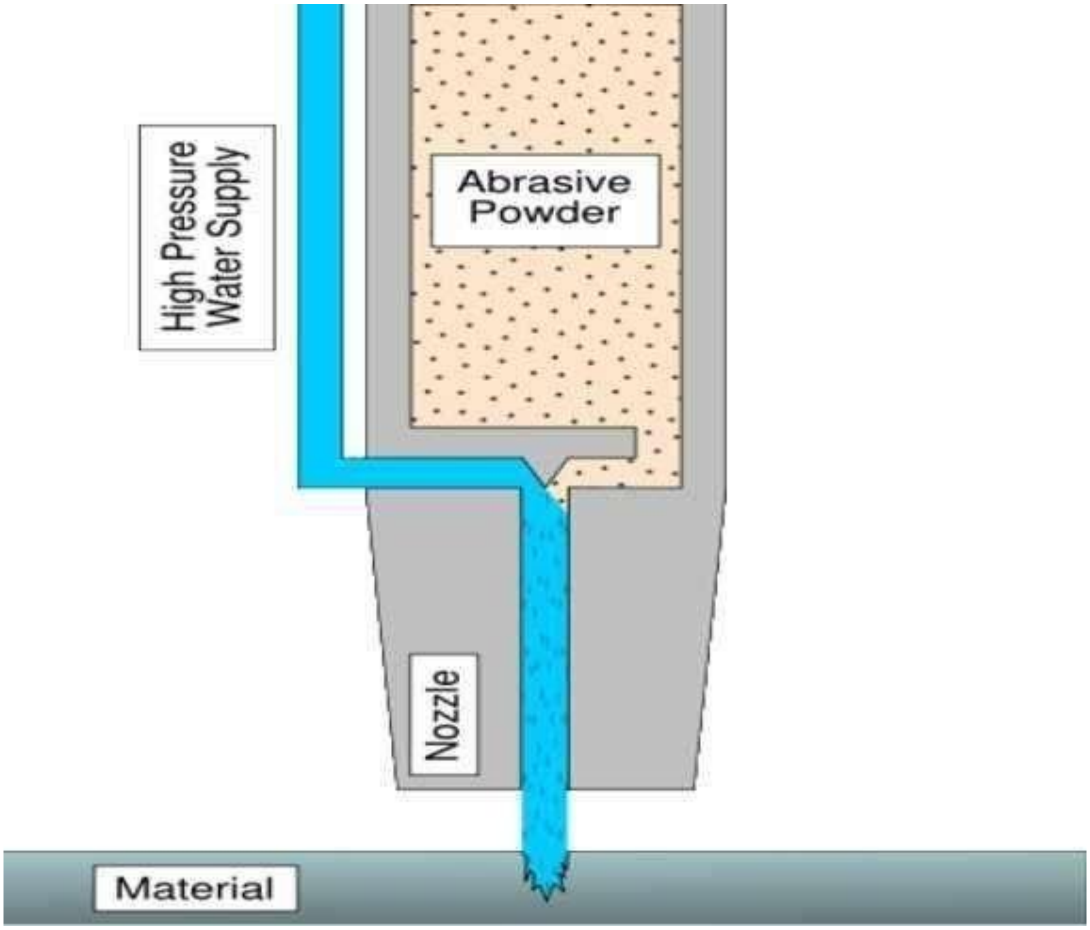
In most of the cases, no secondary finishing required

a) No cutter induced distortion
b) Low cutting forces on work pieces
c) Limited tooling requirements
d) Little to no cutting burr
e) Typical finish 125-250microns
f) Smaller kerf size reduces material wastages

a) No heat affected zone
b) Localizes structural changes
c) No cutter induced metal contamination
d) Eliminates thermal distortion
e) No slag or cutting dross
f) Precise, multi plane cutting of contours, shapes, and bevels of any angle.

Limitations of abrasive water jet cutting

a) Cannot drill flat bottom
b) Cannot cut materials that degrades quickly with moisture
c) Surface finish degrades at higher cut speeds which are frequently used for rough cut

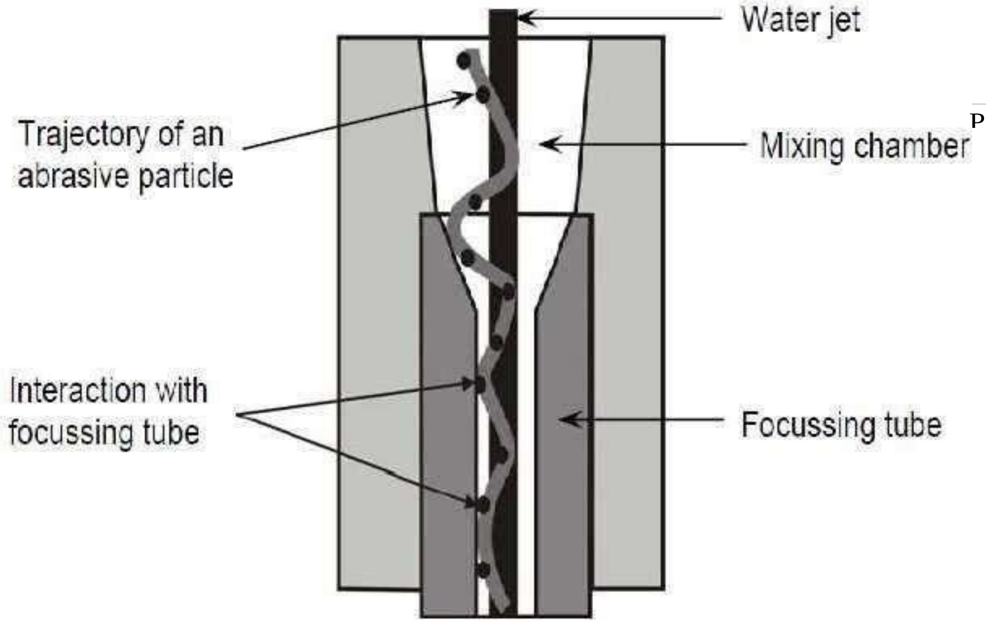


The major disadvantages of abrasive water jet cutting are high capital cost and high noise levels during operation.

A component cut by abrasive water jet cutting is shown in Figure 16. As it can be seen, large parts can but cut with very narrow kerf which reduces material wastages. The complex shape part made by abrasive water jet cutting

Abrasive water jet cutting

a) WJM -Pure
b) WJM – with stabilizer
c) AWJM – entrained – three phase–abrasive, water and air
d) AWJM – suspended – two phase– abrasive and water
e) Direct pumping
   i. Indirect pumping
   ii. Bypass pumping



Components of ABRASIVE WATERJET MACHINING

ULTRASONIC MACHINING (USM)

Introduction

USM is mechanical material removal process or an abrasive process used to erode holes or cavities on hard or brittle work piece by using shaped tools, high frequency mechanical motion and an abrasive slurry. USM offers a solution to the expanding need for machining brittle materials such as single crystals, glasses and polycrystalline ceramics, and increasing complex operations to provide intricate shapes and work piece profiles. It is therefore used extensively in machining hard and brittle materials that are difficult to machine by traditional manufacturing processes. The hard particles in slurry are accelerated toward the surface of the work piece by a tool oscillating at a frequency up to 100 KHz - through repeated abrasions, the tool machines a cavity of a cross section identical to its own.

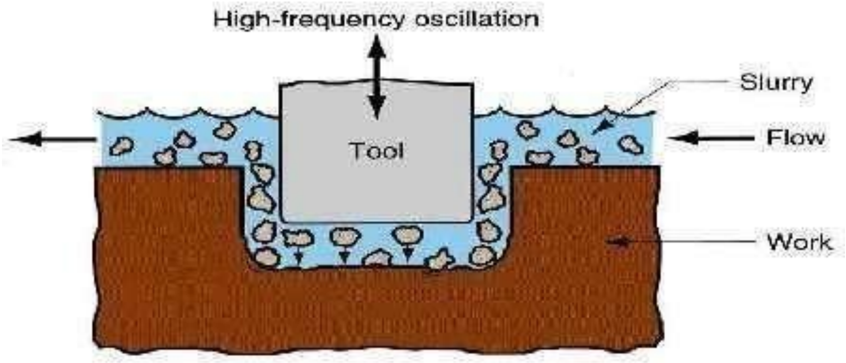


Figure 10: Schematic of ultrasonic machine tool

USM is primarily targeted for the machining of hard and brittle materials (dielectric or conductive) such as boron carbide, ceramics, titanium carbides, rubies, quartz etc. USM is a versatile machining process as far as properties of materials are concerned. This process is able to effectively machine all materials whether they are electrically conductive or insulator.

For an effective cutting operation, the following parameters need to be carefully considered:

- Themachiningtoolmustbeselectedtobehighlywearresistant,suchashigh-carbon steels.
- The abrasives (25-60 µm in dia.) in the (water-based, up to 40% solid volume) slurry includes: Boron carbide, silicon carbide and aluminum oxide.

Applications

The beauty of USM is that it can make non round shapes in hard and brittle materials. Ultrasonically machined non round-hole part is shown in Figure 11.

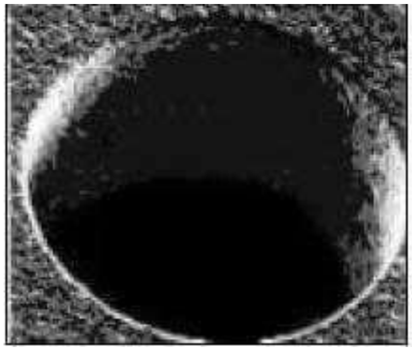


Figure 11: A non-round hole made by USM

Advantage of USM

USM process is a non-thermal, non-chemical, creates no changes in the microstructures, chemical or physical properties of the workpiece and offers virtually stress free machined surfaces.

- Any materials can be machined regardless of their electrical conductivity
- Especially suitable for machining of brittle materials
- Machined parts by USM possess better surface finish and higher structural integrity.
- USM does not produce thermal, electrical and chemical abnormal surface

Some disadvantages of USM

- USM has higher power consumption and lower material-removal rates than traditional fabrication processes.
- Tool wears fast in USM.
- Machining area and depth is restraint in USM.

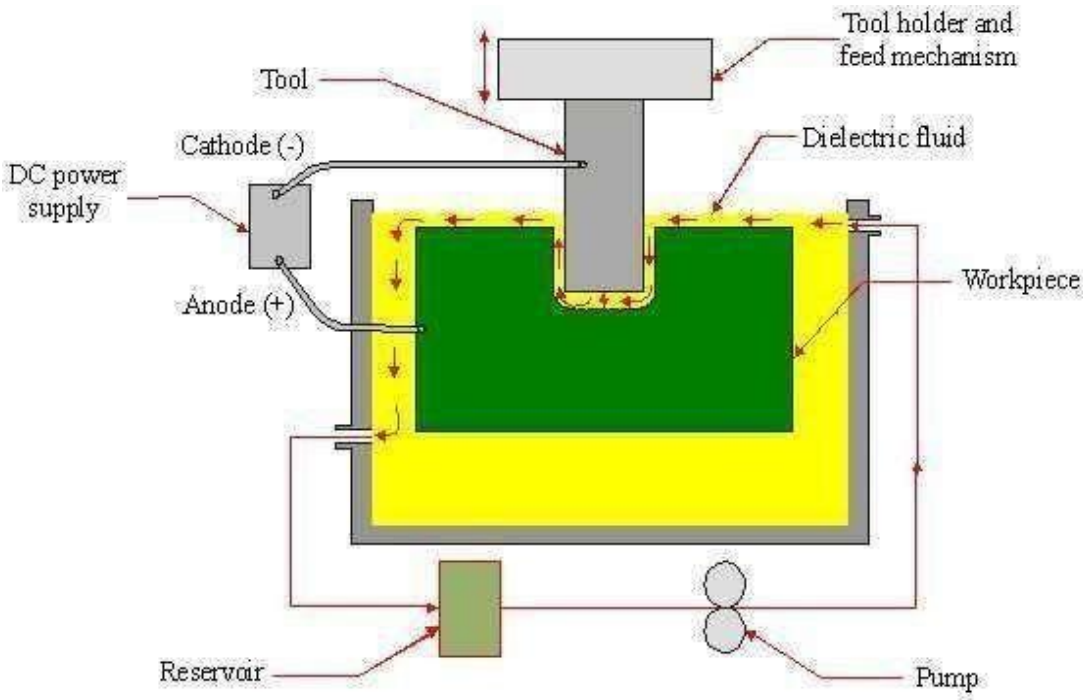
UNIT III - ELECTRICAL BASEDPROCESSES

Electrical Discharge Machining (EDM)

Electrical discharge machining (EDM) is one of the most widely used non- traditional machining processes. The main attraction of EDM over traditional machining processes such as metal cutting using different tools and grinding is that this technique utilizes thermoelectric process to erode undesired materials from the work piece by a series of discrete electrical sparks between the work piece and the electrode. A picture of EDM machine in operation

The traditional machining processes rely on harder tool or abrasive material to remove the softer material whereas non-traditional machining processes such as EDM uses electrical spark or thermal energy to erode unwanted material in order to create desired shape. So, the hardness of the material is no longer a dominating factor for EDM process. A schematic of an EDM process is shown in Figure 2, where the tool and the workpiece are immersed in a dielectric fluid.

Figure 2: Schematic of EDM process



EDM removes material by discharging an electrical current, normally stored in a capacitor bank, across a small gap between the tool (cathode) and the workpiece (anode) typically in order

Application of EDM

The EDM process has the ability to machine hard, difficult-to-machine materials. Parts with complex, precise and irregular shapes for forging, press tools, extrusion dies, difficult internal shapes for aerospace and medical applications can be made by EDM process. Some of the shapes made by EDM process are shown in Figure 3.

Figure 3: Difficult internal parts made by EDM process working

Principle Of EDM

As shown in Figure 1, at the beginning of EDM operation, a high voltage is applied across the narrow gap between the electrode and the workpiece. This high voltage induces an electric field in the insulating dielectric that is present in narrow gap between electrode and workpiece. This cause conducting particles suspended in the dielectric to concentrate at the points of strongest electrical field. When the potential difference between the electrode and the workpiece is sufficiently high, the dielectric breaks down and a transient spark is charges through the dielectric fluid, removing small amount of material from the workpiece surface.

The volume of the material removed per spark discharge is typically in the range of $10^{-6}mm^{3}$.

The material removal rate, MRR, in EDM is calculated by the following formula:

$MRR = 40\ I / T_m^{1.23}$ (cm^3/min)

Where, I is the current amp, T_m is the melting temperature of workpiece in ^0C

Advantages of EDM

The main advantages of DM are:

a. By this process, materials of any hardness can be machined;
b. No burrs are left in machined surface;
c. One of the main advantages of this process is that thin and fragile/brittle components can be machined without distortion;

d. Complex internal shapes can be machined

Limitations of EDM

The main limitations of this process are:

a) This process can only be employed in electrically conductive materials;
b) Material removal rate is low and the process overall is slow compared to conventional machining processes;
c) Unwanted erosion and over cutting of material can occur;
d) Rough surface finish when at high rates of material removal.

Dielectric fluids

Dielectric fluids used in EDM process are hydrocarbon oils, kerosene and deionised water. The functions of the dielectric fluid are to:

a) Act as an insulator between the tool and the workpiece.
b) Act as coolant.
c) Act as a flushing medium for the removal of the chips.

The electrodes for EDM process usually are made of graphite, brass, copper and copper-tungsten alloys.

Design considerations for EDM process are as follows:

a) Deep slots and narrow openings should be avoided.
b) The surface smoothness value should not be specified too fine.

Rough cut should be done by other machining process. Only finishing operation should be done in this process as MRR for this process is slow.

Wire Cut Electrical Discharge Machining (WCEDM)

EDM, primarily, exists commercially in the form of die-sinking machines and wire-cutting machines (Wire EDM). The concept of wire EDM is shown in Figure 4. In this process, a slowly moving wire travels along a prescribed path and removes material from the workpiece. Wire EDM uses electro-thermal mechanisms to cut electrically conductive materials. The material is removed by a series of discrete discharges between the wire electrode and the workpiece in the presence of dielectric fluid, which creates a path for each discharge as the fluid becomes ionized in the gap. The area where discharge takes place is heated to extremely high temperature, so that the surface is melted and removed.

The wire EDM process can cut intricate components for the electric and aerospace industries. This non-traditional machining process is widely used to pattern tool steel for die manufacturing.

Figure 4: Wire erosion of an extrusion die

The wires for wire EDM is made of brass, copper, tungsten, molybdenum. Zinc or brass coated wires are also used extensively in this process. The wire used in this process should posses high tensile strength and good electrical conductivity. Wire EDM can also employ to cut cylindrical objects with high precision. The sparked eroded extrusion dies are presented in Figure 5.

This process is usually used in conjunction with CNC and will only work when a part is to be cut completely through. The melting temperature of the parts to be machined is an important parameter for this process rather than strength or hardness. The surface quality and MRR of the machined surface by wire EDM will depend on different machining parameters such as applied peak current, and wire materials.

UNIT-IV - CHEMICAL AND ELECTRO CHEMICAL ENERGY BASED PROCESSES

CHEMICAL MACHINING (CHM)

Introduction

Chemical machining (CM) is the controlled dissolution of work piece material (etching) by means of a strong chemical reagent (etchant). In CM material is removed from selected areas of work piece by immersing it in a chemical reagents or etchants; such as acids and alkaline solutions. Material is removed by microscopic electrochemical cell action, as occurs in corrosion or chemical dissolution of a metal. This controlled chemical dissolution will simultaneously etch all exposed surfaces even though the penetration rates of the material removal may be only 0.0025–0.1 mm/min. The basic process takes many forms: chemical milling of pockets, contours, overall metal removal, chemical blanking for etching through thin sheets; photochemical machining (pcm) for etching by using of photosensitive resists in microelectronics; chemical or electrochemical polishing where weak chemical reagents are used (sometimes with remote electric assist) for polishing or deburring and chemical jet machining where a single chemically active jet is used. A schematic of chemical machining process is shown in Figure 6.

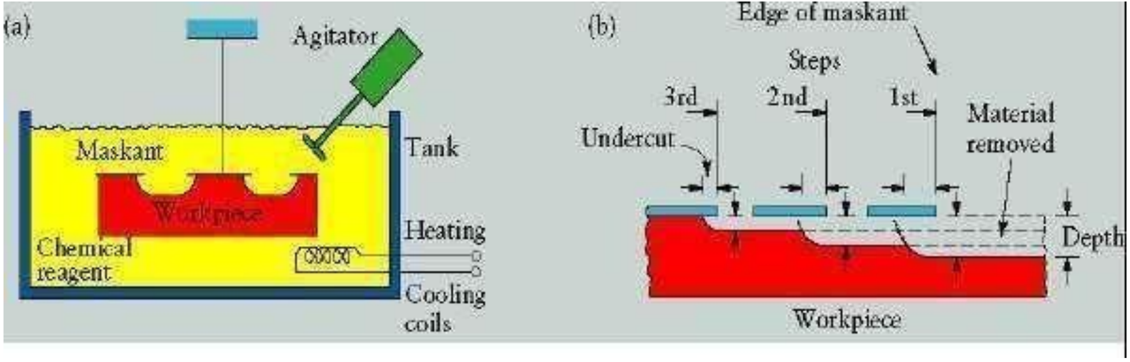


Figure 6: (a) Schematic of chemical machining process (b) Stages in producing a profiled cavity by chemical machining (Kalpakjain & Schmid)

Chemical milling

In chemical milling, shallow cavities are produced on plates, sheets, forgings and extrusions. The two key material used in chemical milling processes are etchant and maskant .Etchants are acid or alkaline solutions maintained within controlled ranges of chemical composition and temperature. Maskants are specially designed elastomeric products that are hand strippable and chemically resistant to the harsh etchants.

Steps in chemical milling

a) Residual stress relieving: If the part to be machined has residual stresses from the previous processing, these stresses first should be relieved in order to prevent warping after chemical milling.

b) Preparing: The surfaces are degreased and cleaned thoroughly to ensure both good adhesion of the masking material and the uniform material removal.

c) Masking: Masking material is applied (coating or protecting areas not to beetched).

d) Etching: The exposed surfaces are machined chemically with etchants.

e) Demasking: After machining, the parts should be washed thoroughly to prevent further reactions with or exposure to any etchant residues. Then the rest of the masking material is removed and the part is cleaned and inspected.

Applications:

Chemical milling is used in the aerospace industry to remove shallow layers of material from large aircraft components missile skin panels (Figure 7), extruded parts for airframes.

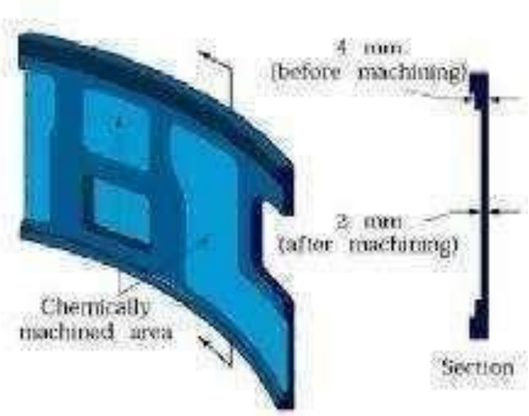


Figure 7: Missile skin-panel section contoured by chemical milling to improve the stiffness- to- weight ratio of the part (Kalpakjain & Schmid)

Electrochemical Machining (ECM) Introduction

Electrochemical machining (ECM) is a metal-removal process based on the principle of reverse electroplating. In this process, particles travel from the anodic material (workpiece) toward the cathodic material (machining tool). A current of electrolyte fluid carries away the deplated material before it has a chance to reach the machining tool. The cavity produced is the female mating image of the tool shape.

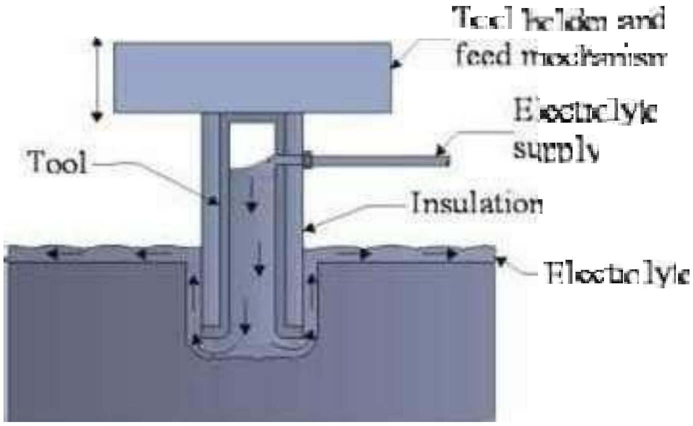


Figure 8: ECM process

Similar to EDM, the workpiece hardness is not a factor, making ECM suitable for machining difficult-to –machine materials. Difficult shapes can be made by this process on materials regardless of their hardness. A schematic representation of ECM process is shown in Figure 8. The ECM tool is positioned very close to the workpiece and a low voltage, high amperage DC current is passed between the workpiece and electrode. Some of the shapes made by ECM process is shown in Figure9.

Figure 9: Parts made by ECM

Advantages of ECM

a) The components are not subject to either thermal or mechanical stress.
b) No tool wear during ECM process.
c) Fragile parts can be machined easily as there is no stress involved.
d) ECM deburring can debur difficult to access areas of parts.
e) High surface finish (up to 25 µm in) can be achieved by ECM process.
f) Complex geometrical shapes in high-strength materials particularly in the aerospace industry for the mass production of turbine blades, jet-engine parts and nozzles can be machined repeatedly and accurately.
g) Deep holes can be made by this process.

Limitations of ECM

a) ECM is not suitable to produce sharp square corners or flat bottoms because of the tendency for the electrolyte to erode away sharp profiles.

b) ECM can be applied to most metals but, due to the high equipment costs, is usually used primarily for highly specialized applications.

Material removal rate, MRR, in ECM MRR = C.I.h (cm^3/min)

C: specific (material) removal rate (e.g.,0.2052cm^3/amp-min for nickel); I: current (amp);

h: current efficiency (90–100%).

The rates at which metal can electrochemically remove are in proportion to the current passed through the electrolyte and the elapsed time for that operation. Many factors other than current influence the rate of machining. These involve electrolyte type, rate of electrolyte flow, and some other process conditions.

ELECTROCHEMICAL HONING

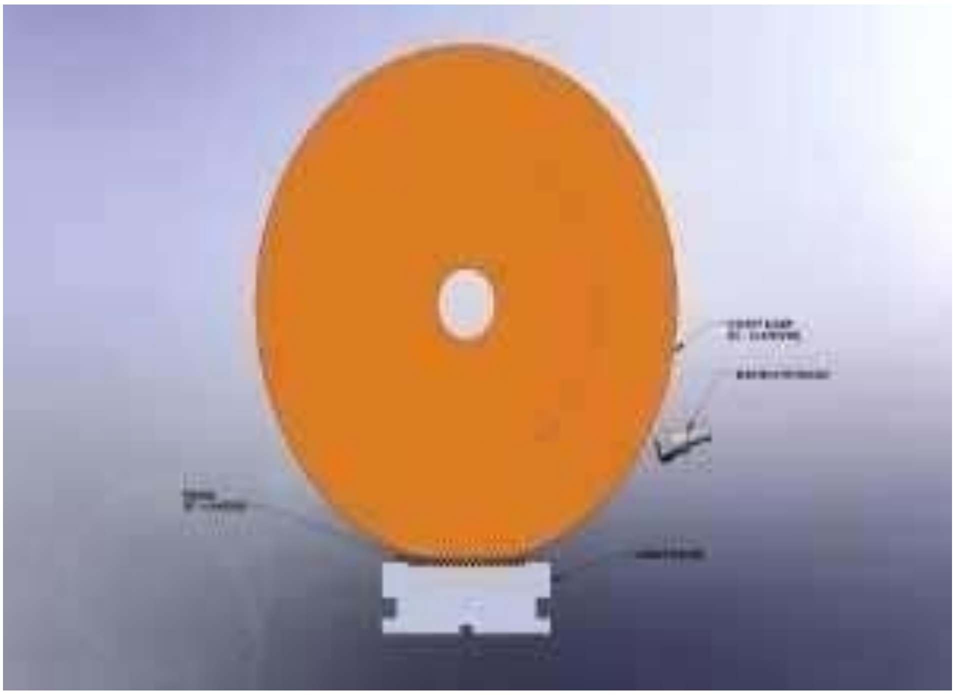
Electrochemical honing is one of the non-equilibrium gap processes in ECM and is a new technique, which in spite of being used in some industrial plants especially to smooth surfaces, is still not fully described due to the variety of the factors affecting the process. More information about the process is required especially the effects of the working parameters on the produced surface roughness. A special honing tool was designed by using different tool tip shapes (rectangular, circular, triangle & inclined) to study the ability for improving the surface roughness. This work presents a study for the factors affecting the electrochemical honing process especially the machining time, workpiece material, initial working gap, tool rotational speed, tool tip shape and the inclined tool tip angle. The results are finally furnished with the aim to generalize a useful guideline for the user to enable proper selection of conditions for obtaining good surface quality.

Electrochemical Grinding Process Overview Electrochemical Grinding (ECG) Process Overview

Electrochemical Grinding, or ECG, is a variation of ECM (Electrochemical Machining)that combines electrolytic activity with the physical removal of material by means of charged grinding wheels. Electrochemical Grinding(ECG) can produce burr free and stress free parts without heat or other metallurgical damage caused by mechanical grinding, eliminating the need for secondary machining operations. Like ECM, Electrochemical Grinding (ECG) generates little or no heat that can distort delicate components.

Electrochemical Grinding (ECG) can process any conductive material that is electrochemically reactive. The most common reason customers choose ELECTROCHEMICAL GRINDING (ECG) is for the burr free quality of the cut. If a part is difficult or costly to deburr, then ELECTROCHEMICAL GRINDING (ECG) is the best option. Materials that are difficult to machine by conventional methods, that work harden easily or are subject to heat damage are also good candidates for the stress free and no heat characteristics of ELECTROCHEMICAL GRINDING (ECG). The stress free cutting capability of the process also make it ideal for thin wall and delicate parts.

The real value of Electrochemical Grinding (ECG) is in metal working applications that are too difficult or time-consuming for traditional mechanical methods (milling, turning, grinding, deburring etc.). It is also effective when compared to non-traditional machining processes such as wire and sinker EDM. ELECTROCHEMICAL GRINDING (ECG) is almost always more cost effective than EDM.



ELECTROCHEMICAL GRINDING (ECG) differ from conventional grinding Conventional surface grinding typically uses shallow reciprocating cuts that sweep across the work surface to create a flat plane or groove. Another conventional surface grinding process, creep feed grinding, typically uses slower feeds than conventional surface grinding and removes material in deep cuts. Because of the abrasive nature of these processes, the equipment used must be rigid and this is especially true of creep feed grinding.

Quality ELECTROCHEMICAL GRINDING (ECG) machines must also be rigid for close tolerance results but since very little of the material removed is done so abrasively the machines do not have to be as massive as their conventional counterparts. To a user familiar with creep feed grinding ELECTROCHEMICAL GRINDING (ECG) will appear to be very similar, that is, relatively slow feeds (as compared to conventional surface grinding) and deep cuts as opposed to shallow reciprocating cuts. ELECTROCHEMICAL GRINDING (ECG) is a combination of electrochemical (Anodic) dissolution of a material, according to Faraday’s Law, and light abrasive action. The metal is decomposed to some degree by the DC current flow between the conductive grinding wheel (Cathode) and the work piece (Anode) in the presence of an electrolyte solution.

Unlike conventional grinding techniques, ELECTROCHEMICAL GRINDING (ECG) offers the ability to machine difficult materials independent of their hardness or strength. ELECTROCHEMICAL GRINDING (ECG) does not rely solely on an abrasive process; the results are precise burr free and stress free cuts with no heat and mechanical distortions.

ELECTROCHEMICAL GRINDING (ECG) compare to EDM, laser, water-jet and other non-traditional technologies

EDM and laser both cut metal by vaporizing the material at very high temperatures. This results in a re-cast layer and a heat affected zone on the material surface. ELECTROCHEMICAL GRINDING (ECG) is a no heat process that never causes metallurgical damage. ELECTROCHEMICAL GRINDING (ECG) is usually much faster than EDM but typically is less accurate. Laser cutting can be very fast and accurate but it is normally limited to thin materials. Water-jet cutting can be quite fast and usually leaves no metallurgical damage but the consumable costs can be very high and the cuts are limited to jigsaw type cuts much like Wire EDM. In most cases, ELECTROCHEMICAL GRINDING (ECG) is a more accurate process than water-jet. Another difference between water jet and laser machining compared to ELECTROCHEMICAL GRINDING (ECG) is laser and water jet can both process materials that are not conductive. EDM and ELECTROCHEMICAL GRINDING (ECG) processes can only work on materials that are conductive.

Tolerances can be achieved with ELECTROCHEMICAL GRINDING(ECG)

The tolerances that can be achieved using ELECTROCHEMICAL GRINDING (ECG) depend greatly on the material being cut, the size and depth of cut and ECG parameters being used. On small cuts, tolerances of .0002” (.005mm) can be achieved with careful control of the grinding parameters.

Surface finishes can be achieved with ELECTROCHEMICAL GRINDING (ECG)

The ELECTROCHEMICAL GRINDING (ECG) process does not leave the typical shiny finish of abrasive grinding. This is because there is no smearing of the metal as in conventional grinding. A 16 micro inch finish or better can be achieved but it will have a matte (dull) rather than a polished look.

Materials can be cut with ELECTROCHEMICAL GRINDING (ECG). Almost any conductive metal can cut with ELECTROCHEMICAL GRINDING (ECG). Steel, Aluminum, Copper, Stainless Steels, Inconel and Hastelloy cut very freely with ELECTROCHEMICAL GRINDING (ECG). Nickel/Titanium, Cobalt alloys, Amorphous metals, Berilium, Berilium Copper, Iridium Neodymium Iron/Boron, Titanium, Nickel/Titanium, Nitinol, Powdered Metals, Rene41, Rhenium, Rhodium, Vitalium, Zirconium and Tungsten can also be cut effectively.

ADVANTAGES OF ELECTROCHEMICAL GRINDING (ECG)

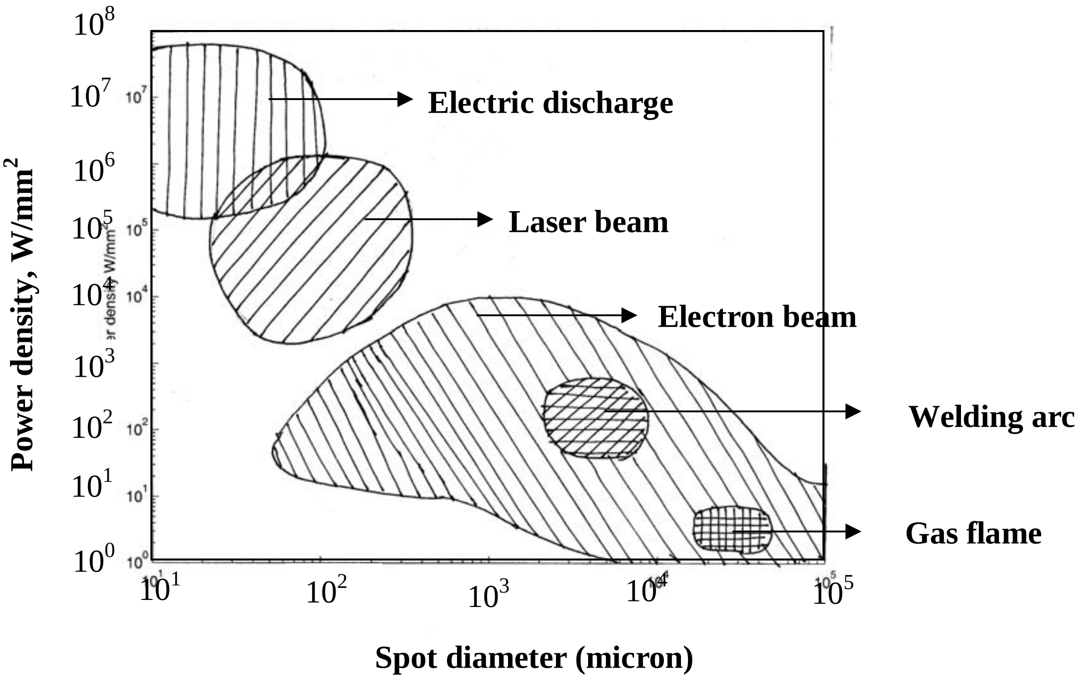
a) Improved wheel life
b) Burr free
c) No work hardening
d) Stress free
e) Better finish
f) No cracking
g) Less frequent wheel dressing
h) No metallurgical damage from heat
i) Faster for tough materials
j) No wheel loading or glazing
k) More precise tolerances

UNIT-V - THERMAL ENERGY BASEDPROCESSES

Introduction

Electron Beam Machining (EBM) and Laser Beam Machining (LBM) are thermal processes considering the mechanisms of material removal. However electrical energy is used to generate high-energy electrons in case of Electron Beam Machining (EBM) and high-energy coherent photons in case of Laser Beam Machining (LBM). Thus these two processes are often classified as electro-optical-thermal processes.

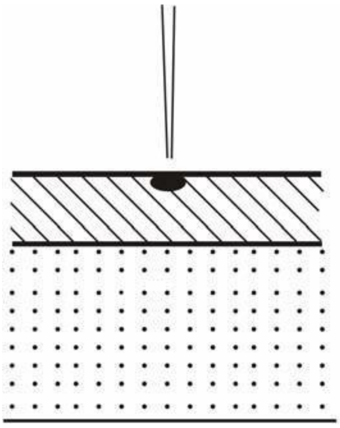
There are different jet or beam processes, namely Abrasive Jet, Water Jet etc. These two are mechanical jet processes. There are also thermal jet or beams. A few are oxyacetylene flame, welding arc, plasma flame etc. EBM as well as LBM are such thermal beam processes. Fig. 9.6.1 shows the variation in power density vs. the characteristic dimensions of different thermal beam processes. Characteristic length is the diameter over which the beam or flame is active. In case of oxyacetylene flame or welding arc, the characteristic length is in mm to tens of mm and the power density is typically low. Electron Beam may have a characteristic length of tens of microns to mm depending on degree of focusing of the beam. In case of defocused electron beam, power density would be as low as 1 Watt/mm^2. But in case of focused beam the same can be increased to tens of kW/mm^2. Similarly as can be seen in Fig. 9.6.1, laser beams can be focused over a spot size of 10 – 100 μm with a power density as high as 1 MW/mm^2. Electrical discharge typically provides even higher power density with smaller spot size.

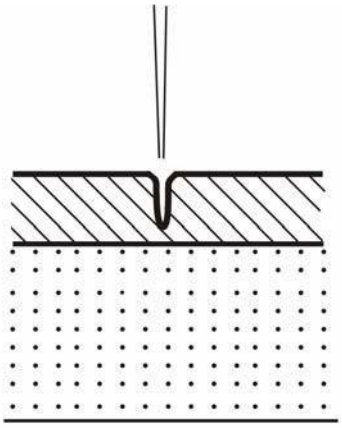


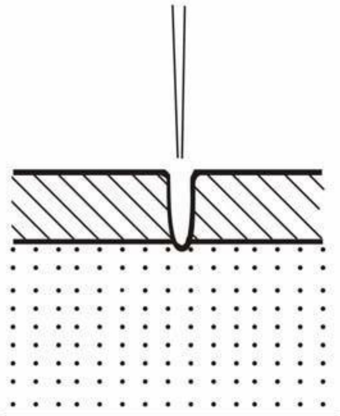
EBM and LBM are typically used with higher power density to machine materials. The mechanism of material removal is primarily by melting and rapid vaporisation due to intense heating by the electrons and laser beam respectively.

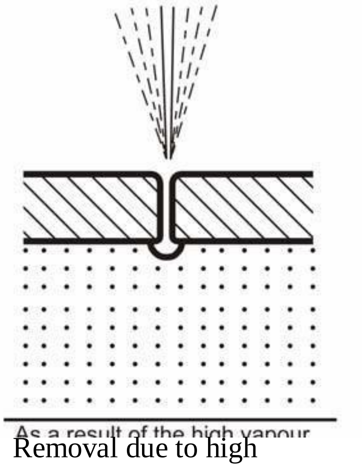
Electron Beam Machining – Process

Electron beam is generated in an electron beam gun. The construction and working principle of the electron beam gun would be discussed in the next section. Electron beam gun provides high velocity electrons over a very small spot size. Electron Beam Machining is required to be carried out in vacuum. Otherwise the electrons would interact with the air molecules, thus they would lose their energy and cutting ability. Thus the workpiece to be machined is located under the electron beam and is kept under vacuum. The high-energy focused electron beam is made to impinge on the workpiece with a spot size of 10 – 100 μm.The kinetic energy of the high velocity electrons is converted to heat energy as the electrons strike the work material. Due to high power density instant melting and vaporization starts and “melt – vaporization” front gradually progresses, as shown in Fig. 9.6.2. Finally the molten material, if any at the top of the front, is expelled from the cutting zone by the high vapor pressure at the lower part. Unlike in Electron Beam Welding, the gun in EBM is used in pulsed mode. Holes can be drilled in thin sheets using a single pulse. For thicker plates, multiple pulses would be required. Electron beam can also be manoeuvred using the electromagnetic deflection coils for drilling holes of any shape.


Localized heating by
focused electron beam


Gradual formation of hole


Penetration till
the auxiliary
support

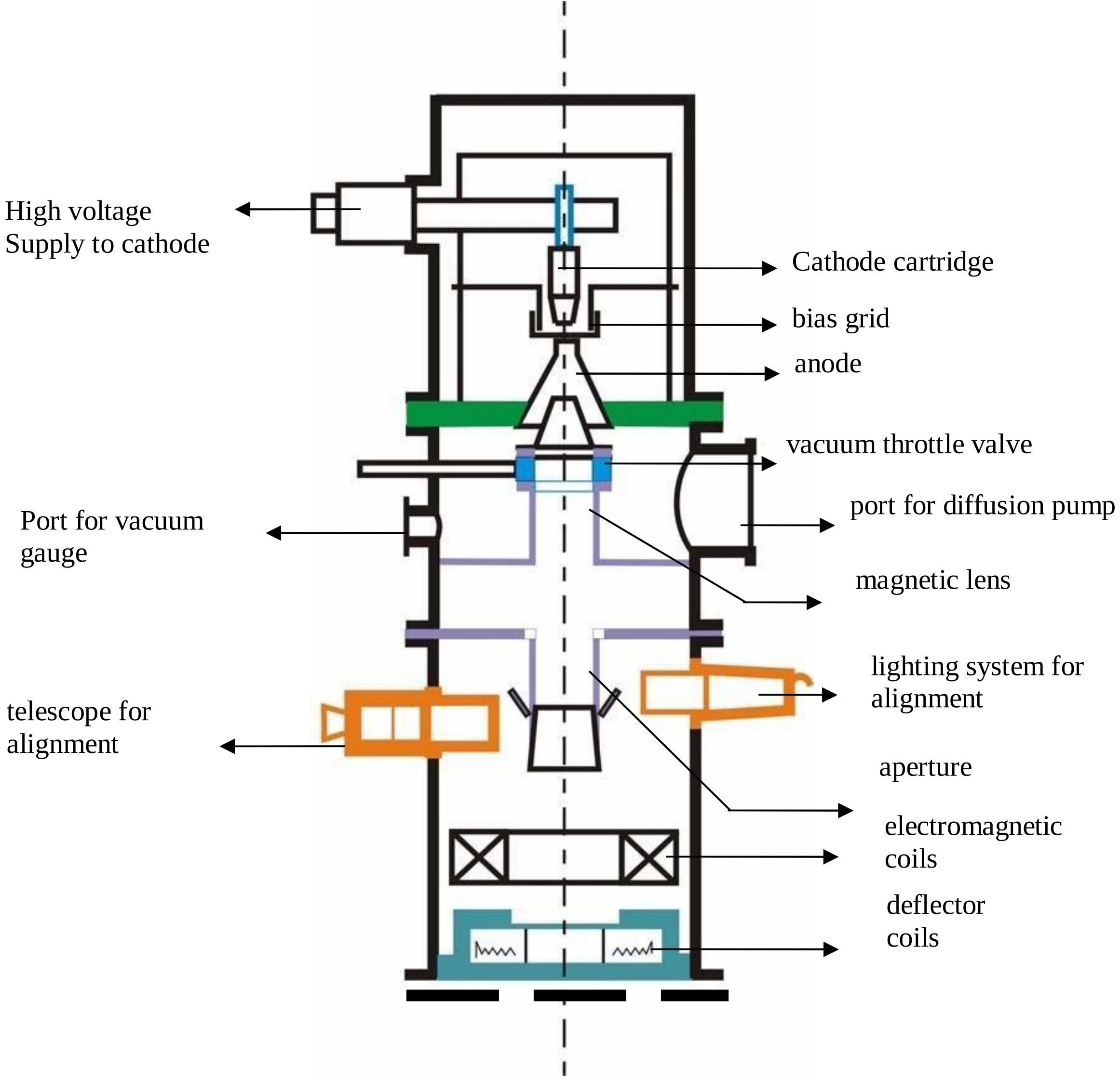


Removal due to high
vapour pressure

Electron Beam Machining – Equipment

Fig. 9.6.3 shows the schematic representation of an electron beam gun, which is the heart of any electron beam machining facility. The basic functions of any electron beam gun are to generate free electrons at the cathode, accelerate them to a sufficiently high velocity and to focus them over a small spot size. Further, the beam needs to be manoeuvred if required by thegun.

The cathode as can be seen in Fig. 9.6.3 is generally made of tungsten or tantalum. Such cathode filaments are heated, often inductively, to a temperature of around 2500^0C. Such heating leads to thermo-ionic emission of electrons, which is further enhanced by maintaining very low vacuum within the chamber of the electron beam gun. Moreover, this cathode cartridge is highly negatively biased so that the thermo-ionic electrons are strongly repelled away form the cathode. This cathode is often in the form of a cartridge so that it can be changed very quickly to reduce down time in case of failure.



Just after the cathode, there is an annular bias grid. A high negative bias is applied to this grid so that the electrons generated by this cathode do not diverge and approach the next element, the annular anode, in the form of a beam. The annular anode now attracts the electron beam and gradually gets accelerated. As they leave the anode section, the electrons may achieve a velocity as high as half the velocity of light.

The nature of biasing just after the cathode controls the flow of electrons and the biased grid is used as a switch to operate the electron beam gun in pulsed mode.

After the anode, the electron beam passes through a series of magnetic lenses and apertures. The magnetic lenses shape the beam and try to reduce the divergence. Apertures on the other hand allow only the convergent electrons to pass and capture the divergent low energy electrons from the fringes. This way, the aperture and the magnetic lenses improve the quality of the electron beam.

Then the electron beam passes through the final section of the electromagnetic lens and deflection coil. The electromagnetic lens focuses the electron beam to a desired spot. The deflection coil can manoeuvre the electron beam, though by small amount, to improve shape of the machined holes.

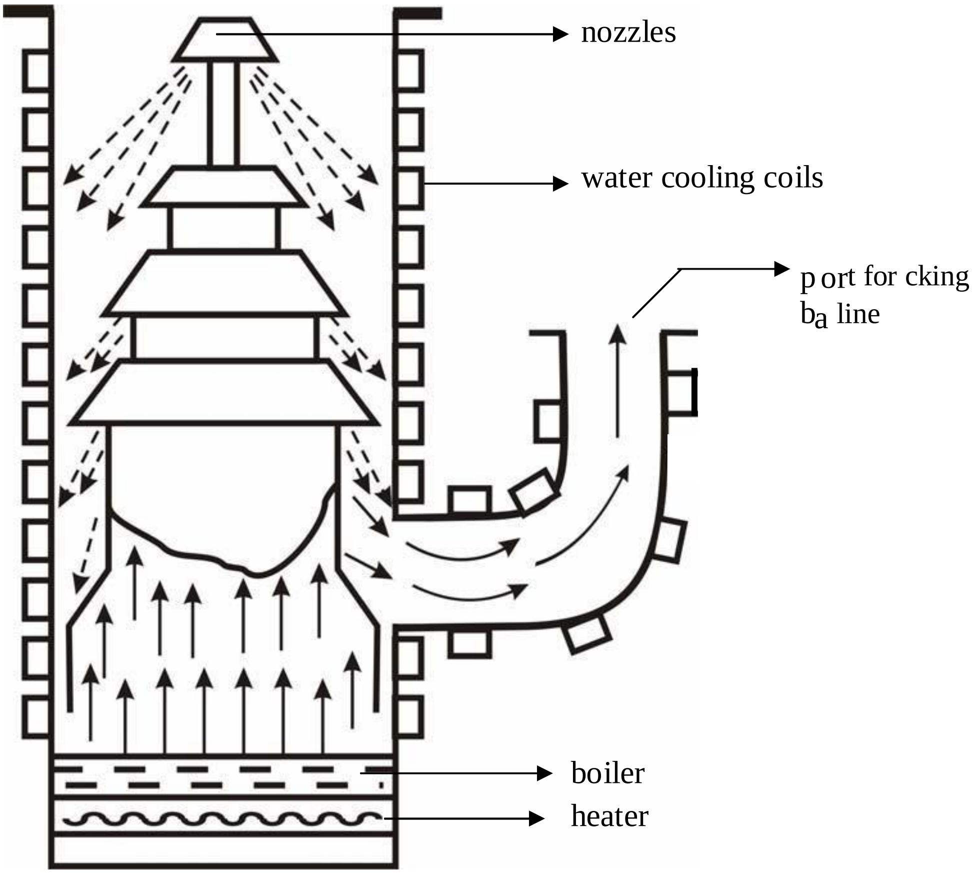
Generally in between the electron beam gun and the workpiece, which is also under vacuum, there would be a series of slotted rotating discs. Such discs allow the electron beam to pass and machine materials but helpfully prevent metal fumes and vapour generated during machining to reach the gun. Thus it is essential to synchronize the motion of the rotating disc and pulsing of the electron beam gun.

Electron beam guns are also provided with illumination facility and a telescope for alignment of the beam with the workpiece.

Workpiece is mounted on a CNC table so that holes of any shape can be machined using the CNC control and beam deflection in-built in the gun.

One of the major requirements of EBM operation of electron beam gun is maintenance of desired vacuum. Level of vacuum within the gun is in the order of 10^{-4} to 10^{-6} Torr. *{1 Torr = 1mm of Hg}* Maintenance of suitable vacuum is essential so that electrons do not lose their energy and a significant life of the cathode cartridge is obtained. Such vacuum is achieved and maintained using a combination of rotary pump and diffusion pump. Diffusion pump, as shown in Fig. is attached to the diffusion pump port of the electron beam gun

Diffusion pump is essentially an oil heater. As the oil is heated the oil vapour rushes upward where gradually converging structure as shown in Fig. 9.6.4 is present. The nozzles change the direction of motion of the oil vapour and the oil vapour starts moving downward at a high velocity as jet. Such high velocity jets of oil vapour entrain any air molecules present within the gun. This oil is evacuated by a rotary pump via the backing line. The oil vapour condenses due to presence of cooling water jacket around the diffusion pump.



Electron Beam Process – Parameters

The process parameters, which directly affect the machining characteristics in Electron Beam Machining, are:

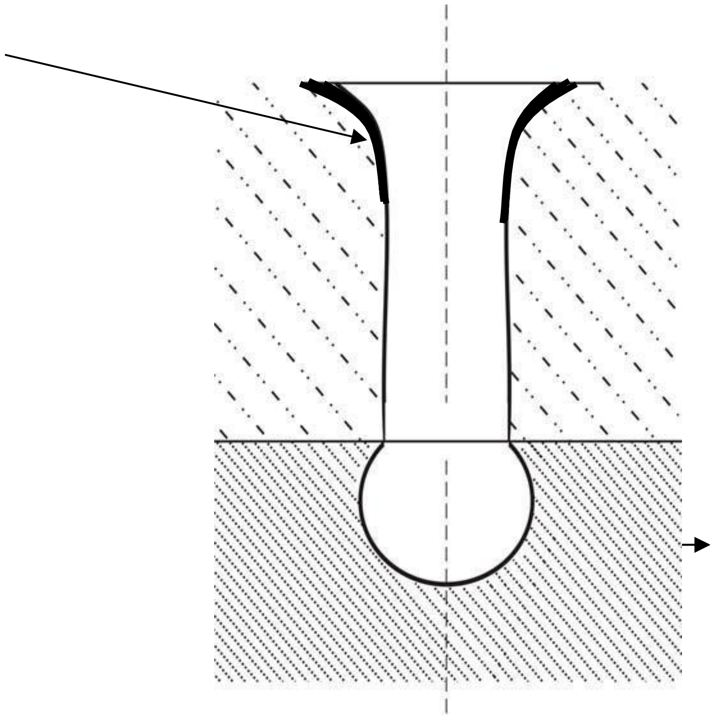
a) The accelerating voltage
b) The beam current
c) Pulse duration
d) Energy per pulse
e) Power per pulse
f) Lens current
g) Spot size
h) Power density

As has already been mentioned in EBM the gun is operated in pulse mode. This is achieved by appropriately biasing the biased grid located just after the cathode. Switching pulses are given to the bias grid so as to achieve pulse duration of as low as 50 μs to as long as 15ms. Beam current is directly related to the number of electrons emitted by the cathode or available in the beam. Beam current once again can be as low as 200 μamp to 1 amp.

Increasing the beam current directly increases the energy per pulse. Similarly increase in pulse duration also enhances energy per pulse. High-energy pulses (in excess of 100 J/pulse) can machine larger holes on thicker plates.

The energy density and power density is governed by energy per pulse duration and spot size. Spot size, on the other hand is controlled by the degree of focusing achieved by the electromagnetic lenses. A higher energy density, i.e., for a lower spot size, the material removal would be faster though the size of the hole would be smaller.

The plane of focusing would be on the surface of the workpiece or just below the surface of the workpiece. This controls the kerf shape or the shape of the hole as schematically shown in Fig. re solidified layer at entry



As has been indicated earlier, the final deflection coil can manoeuvre the electron beam providing holes of non-circular cross-section as required.

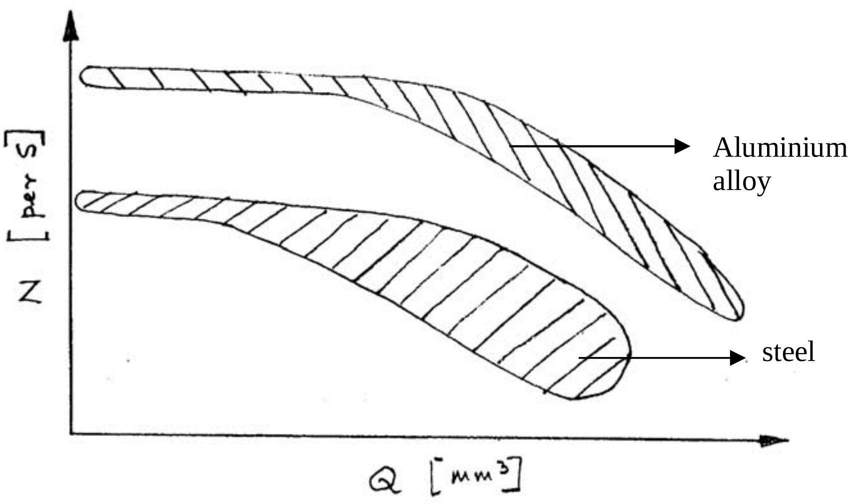
Electron Beam Process Capability

EBM can provide holes of diameter in the range of 100 μm to 2 mm with a depth upto 15 mm, i.e., with a l/d ratio of around 10. Fig. schematically represents a typical hole drilled by electron beam. The hole can be tapered along the depth or barrel shaped. By focusing the beam below the surface a reverse taper can also be obtained. Typically as shown in Fig., there would be an edge rounding at the entry point along with presence of recast layer. Generally burr formation does not occur in EBM.

A wide range of materials such as steel, stainless steel, Ti and Ni super- alloys, aluminum as well as plastics, ceramics, leathers can be machined successfully using electron beam. As the mechanism of material removal is thermal in nature as for example in electro-discharge machining, there would be thermal damages associated with EBM. However, the heat-affected zone is rather narrow due to shorter pulse duration in EBM. Typically the heat-affected zone is around 20 to 30 μm.

Some of the materials like Al and Ti alloys are more readily machined compared to steel. Number of holes drilled per second depends on the hole diameter, power density and depth of the hole as well as material type as mentioned earlier. Fig. 9.6.6 depicts the variation in drilling speed against volume of material removed for steel and Aluminum alloy.

EBM does not apply any cutting force on the workpieces. Thus very simple work holding is required. This enables machining of fragile and brittle materials by EBM. Holes can also be drilled at a very shallow angle of as less as 20 to 30^0.



Electron Beam Machining – Advantages and Limitations

EBM provides very high drilling rates when small holes with large aspect ratio are to be drilled. Moreover it can machine almost any material irrespective of their mechanical properties. As it applies no mechanical cutting force, work holding and fixturing cost is very less. Further for the same reason fragile and brittle materials can also be processed. The heat affected zone in EBM is rather less due to shorter pulses. EBM can provide holes of any shape by combining beam deflection using electromagnetic coils and the CNC table with high accuracy.

However, EBM has its own share of limitations. The primary limitations are the high capital cost of the equipment and necessary regular maintenance applicable for any equipment using vacuum system. Moreover in EBM there is significant amount of non-productive pump down period for attaining desired vacuum. However this can be reduced to some extent using vacuum load locks. Though heat affected zone is rather less in EBM but recast layer formation cannot be avoided.

Laser Beam Machining – Introduction

Laser Beam Machining or more broadly laser material processing deals with machining and material processing like heat treatment, alloying, cladding, sheet metal bending etc. Such processing is carried out utilizing the energy of coherent photons or laser beam, which is mostly converted into thermal energy upon interaction with most of the materials. Nowadays, laser is also finding application in regenerative machining or rapid prototyping as in processes like stereo-lithography, selective laser sintering etc.

Laser stands for light amplification by stimulated emission of radiation. The underline working principle of laser was first put forward by Albert Einstein in 1917 through the first industrial laser for experimentation was developed around1960s.

Laser beam can very easily be focused using optical lenses as their wavelength ranges from half micron to around 70 microns. Focused laser beam as indicated earlier can have power density in excess of 1 MW/mm^2. As laser interacts with the material, the energy of the photon is absorbed by the work material leading to rapid substantial rise in local temperature. This in turn results in melting and vaporisation of the work material and finally material removal.

Laser Beam Machining – the lasing process

Lasing process describes the basic operation of laser, i.e. generation of coherent (both temporal and spatial) beam of light by “light amplification” using “stimulated emission”.

In the model of atom, negatively charged electrons rotate around the positively charged nucleus in some specified orbital paths. The geometry and radii of such orbital paths depend on a variety of parameters like number of electrons, presence of neighboring atoms and their electron structure, presence of electromagnetic field etc. Each of the orbital electrons is associated with unique energy levels. At absolute zero temperature an atom is considered to be at ground level, when all the electrons occupy their respective lowest potential energy. The electrons at ground state can be excited to higher state of energy by absorbing energy form external sources like increase in electronic vibration at elevated temperature, through chemical reaction as well as via absorbing energy of the photon. Fig depicts schematically the absorption of a photon by an electron. The electron moves from a lower energy level to a higher energy level.

On reaching the higher energy level, the electron reaches an unstable energy band. And it comes back to its ground state within a very small time by releasing a photon. This is called spontaneous emission. Schematically the same is shown in Fig.. The spontaneously emitted photon would have the same frequency as that of the “exciting” photon.

Sometimes such change of energy state puts the electrons in a meta-stable energy band. Instead of coming back to its ground state immediately (within tens of ns) it stays at the elevated energy state for micro to milliseconds. In a material, if more number of electrons can be somehow pumped to the higher meta-stable energy state as compared to number of atoms at ground state, then it is called “population inversion”. Such electrons,

Laser-beam machining is a thermal material-removal process that utilizes a high-energy, coherent light beam to melt and vaporize particles on the surface of metallic and non-metallic workpieces. Lasers can be used to cut, drill, weld and mark. LBM is particularly suitable for making accurately placed holes. A schematic of laser beam machining is shown in Figure 12. Different types of lasers are available for manufacturing operations which are as follows:

- CO_2 (pulsed or continuous wave): It is a gas laser that emits light in the infrared region. It can provide up to 25 kW in continuous-wave mode.
- Nd:YAG: Neodymium-doped Yttrium-Aluminum-Garnet ($Y_3Al_5O_{12}$) laser is a solid-state laser which can deliver light through a fibre-optic cable. It can provide up to50kW power in pulsed mode and 1 kW in continuous-wave mode.

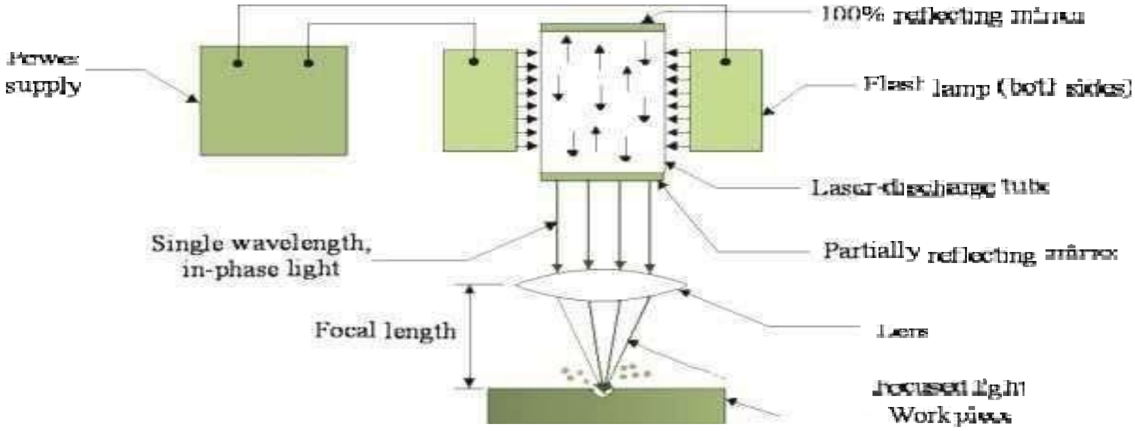


Figure 12: Laser beam machining schematic

Applications

LBM can make very accurate holes as small as 0.005 mm in refractory metals ceramics, and composite material without warping the workpieces. This process is used widely for drilling

Laser beam cutting (drilling)

a) In drilling, energy transferred (e.g., via a Nd:YAG laser) into the workpiece melts the material at the point of contact, which subsequently changes into a plasma and leaves the region.

b) A gas jet (typically, oxygen) can further facilitate this phase transformation and departure of material removed.

c) Laser drilling should be targeted for hard materials and hole geometries that are difficult to achieve with other methods.

A typical SEM micrograph hole drilled by laser beam machining process employed in making a hole is shown in Figure 13.

Figure 13: SEM micrograph hole drilled in 250 micro meter thick Silicon Nitride with 3rd harmonic Nd: YAG laser

Laser beam cutting (milling)

a) A laser spot reflected onto the surface of a workpiece travels along a prescribed trajectory and cuts into the material.

b) Continuous-wave mode (CO_2) gas lasers are very suitable for laser cutting providing high-average power, yielding high material-removal rates, and smooth cutting surfaces.

Advantage of laser cutting

a) No limit to cutting path as the laser point can move any path.

b) The process is stress less allowing very fragile materials to be laser cut without any support.

c) Very hard and abrasive material can be cut.

d) Sticky materials are also can be cut by this process.

e) It is a cost effective and flexible process.

f) High accuracy parts can be machined.
g) No cutting lubricants required
h) No tool wear
i) Narrow heat effected zone

Limitations of laser cutting

a) Uneconomic on high volumes compared to stamping
b) Limitations on thickness due to taper
c) High capital cost
d) High maintenance cost
e) Assist or cover gas required

ELECTRON BEAM MACHINING (EBM)

INTRODUCTION

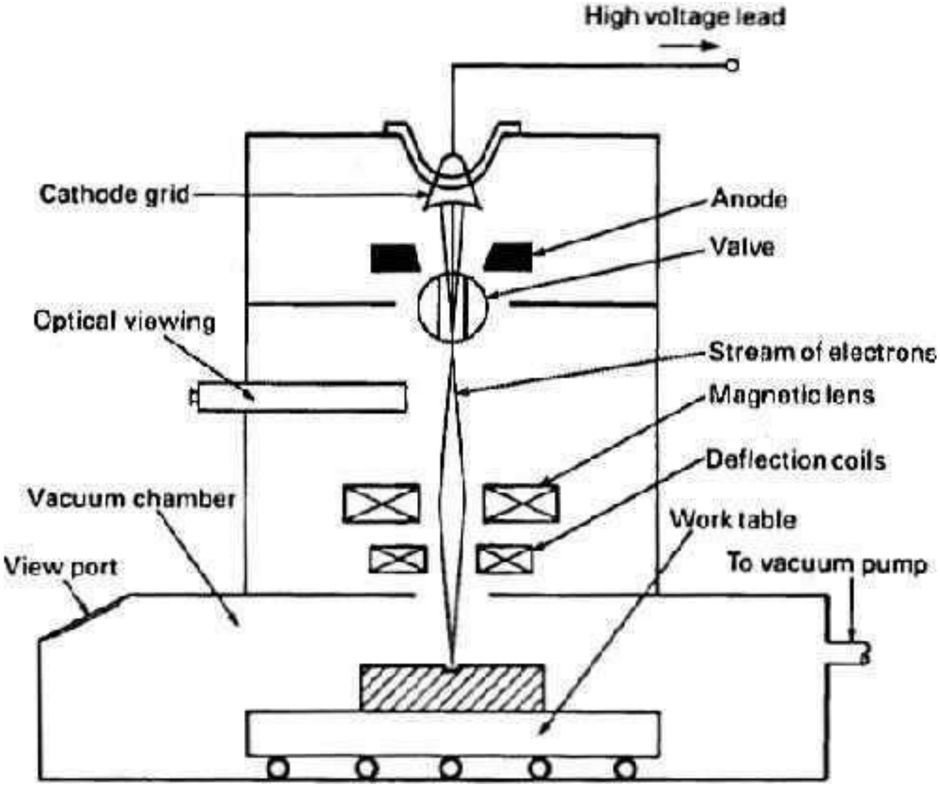
As has already been mentioned in EBM the gun is operated in pulse mode. This is achieved by appropriately biasing the biased grid located just after the cathode. Switching pulses are given to the bias grid so as to achieve pulse duration of as low as 50 μs to as long as 15 ms. Beam current is directly related to the number of electrons emitted by the cathode or available in the beam. Beam current once again can be as low as 200 μamp to 1 amp. Increasing the beam current directly increases the energy per pulse. Similarly increase in pulse duration also enhances energy per pulse. High-energy pulses (in excess of 100 J/pulse) can machine larger holes on thicker plates. The energy density and power density is governed by energy per pulse duration and spot size. Spot size, on the other hand is controlled by the degree of focusing achieved by the electromagnetic lenses. A higher energy density, i.e., for a lower spot size, the material removal would be faster though the size of the hole would be smaller. The plane of focusing would be on the surface of the work piece or just below the surface of the work piece.

a) Electrons generated in a vacuum chamber
b) Similar to cathode ray tube
c) 10^{-4} torr
d) Electron gun
e) Cathode - tungsten filament at 2500 – 3000degC
f) Emission current – between 25 and 100mA (a measure of electron beamdensity)

MRR:

In the region where the beam of electrons meets the workpiece, their energy is converted into heat workpiece surface is melted by a combination of electron pressure and surface tension Melted liquid is rapidly ejected and vaporized to effect material removal temperature of the workpiece specimen outside the region being machined is reduced by pulsing the electron beam (10kHz or less)

Material	Volumetric removal rate (mm^3s^{-1})
Tungsten	1.5
Aluminum	3.9



ADVANTAGES OF EBM:

Large depth-to-width ratio of material penetrated by the beam with applications of very fine hole drilling becoming feasible. There is a minimum number of pulses n_e associated with an optimum accelerating voltage. In practice the number of pulses to produce a given hole depth is usually found to decrease with increase in accelerating voltage.

PLASMA ARC MACHINING (PAM)

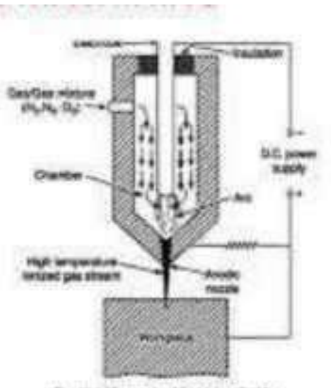


Fig. 22.8 Plasma Arc Machining (PAM)

Introduction:

The plasma welding process was introduced to the welding industry in 1964 as a method of bringing better control to the arc welding process in lower current ranges. Today, plasma retains the original advantages it brought to industry by providing an advanced level of control and accuracy to produce high quality welds in miniature or precision applications and to provide long electrode life for high production requirements.

The plasma process is equally suited to manual and automatic applications. It has been used in a variety of operations ranging from high volume welding of strip metal, to precision welding of surgical instruments, to automatic repair of jet engine blades, to the manual welding of kitchen equipment for the food and dairy industry.

Plasma Arc welding (PAW):

Plasma arc welding (PAW) is a process of joining of metals, produced by heating with a constricted arc between an electrode and the work piece (transfer arc) or the electrode and the constricting nozzle (non transfer arc). Shielding is obtained from the hot ionized gas issuing from the orifice, which may be supplemented by an auxiliary source of shielding gas.

Transferred arc process produces plasma jet of high energy density and may be used for high speed welding and cutting of Ceramics, steels, Aluminum alloys, Copper alloys, Titanium alloys, Nickel alloys.

Non-transferred arc process produces plasma of relatively low energy density. It is used for welding of various metals and for plasma spraying (coating). Equipment:

a) Power source. A constant current drooping characteristic power source supplying the dc welding current is required. It should have an open circuit voltage of 80 volts and have a duty cycle of 60 percent.

b) Welding torch. The welding torch for plasma arc welding is similar in appearance to a gas tungsten arc torch but it is more complex.

i. All plasma torches are water cooled, even the lowest-current range torch. This is because the arc is contained inside a chamber in the torch where it generates considerable heat. During the non-transferred period, the arc will be struck between the nozzle or tip with the orifice and the tungsten electrode.

ii. The torch utilizes the 2 percent thoriated tungsten electrode similar to that used for gas tungsten welding.

c) Control console. A control console is required for plasma arc welding. The plasma arc torches are designed to connect to the control console rather than the power source. The console include a power source for the pilot arc, delay timing systems for transferring from the pilot arc to the transferred arc, and water and gas valves and separate flow meters for the plasma gas and the shielding gas. The console is usually connected to the power source. The high-frequency generator is used to initiate the pilot arc.

Principles of Operation:

a) The plasma arc welding process is normally compared to the gas tungsten arc process. But in the TIG-process, the arc is burning free and unchanneled, whereas in the plasma-arc system, the arc is necked by an additional water-cooled plasma-nozzle. A plasma gas – almost always 100 % argon –flows between the tungsten electrode and the plasma nozzle.

b) The welding process involves heating a gas called plasma to an extremely high temperature and then ionizing it such that it becomes electrically conductive. The plasma is used to transfer an electric arc called pilot arc to a work piece which burns between the tungsten electrode and the plasma nozzle. By forcing the plasma gas and arc through a constricted orifice the metal, which is to be welded is melted by the extreme heat of the arc. The weld pool is protected by the shielding gas, flowing between the outer shielding gas nozzle and the plasma nozzle. As shielding gas pure argon-rich gas-mixtures with hydrogen or helium are used.

c) The high temperature of the plasma or constricted arc and the high velocity plasma jet provide an increased heat transfer rate over gas tungsten arc welding when using the same current.

d) This results in faster welding speeds and deeper weld penetration. This method of operation is used for welding extremely thin material and for welding multi pass groove and welds and fillet welds.

Uses & Applications:

Plasma arc welding machine is used for several purposes and in various fields. The common application areas of the machine are:

a) Single runs autogenous and multi-run circumferential pipe welding.

b) In tube mill applications.

c) Welding cryogenic, aerospace and high temperature corrosion resistant alloys.

d) Nuclear submarine pipe system (non-nuclear sections, subassemblies).

e) Welding steel rocket motor cases.

f) Welding of stainless steel tubes (thickness 2.6 to 6.3mm).

g) Welding of carbon steel, stainless steel, nickel, copper, brass, monel, inconel, aluminum, titanium, etc.

h) Welding titanium plates up to 8 mm thickness.

i) Welding nickel and high nickel alloys.

j) or melting, high melting point metals.

k) Plasma torch can be applied to spraying, welding and cutting of difficult to cut metals and alloys.

Plasma Arc Machining (PAM):

Plasma-arc machining (PAM) employs a high-velocity jet of high-temperature gas to melt and displace material in its path called PAM, this is a method of cutting metal with a plasma-arc, or tungsten inert-gas-arc, torch. The torch produces a high velocity jet of high-temperature ionized gas called plasma that cuts by melting and removing material from the work piece.

Temperaturesintheplasmazonerangefrom20,000°to50,000°F(11,000°to28,000°C). It is used as an alternative to oxy fuel-gas cutting, employing an electric arc at very high temperatures to melt and vaporize the metal. Equipment:

A plasma arc cutting torch has four components:

a) The electrode carries the negative charge from the power supply.

b) The swirl ring spins the plasma gas to create a swirling flow pattern.

c) The nozzle constricts the gas flow and increases the arc energy density.

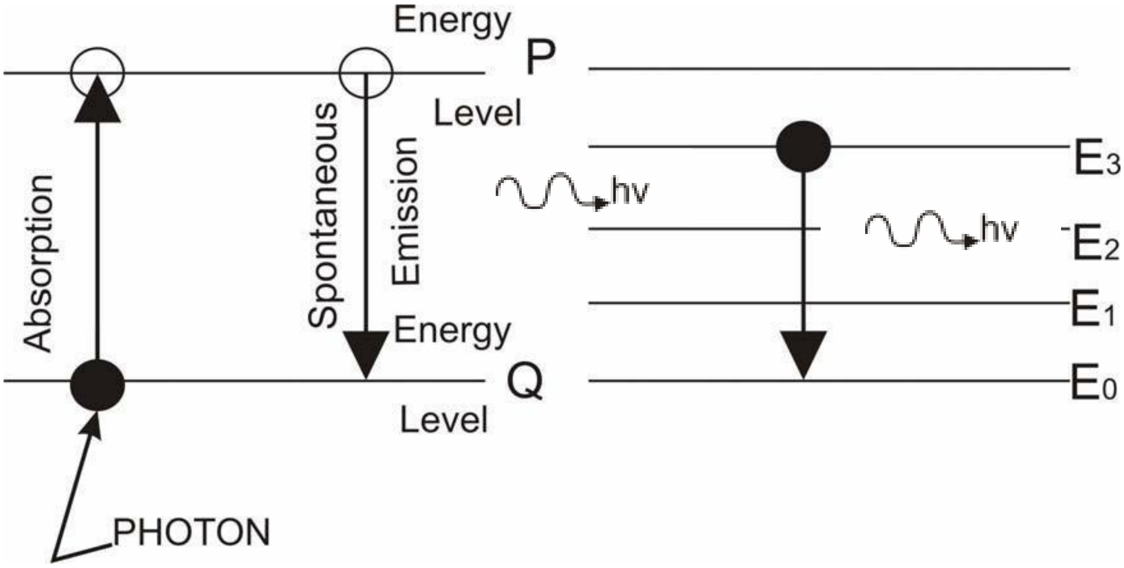
d) The shield channels the flow of shielding gas and protects the nozzle from metal spatter.

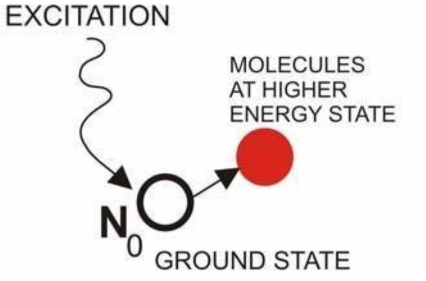
Principle of operation:

PAM is a thermal cutting process that uses a constricted jet of high-temperature plasma gas to melt and separate metal. The plasma arc is formed between a negatively charged electrode inside the torch and a positively charged work piece. Heat from the transferred arc rapidly melts the metal, and the high-velocity gas jet expels the molten material from the cut.

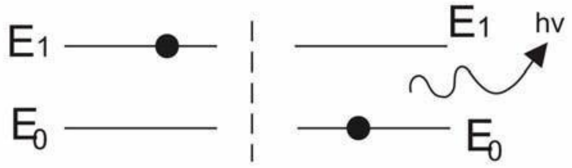
The materials cut by PAM are generally those that are difficult to cut by any other means, such as stainless steels and aluminum alloys. It has an accuracy of about 0.008".

In the latest field of technology respect to welding and machining, plasma arc welding and machining have a huge success. Due to its improved weld quality and increased weld output it is been used for precision welding of surgical instruments, to automatic repair of jet engine blades to the manual welding for repair of components in the tool, die and mold industry. But due to its high equipment expense and high production of ozone, it’s been outnumbered by other advance welding equipment like laser beam welding and electro beam welding. To overcome the mentioned problem, it is been expected that soon it will fetch with its minimum cons.

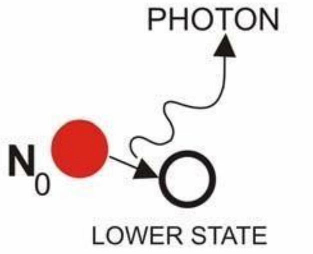




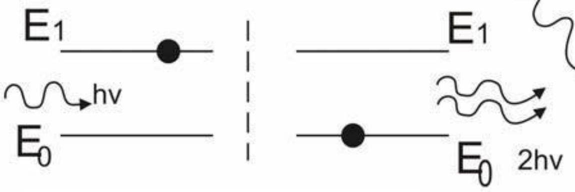
Stimulated absorption



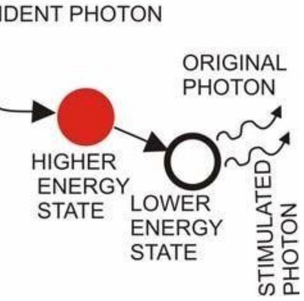
Spontaneous emission



POPULATION INVERSION

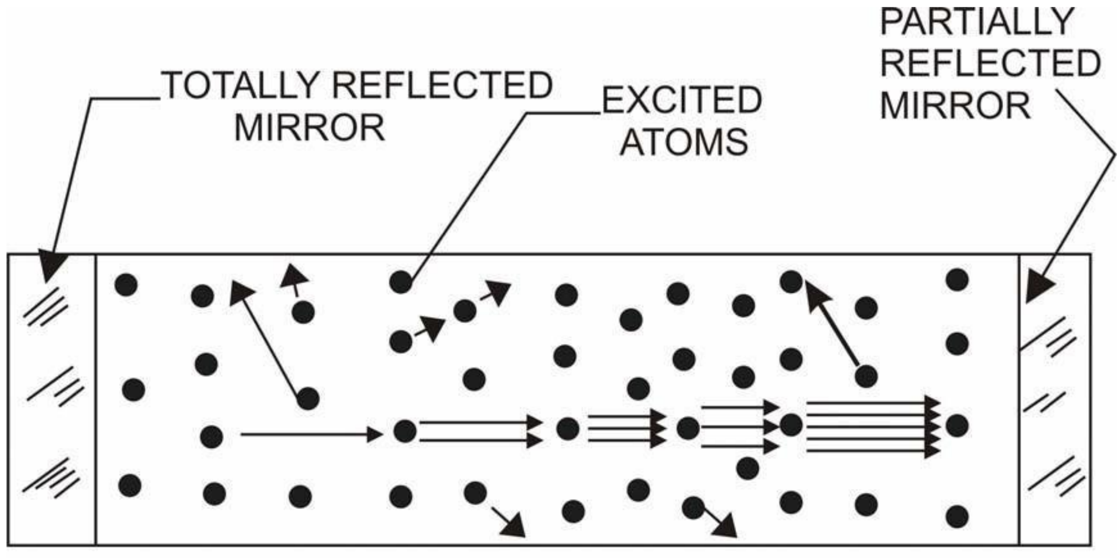


Stimulated emission



at higher energy meta-stable state, can return to the ground state in the form of an avalanche provided stimulated by a photon of suitable frequency or energy. This is called stimulated emission. Fig. shows one such higher state electron in meta-stable orbit. If it is stimulated by a photon of suitable energy then the electron will come down to the lower energy state and in turn one original photon, another emitted photon by stimulation having some temporal and spatial phase would be available. In this way coherent laser beam can be produced.

Fig schematically shows working of a laser. There is a gas in a cylindrical glass vessel. This gas is called the lasing medium. One end of the glass is blocked with a 100% reflective mirror and the other end is having a partially reflective mirror. Population inversion can be carried out by exciting the gas atoms or molecules by pumping it with flash lamps. Then stimulated emission would initiate lasing action. Stimulated emission of photons could be in all directions. Most of the stimulated photons, not along the longitudinal direction would be lost and generate waste heat. The photons in the longitudinal direction would form coherent, highly directional, intense laser beam.



Lasing Medium

Many materials can be used as the heart of the laser. Depending on the lasing medium lasers are classified as solid state and gas laser. Solid-state lasers are commonly of the following type

a)Ruby which is a chromium – alumina alloy having a wavelength of0.7□ m

b) Nd-glass lasers having a wavelength of 1.64□ m

c)Nd-YAG laser having a wavelength of 1.06 □ m these solid-state lasers are generally used in material processing.

The generally used gas lasers are

a) Helium –Neon
b) Argon
c) CO_2etc.

Lasers can be operated in continuous mode or pulsed mode. Typically CO_2 gas laser is operated in continuous mode and Nd – YAG laser is operated in pulsed mode.

Laser Construction

Fig shows a typical Nd-YAG laser. Nd-YAG laser is pumped using flash tube. Flash tubes can be helical, as shown in Fig., or they can be flat. Typically the lasing material is at the focal plane of the flash tube. Though helical flash tubes provide better pumping, they are difficult to maintain.

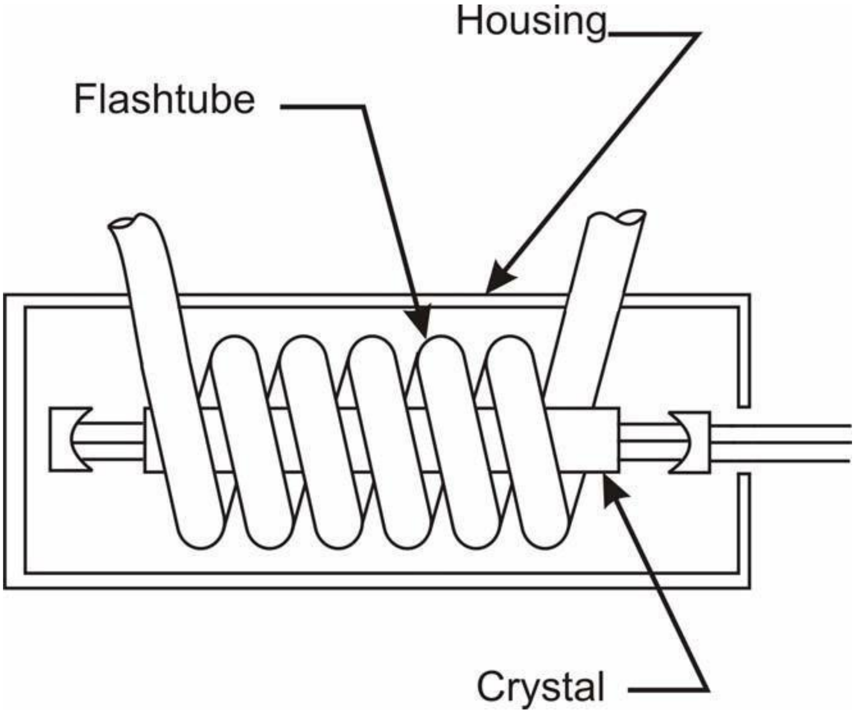


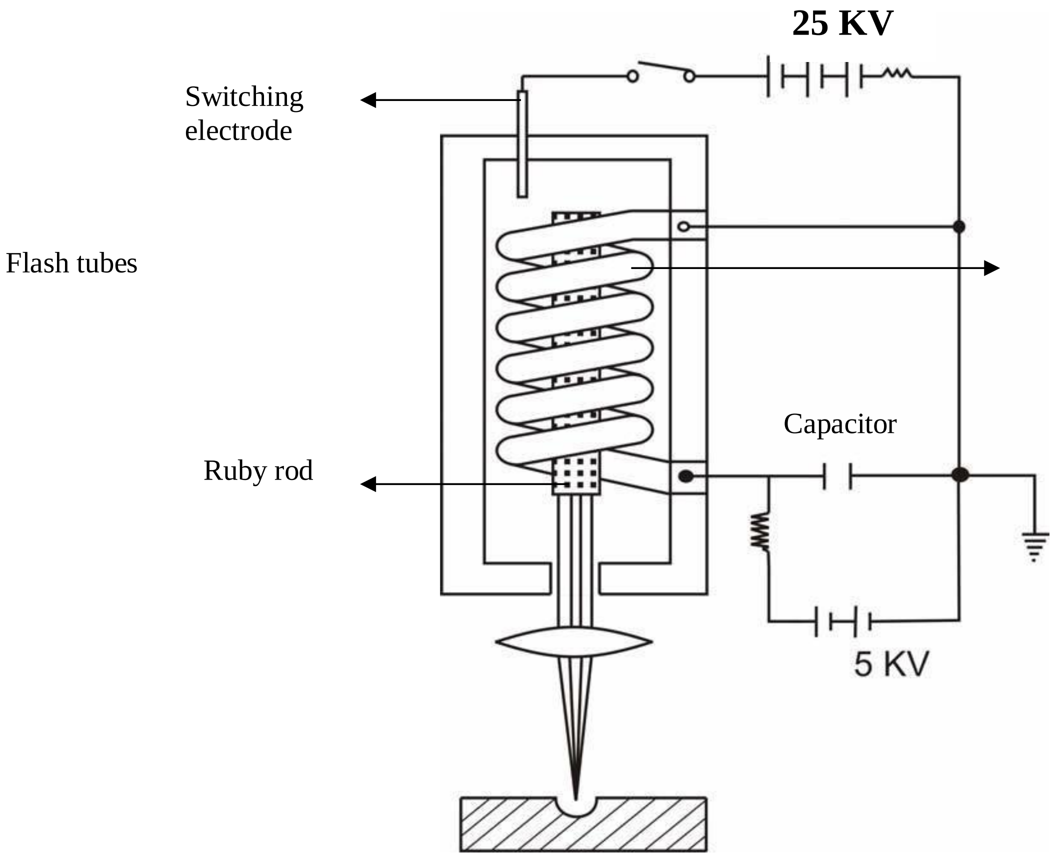
Fig shows the electrical circuit for operation of a solid-state laser. The flash tube is operated in pulsed mode by charging and discharging of the capacitor. Thus the pulse on time is decided by the resistance on the flash tube side and pulse off time is decided by the charging resistance. There is also a high voltage switching supply for initiation of pulses.

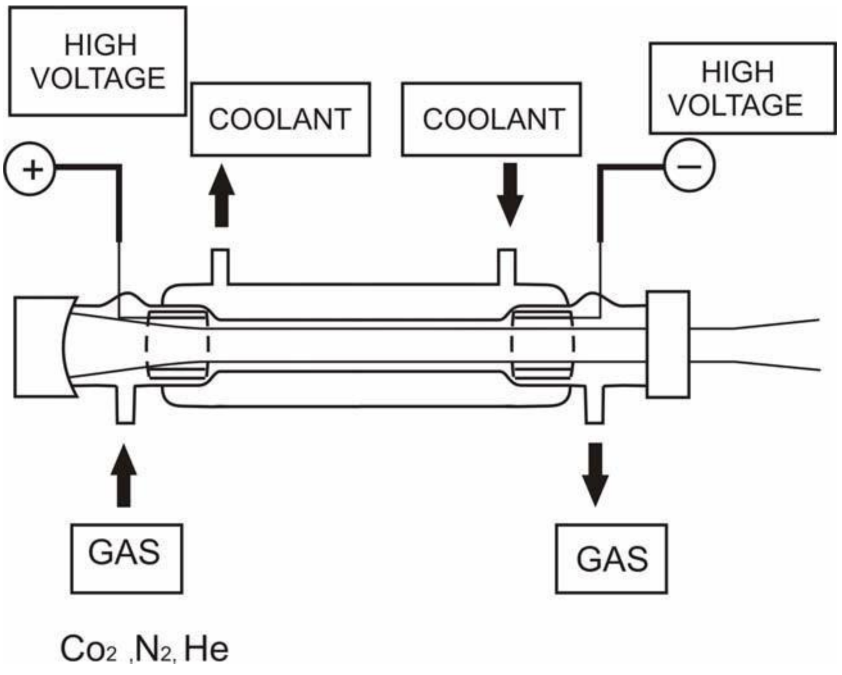
Fig shows a CO_2 laser. Gas lasers can be axial flow, as shown in Fig, transverse flow and folded axial flow as shown in Fig.. The power of a CO_2laser is typically around 100 Watt per meter of tube length. Thus to make a high power laser, a rather long tube is required which is quite inconvenient. For optimal use of floor space, high- powered CO_2 lasers are made of folded design.

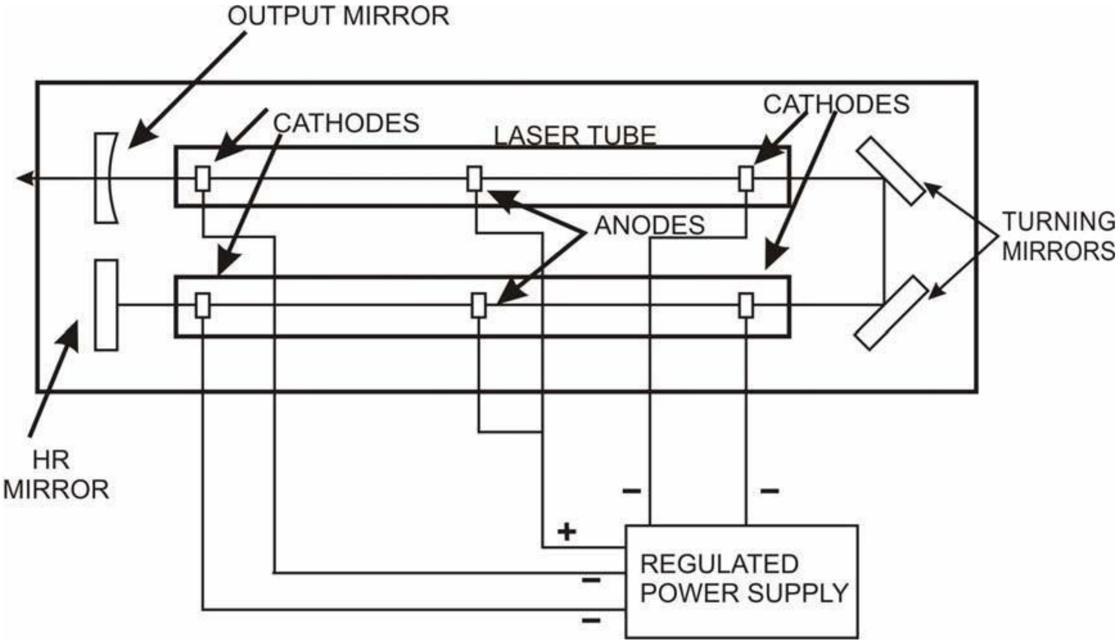
In a CO_2 laser, a mixture of CO_2, N_2 and He continuously circulate through the gas tube. Such continuous recirculation of gas is done to minimize consumption of gases. CO_2 acts as the main lasing medium whereas Nitrogen helps in sustaining the gas plasma. Helium on the other hand helps in cooling the gases.

As shown in Fig high voltage is applied at the two ends leading to discharge and formation of gas plasma. Energy of this discharge leads to population inversion and lasing action. At the two ends of the laser we have one 100% reflector and one partial reflector. The 100% reflector redirects the photons inside the gas tube and partial reflector allows a part of the laser beam to be issued so that the same can be used for material processing. Typically the laser tube is cooled externally as well.

As had been indicated earlier CO_2 lasers are folded to achieve high power. Fig shows a similar folded axial flow laser. In folded laser there would be a few 100% reflective turning mirrors for manoeuvring the laser beam from gas supply as well as high voltage supply as shown in Fig.


25 KV
Switching electrode
Flash tubes
Capacitor
Ruby rod
5 KV


HIGH VOLTAGE
COOLANT
COOLANT
HIGH VOLTAGE
+
−
GAS
GAS
Co2 ,N2, He


OUTPUT MIRROR
CATHODES
LASER TUBE
CATHODES
ANODES
TURNING
MIRRORS
HR
MIRROR
+
–
–
–
–
REGULATED
POWER SUPPLY

Application	Type of laser
Large holes upto 1.5 mm dia. Large holes (trepanned) Small holes > 0.25 mm dia. Drilling (punching or percussion)	Ruby, Nd-glass, Nd-YAG Nd-YAG, CO_2 Ruby, Nd-glass, Nd-YAG Nd-YAG, Ruby
Thick cutting Thin slitting of metals Thin slitting of plastics	CO_2 with gas assist Nd-YAG CO_2
Plastics Metals Organics, Non-metal Ceramics	CO_2 Nd-YAG, ruby, Nd-glass Pulsed CO_2 Pulsed CO_2, Nd-YAG

Lasing materials	Ruby	**Nd-YAG**	Nd-glass	**CO_2**
Type	Solid state	**Solid state**	Solid state	**Gas**
Composition	0.03 – 0.7% Nd in Al_3O_2	**1% Nd doped Yttrium – Aluminium-Garnet**	2-6% Nd in glass	**CO_2+He+N_2(3:8:4)**
Wavelength (radiation)	0.69 μm	**1.064 μm**	1.064 μm	**10.6 μm**
Efficiency	1% max.	**2%**	2%	**10-15%**
Beam mode	Pulsed or CW	**Pulsed or CW**	Pulsed	**Pulsed or CW**
Spot size	0.015 mm	**0.015 mm**	0.025 mm	**0.075 mm**
Pulse repetition rate (normal operation).	1-10 pps	**1-300 pps or CW**	1-3 pps	**CW**
Beam output	10-100 W	**10-1000 W**	10 – 100 W	**0.1 – 10 kW**
Peak power	200 kW	**400 kW**	200 kW	**100 kW**

Laser Beam Machining – Application

Laser can be used in wide range of manufacturing applications

a) Material removal – drilling, cutting and tre-panning
b) Welding
c) Cladding
d) Alloying

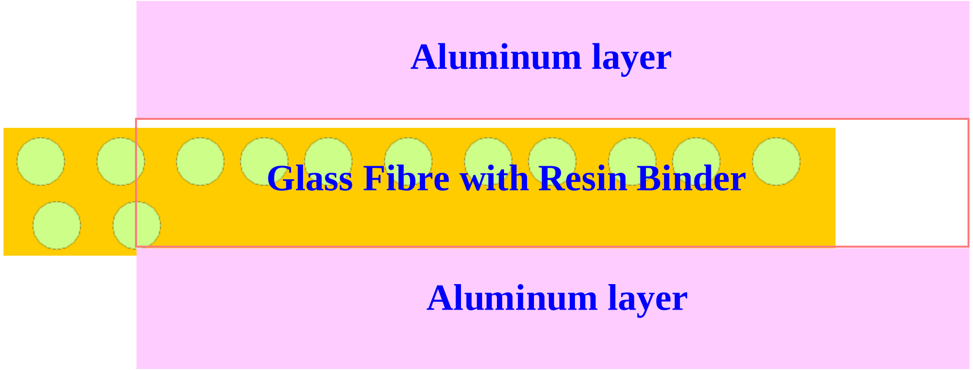
Drilling micro-sized holes using laser in difficult – to – machine materials is the most dominant application in industry. In laser drilling the laser beam is focused over the desired spot size. For thin sheets pulse laser can be used. For thicker ones continuous laser may be used.

Laser Beam Machining – Advantages

a) In laser machining there is no physical tool. Thus no machining force or wear of the tool takes place.
b) Large aspect ratio in laser drilling can be achieved along with acceptable accuracy or dimension, form or location
c) Micro-holes can be drilled in difficult – to – machine materials
d) Though laser processing is a thermal processing but heat affected zone specially in pulse laser processing is not very significant due to shorter pulse duration.

Laser Beam Machining – Limitations

a) High initial capital cost
b) High maintenance cost
c) Not very efficient process
d) Presence of Heat Affected Zone – specially in gas assist CO_2 laser cutting
e) Thermal process – not suitable for heat sensitive materials like aluminum glass fibre laminate as shown in Fig.



Comparative Analysis of Non-Traditional Machining Processes

A particular Non-Traditional Machining Process (NTMP) found suitable under the given conditions may not be equally efficient under other conditions. Therefore, a careful selection of the process for a given machining problem is essential. The analysis of NTMPs can be made from the point of view of the following (Singh 2007):

a) Physical parameters involved in the processes.
b) Capability of machining different shapes of work material.
c) Applicability of different processes to various types of materials, e.g. metals, alloys, and non-metals.
d) Operational characteristics of NTMPs, and Economics involved in the various processes.

Physical Parameters

The physical parameters of NTMPs have a direct impact on the metal removal as well as on the energy consumed in different processes and it is shown in Table

Capability to Shape

The capability of different processes can be analysed on the basis of various machining operation point of view such as micro-drilling, drilling, cavity sinking, pocketing (shallow and deep), contouring a surface, and through cutting (shallow and deep). The shape application of various NTMPs is shown in Table.

For micro-drilling operation, the only process which has good capability to drill is LBM, whereas for drilling shapes having slenderness ratio, L/D< 20, the process USM, ECM, and EDM will be most suitable. EDM and ECM processes have good capacity to make pocketing operation (shallow and deep). For surface contouring operation, ECM is most suitable but other processes except EDM have no application for this operation.

Table Classification of NTMPs (Singh 2007)

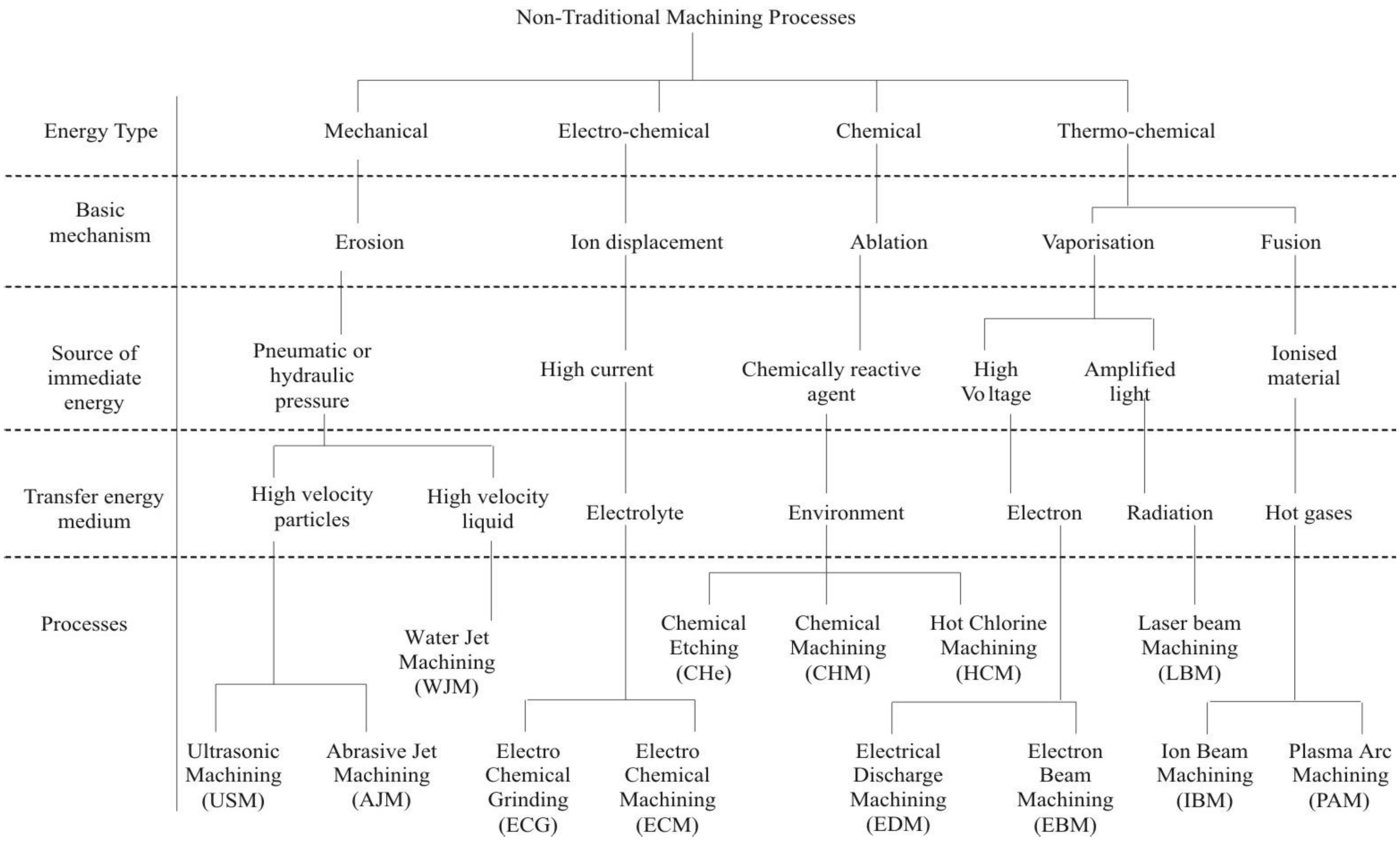


Table Physical parameters of NTMPs (Singh 2007)

Parameters	**USM**	**AJM**	**ECM**	**CHM**	**EDM**	**EBM**	**LBM**	**PAM**
Potential (V)	220	220	10	-	45	1,50,000	4,500	100
Current (Amp)	12 (AC)	1.0	10,000 (D.C)	-	50 (Pulsed D.C)	0.001 (Pulsed D.C)	2 (Average) 200 (Peak)	500 (D.C)
Power (W)	2,400	220	1,00,000	-	2,700	150	-	50,000
Gap (mm)	0.25	0.75	0.20	-	0.025	100	150	7.5
Medium	Abrasive in water	Abrasive in gas	Electrolyte	Liquid chemical	Liquid dielectric	Vacuum	Air	Argon or Hydrogen

Table Shape Application of NTMPs (Mishra 1997)

	Holes				**Through cavities**		**Surfacing**		**Through cutting**	
Process	**Precision small holes**		**Standard**		**Precision**	**Standard**	**Double contouring**	**Surface of revolution**	**Shallow**	**Deep**
	Dia <.025 mm	**Dia >.025 mm**	**L/D <20**	**L/D >20**						
USM	-	-	good	poor	good	good	poor	-	poor	-
AJM	-	-	fair	poor	poor	fair	-	-	good	-
ECM	-	-	good	good	fair	good	good	fair	good	good
CHM	fair	fair	-	-	poor	fair	-	-	good	-
EDM	-	-	good	fair	good	good	fair	-	poor	-
EBM	good	good	fair	poor	poor	poor	-	-	-	-
LBM	good	good	fair	poor	poor	poor	-	-	good	fair
PAM	-	-	fair	-	poor	poor	-	poor	good	good

Table Material Applications for Metals and Alloys (Cogun 1994)

Process	Aluminium	Steel	Super alloy	Titanium	Refractory Material
USM	poor	fair	poor	fair	good
AJM	fair	fair	good	fair	good
ECM	fair	good	good	fair	fair
CHM	good	good	fair	fair	poor
EDM	fair	good	good	good	good
EBM	fair	fair	fair	fair	good
LBM	fair	fair	fair	fair	poor
PAM	good	good	good	fair	poor

Table Material Applications for Non-metals (Cogun 1994)

Process	Ceramics	Plastic	Glass
USM	good	fair	good
AJM	good	fair	good
ECM	NA	NA	NA
CHM	poor	poor	fair
EDM	NA	NA	NA
EBM	good	fair	fair
LBM	good	fair	fair
PAM	NA	NA	NA

NA – Not Applicable

Machining Characteristics

The machining characteristics of different NTMPs can be analysed with respect to:

- a) Metal removal rate(MRR),
- b) Tolerance maintained,
- c) Surface finish obtained,
- d) Depth of surface damage, and
- e) Power required for machining.

The metal removal rates by ECM and PAM are respectively one- fourth and 1.25 times that of conventional rates whereas others are only a small fraction of it. Power requirement of ECM and PAM is also very high when compared with other NTMPs. The surface finish and tolerance obtained by various NTMPs except that of PAM is satisfactory. The process capabilities of various NTMPs are summarized in Table (ElHofy 2005).

Table Process Capabilities of NTMPs (El Hofy 2005)

Process	**MRR (mm^3/min)**	**Tolerance (µm)**	**Surface finish (µm)**	**Depth of surface damage (µm)**	**Power (watts)**
USM	300	7.5	0.2 – 0.5	25	2,400
AJM	0.8	50	0.5 – 1.2	2.5	250
ECM	15,000	50	0.1 – 2.5	5.0	1,00,000
CHM	15	50	0.5 – 2.5	50	-
EDM	800	15	0.2 – 1.2	125	2,700
EBM	1.6	25	0.5 – 2.5	250	150(average) 2,000 (peak)
LBM	0.1	25	0.5 – 1.2	125	2 (average)
PAM	75,000	125	Rough	500	50,000

Economics of the Non-Traditional Machining Processes

The economics of the various NTMPs are analyzed on the basis of the following factors and is given in Table 2.7:

a) Capital cost,
b) Tooling cost,
c) Power consumption cost,
d) Material removal rate efficiency, and
e) Tool wear.

Table Economics of the various NTMPs (Yurdakul et al 2003)

Process	**Capital cost**	**Tooling cost**	**Power consumption cost**	**Material removal rate efficiency**	**Tool wear**
USM	low	low	low	high	medium
AJM	very low	low	low	high	low
ECM	very high	medium	medium	low	very low
CHM	medium	low	high*	medium	very low
EDM	medium	high	low	high	high
EBM	high	low	low	very high	very low
LBM	low	low	very low	very high	very low
PAM	very low	low	very low	very low	very low

* indicates cost of chemicals

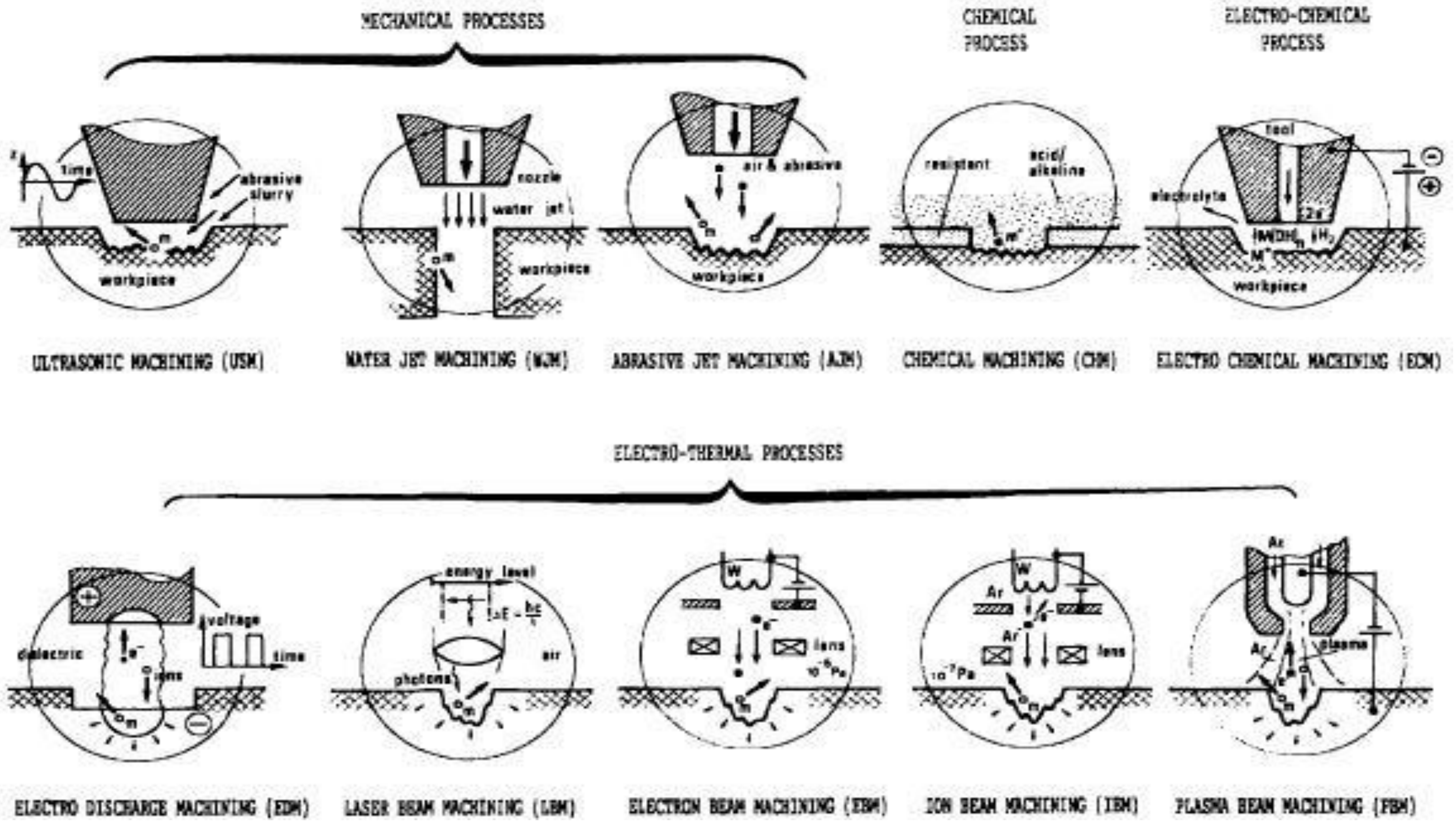
The capital cost of ECM is very high, whereas capital costs for AJM and PAM are comparatively low. EDM has got higher tooling cost than other machining processes. Power consumption is very low for PAM and LBM processes, whereas it is greater in the case of ECM. The material removal rate efficiency is very high for EBM and LBM than for other processes. In conclusion, the suitability of application of any of the processes is dependent on various factors and must be considered, all or some of them, before selecting any NTMPs.

Overview Of Non-Traditional And Hybrid Non-Traditional Machining Processes

Non-Traditional Machining Processes (NTMPs) are defined as a group of processes that remove excess material by various techniques involving mechanical, thermal, electrical or chemical energy, or combinations of these energies but do not use sharp cutting tools as it needs to be used for traditional machining processes (Bhattacharya 1973). Extremely hard and brittle materials are difficult to machine by traditional machining processes such as turning, drilling, shaping, and milling. NTMPs are employed where traditional machining processes are not feasible, satisfactory, or economical due to special reasons as outlined below (Kalpakjian et al2006):

a) Machinability of work piece material,
b) Workpiece shape complexity,
c) Automation of data communication,
d) Surface integrity and precision requirements, and
e) Miniaturization requirements.

The various techniques may be conveniently classified according to the appearance of the applied energy, as shown in Figure 2.1 (Snoeys et al 1986).



ULTRASONIC MACHINING (USM)

WATER JET MACHINING (WJM)

ABRASIVE JET MACHINING (AJM)

CHEMICAL MACHINING (CHM)

ELECTRO CHEMICAL MACHINING (ECM)

ELECTRO DISCHARGE MACHINING (EDM)

LASER BEAM MACHINING (LBM)

ELECTRON BEAM MACHINING (EBM)

ION BEAM MACHINING (IBM)

PLASMA BEAM MACHINING (PBM)

Figure Models of various NTMPs (Snoeys et al 1986)

Machinability

In modern manufacturing practice a more frequent use of harder, tougher or stronger workpiece materials is noticed: Materials, in other words, which are much more difficult to machine with traditional methods. Reference is made to all kinds of high strength thermal resistant alloys, to various kinds of carbides; fiber reinforced composite materials, stellites, ceramic materials, various modern composite tool materials etc. The introduction of new ways of machining is stimulated because of the high force levels observed. In some particular cases, those levels may simply not be sustained by the workpiece. Therefore, more attention is directed towards machining processes in which mechanical properties of the workpiece (mechanical strength, hardness, toughness etc.) are not imposing any limits. In electro-physical processes the ‘cutability’ limits are indeed more associated with material properties such as thermal conductivity, melting temperature, electrical resistivity, and atomic valence (Snoeys et al1986).

Shape Complexity

Geometrical restrictions, design requirements, problems related to accessibility during machining or what could be conveniently defined as 'shape complexity', states another group of reasons for an increased interest in using one of the more recent material removal processes. To give a rather simple example: it is quite easy to drill a circular hole with conventional techniques, however, to drill a square hole or just any other shape would be impossible. For EDM or ECM on the contrary, the cross sectional shape of the hole is of little concern. To cut some pattern of grooves with a depth of a few microns would be a difficult task in conventional machining. A CHM operation using some kind of masking procedure could yield a simple solution (Snoeys et al1986).

Automated Data Transmission

In mechanical production, the automation of communication is crucial. If the information flow is more automated, a considerable reduction of the throughput time can be achieved, yielding decreased production cost, reduced inventory etc. This aspect has been one of the reasons of the considerable success of the introduction of Numerically Controlled (NC) machines and later of Computer Aided Design (CAD), Computer Aided Manufacturing (CAM), and Computer Integrated Manufacturing (CIM). Those techniques may in some cases be integrated much easier with some NTMPs. EDM and Wire Electric Discharge Machining (WEDM) are obvious examples. Also NC Laser or electron beam cutting are applied partially because of the improved automation in data transmission. There are many other types of applications in which the use of NTMPs drastically reduced the number of successive elementary machine jobs. A die plate made of carbides for example, could be machined out of one piece using spark erosion; the classical way would require at least two pieces fitted together and produced separately on a profile grinder (Snoeys et al1986).

Precision Requirements

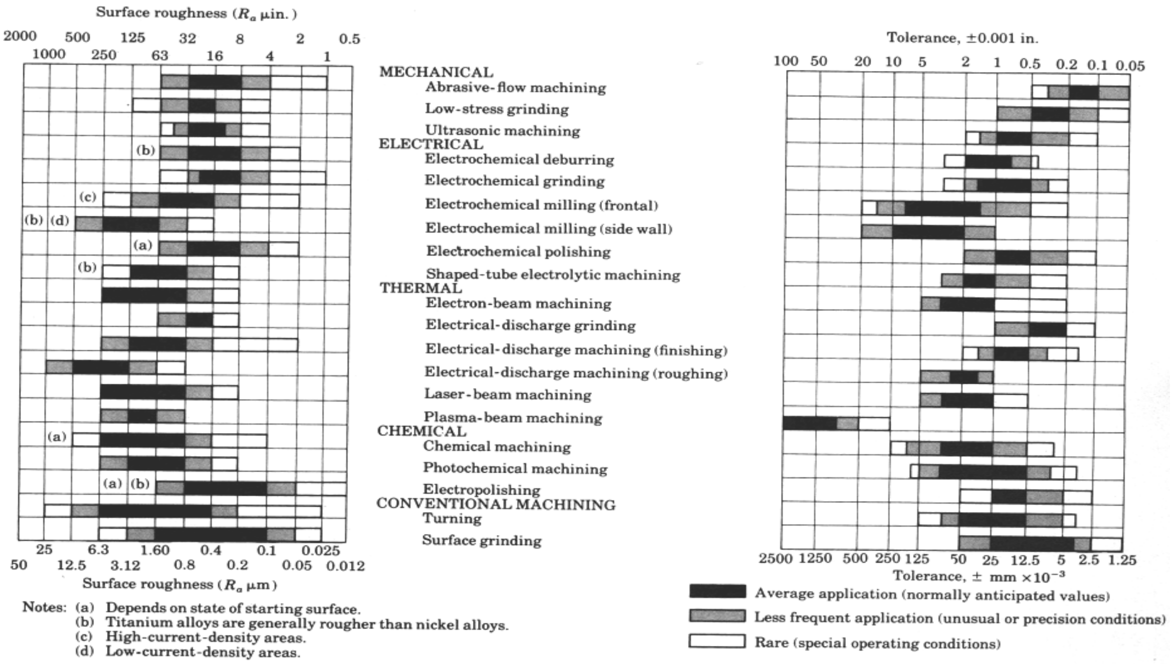
The trend of precision requirement as indicated by Taniguchi (1983) refers to nano-machining in tomorrow's ultra-high precision machining. This kind of precision may be obtained by removing atoms or molecules, rather than chips. Machining operations like sputtering IBM etc. would be possible candidates. The distortion of the surface layer due to mechanical or thermal action may be another reason to call upon some of the same NTMPs.

Miniaturisation

Trends toward reducing the workpiece dimensions already exist for some time. Ultra small diameter holes (10 – 100 µm) would not be possible to drill with conventional techniques. EDM, LBM, EBM or even Micro Electro chemical Machining (Micro-ECM) techniques are now frequently applied for such purposes. Micromachining has recently become an important issue, further reducing possible attainable workpiece dimensions. Various techniques developed for the production of micro electronic circuitry may be used for manufacturing extremely small items. Especially in the area of sensors, an integration of mechanical parts with the electronic circuitry may become a new possibility bringing the design and production of various sensors on the verge of drastic cost reductions. Several types of NTMPs have been developed to meet a wide range of machining requirements. When these processes are employed properly, they offer many advantages over traditional machining processes. The most common NTMPs and selected Hybrid NTMPs (HNTMPs) are described in this section (Snoeys et al 1986). The Surface Roughness and Tolerance of various machining processes are shown in Fig respectively.

Ultrasonic Machining

Ultrasonic Machining (USM) is a mechanical material removal process or an abrasive process used to erode holes or cavities on hard or brittle work piece by using shaped tools, high frequency mechanical motion, and an abrasive slurry. USM offers a solution to the expanding need for machining brittle materials such as single crystals, glasses and polycrystalline ceramics, and increasing complex operations to provide intricate shapes and work piece profiles. It is therefore used extensively in machining hard and brittle materials that are difficult to machine by traditional manufacturing processes (Kramer et al 1981). The hard particles in slurry are accelerated



Notes: (a) Depends on state of starting surface.
(b) Titanium alloys are generally rougher than nickel alloys.
(c) High-current-density areas.
(d) Low-current-density areas.