UNIT I

Need for non-traditional machining Processes -Classification of modern machining processes. Ultrasonic Machining – Elements of the process, mechanics of metal removal process parameters, economic considerations, applications and limitations, recent development.

UNIT II

Abrasive jet machining, Water jet machining and abrasive water jet machine: Basic principles, equipments, process variables, mechanics of metal removal, MRR, application and limitations.

UNIT – III

Electro – Chemical Processes: Fundamentals of electro chemical machining, electrochemical grinding, electro chemical honing and deburring process, metal removal rate in ECM, Tools, Surface finish and accuracy economic aspects of ECM.

UNIT – IV


UNIT – V


UNIT-VI

Unit-1

Introduction

- Need for non-traditional machining methods
- Classification of modern machining processes
- Considerations in process selection.
- Materials.
- Applications.

History:

In the early stage of mankind, tools were made of stone for the item being made. When iron tools were invented, desirable metals and more sophisticated articles could be produced. In twentieth century products were made from the most durable and the most un-machinable materials. In an effort to meet the manufacturing challenges created by these materials, tools have now evolved to include materials such as alloy steel, carbide, diamond and ceramics.

A similar evolution has taken place with the methods used to power our tools. Initially, tools were powered by muscles; either human or animal. However as the powers of water, wind, steam and electricity were harnessed, mankind was able to further extend manufacturing capabilities with new machines, greater accuracy and faster machining rates. Every time new tools, tool materials, and power sources are utilized, the efficiency and capabilities of manufacturers are greatly enhanced. But with the increasing demand for the usage of new types of material and combinational materials for aerospace applications, unconventional manufacturing processes came into existence to process the new material requirements.

Traditional Machining processes that involve chip formation have a number of inherent limitations which limit their application in industry.

- Large amounts of energy are expended to produce unwanted chips which must be removed and discarded.
- Much of the machining energy ends up as undesirable heat that often produces problems of distortion and surface cracking.
- Cutting forces require that the work piece be held which can also lead distortion.
- Unwanted distortion, residual stress, and burrs caused by the machining process often require further processing.

In view of these limitations, many nontraditional machining (NTM) methods have been developed since World War II to address the growing list of machining requirement which cannot be handled by conventional machining alone. Advantages of NTM methods may include the ability to machine:

- Complex geometries beyond simple planar or cylindrical features
- Parts with extreme surface finish and tolerance requirements
Delicate components that cannot withstand large cutting forces
Parts without producing burrs or inducing residual stresses
Brittle materials or materials with very high hardness.

Modern machining methods are also named as non-conventional machining methods. These methods form a group of processes which removes excess material by various techniques involving mechanical, thermal, electrical chemical energy or combination of these energies. There is no cutting of metal with the help of metallic tool having sharp cutting edge. The major reasons of development and popularity of modern machining methods are listed below.

(a) Need of machine newly developed metals and non-metals having some special properties like high strength, high hardness and high toughness. A material possessing the above mentioned properties are difficult to be machined by the conventional machining methods.

(b) Sometimes it is required to produce complex part geometries that cannot be produced by following conventional machining techniques. Non-conventional machining methods also provide very good quality of surface finish which may also be an encouragement to these methods.

- Traditional machining processes
  - Material removal by mechanical means, such as chip forming, abrasion, or micro-chipping
- Advanced machining processes
  - Utilize chemical, electrical, and high-energy beams
- The following cannot be done by traditional processes:
  - Workpiece strength and hardness very high, >400HB
  - Workpiece material too brittle, glass, ceramics, heat-treated alloys
  - Workpiece too slender and flexible, hard to clamp
  - Part shape complex, long and small hole
  - Special surface and dimensional tolerance requirements

Situations where traditional machining processes are unsatisfactory or uneconomical:

- Workpiece material is too hard, strong, or tough.
- Workpiece is too flexible to resist cutting forces or too difficult to clamp.
- Part shape is very complex with internal or external profiles or small holes.
- Requirements for surface finish and tolerances are very high.
- Temperature rise or residual stresses are undesirable or unacceptable

Non Conventional Machining is mainly used for parts like:-

- Skin panel for missiles and aircraft
- Turbine blades, nozzles, sheet metal, small-diameter deep holes, dies, thick metallic and nonmetallic parts

Economical considerations to be studied before going for Non Conventional Machining:
- High cost of equipment, which typically includes computer control
- May use hard tooling, soft tooling, or both
- Low production rates.
- Can be used with difficult-to-machine materials
- Highly repeatable
- Typically requires highly skilled operators

NTM processes typically have lower feed rates and require more power consumption when compared to machining. However, some processes permit batch processing which increases the overall throughput of these processes and enables them to compete with machining.

Advantages:

A major advantage of some NTM processes is that feed rate is independent of the material being processed. As a result, these processes are often used for difficult to machine materials.

NTM processes typically have better accuracy and surface finish with the ability of some processes to machine larger feature sizes at lower capital costs.

Classification of modern machining processes:-

Classification along with the principle of working (type of energy used for material removal) is described below.

**Use of Mechanical Energy**

Mechanical energy is used for removing material from work piece. In this process, cutting tool with sharp edge is not used but material is removed by the abrasive action of high velocity of stream of hard, tiny abrasive particles. The particles are kept vibrating with very high velocity and ultra high frequency to remove the material.

**Electrical Energy**

In this category of non-traditional machining electrical energy is used in the form of electrochemical energy or electro-heat energy to erode the material or to melt and vapourized it respectively. Electrochemical machining, electroplating or electro discharge machining are the examples work on this principle.

**Use of Thermal Energy**

According to this principle heat is generated by electrical energy. The generated thermal energy is focused to a very small portion of workpiece. This heat is utilized in melting and evaporating of metal. The example based o this principle is electric discharge machining.

**Use of Chemical Energy**

According to this principle of working chemicals are used to erode material from the workpiece. Selection of a chemical depends upon the workpiece material. Example of this type of machining is electrochemical machining. The dame principle can also be applied in reversed way in the process of electrochemical plating.
There can be one more way of classification of the non-conventional machining processes which is mechanisms of metal removal.

**Abrasion and Shear**

When small and hard metallic particles are made vibrating against the work piece to be machined, the material is removed by shear action and abrasion. This phenomenon generally takes place in case of ultrasonic machining.

**Chemical Ablation and Ionic Dissolution**

This is the dissolution of work piece material into electrolyte solution (chemical) which takes place atom by atom. This happens in case electrochemical machining.

**Vaporization by Spark Erosion**

Concentrated heat is focused at a point of the work piece by electric spark which melts and evaporates the work piece material like electric discharge machining and LBM.

NTM processes can be divided into four groups based upon the material removal mechanism:

1. **Chemical-Chemical** reaction between a liquid reagent and the work piece results in etching.

2. **Electrochemical**- An electrolytic reaction at the work piece surface is responsible material removal.

3. **Mechanical**- High velocity abrasives or liquids remove material.

4. **Thermal**- High temperatures in localized regions evaporate materials.

**Unconventional Machining processes can be classified as below**

Table-1 Classification of unconventional machining processes
The non-conventional manufacturing processes are not affected by hardness, toughness or brittleness of material and can produce any intricate shape on any work piece material by suitable control over the various physical parameters of the processes. The non-conventional manufacturing processes may be classified on the basis of type of energy namely, mechanical, electrical, chemical, thermal or magnetic, apply to the work piece directly and have the desired shape transformation or material removal from the work surface by using different scientific mechanism. Thus, these non-conventional processes can be classified into various groups according to the basic requirements which are as follows:

(i) Type of energy required, namely, mechanical, electrical, chemical etc.

(ii) Basic mechanism involved in the processes, like erosion, ionic dissolution, vaporization etc.

(iii) Source of immediate energy required for material removal, namely, hydrostatic pressure, high current density, high voltage, ionised material, etc.

(iv) Medium for transfer of those energies, like high velocity particles, electrolyte, electron, hot gases, etc.
TABLE 1.1. Classification of Non-conventional Manufacturing Processes

Non-conventional manufacturing processes

<table>
<thead>
<tr>
<th>Energy type</th>
<th>Mechanical</th>
<th>Electro-chemical</th>
<th>Chemical</th>
<th>Thermo-electrical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic mechanism</td>
<td>Shear</td>
<td>Erosion</td>
<td>Ion displacement</td>
<td>Ablative action</td>
</tr>
<tr>
<td>Source of immediate energy</td>
<td>Cutting tool</td>
<td>Pneumatic or hydraulic pressure</td>
<td>High current</td>
<td>Chemically reactive agent</td>
</tr>
<tr>
<td>Transfer energy medium</td>
<td>Physical contact</td>
<td>High velocity particles</td>
<td>High velocity liquid</td>
<td>Electrolyte</td>
</tr>
<tr>
<td>Processes</td>
<td>Mechanical contour grinding</td>
<td>Whirling jet machining</td>
<td>Chemical etching</td>
<td>Chemical machining</td>
</tr>
<tr>
<td></td>
<td>Ultrasonic machining</td>
<td>Abrasive jet machining</td>
<td>Electro chemical grinding</td>
<td>Electro chemical machining</td>
</tr>
</tbody>
</table>
A comparative analysis of the various unconventional manufacturing processes should be made so that a guide-line may be drawn to find the suitability of application of different processes.

A particular manufacturing process found suitable under the given conditions may not be equally efficient under other conditions. Therefore, a careful selection of the process for a given manufacturing problem is essential. The analysis has been made from the point of view of:

(i) Physical parameters involved in the processes;
(ii) Capability of machining different shapes of work material;
(iii) Applicability of different processes to various types of material, e.g. metals, alloys and non-metals;
(iv) Operational characteristics of manufacturing and
(v) Economics involved in the various processes.

### Physical parameters

The physical parameters of non-conventional machining processes have a direct impact on the metal removal as well as on the energy consumed in different processes. (Table 1.2)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>USM</th>
<th>AJM</th>
<th>ECM</th>
<th>CHM</th>
<th>EDM</th>
<th>EBM</th>
<th>LBM</th>
<th>PAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential (V)</td>
<td>220</td>
<td>220</td>
<td>10</td>
<td>—</td>
<td>45</td>
<td>15000</td>
<td>4500</td>
<td>100</td>
</tr>
<tr>
<td>Current (Amp)</td>
<td>12</td>
<td>1.0</td>
<td>1000</td>
<td>(D.C.)</td>
<td>—</td>
<td>0.001</td>
<td>4500</td>
<td>500</td>
</tr>
<tr>
<td>(A.C.)</td>
<td></td>
<td></td>
<td>(Pulsed D.C.)</td>
<td></td>
<td>(Pulsed D.C.)</td>
<td></td>
<td>(Average)</td>
<td></td>
</tr>
<tr>
<td>Power (W)</td>
<td>2400</td>
<td>220</td>
<td>10000</td>
<td>—</td>
<td>2700</td>
<td>150</td>
<td>150</td>
<td>50000</td>
</tr>
<tr>
<td>Gap (m.m.)</td>
<td>0.25</td>
<td>0.75</td>
<td>0.20</td>
<td>0.025</td>
<td>100</td>
<td>150</td>
<td>7.5</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>Abrasive in water</td>
<td>Abrasive in gas</td>
<td>Electrolyte</td>
<td>Liquid chemical</td>
<td>Liquid dielectric</td>
<td>Vacuum</td>
<td>Air</td>
<td>Argon or hydrogen</td>
</tr>
</tbody>
</table>

From a comparative study of the effect of metal removal rate on the power consumed by various non-conventional machining processes shown in fig. 1.2.

![Fig 1.2 Effect of metal removal rate on power consumption.](image-url)
It is found that some of the processes (e.g. EBM, ECM) above the mean power consumption line consume a greater amount of power than the processes (e.g. EDM, PAM, ECG) below the mean power consumption line. Thus, the capital cost involved in the processes (EBM, ECM etc.) lying above the mean line is high whereas for the processes below that line (e.g., EDM, PAM, MCG) is comparatively low.

**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, through cutting (shallow and deep) etc.

<table>
<thead>
<tr>
<th>TABLE 1.3. Shape Application of Non-conventional Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
</tr>
<tr>
<td>Dial &lt; .025 mm</td>
</tr>
<tr>
<td>USM</td>
</tr>
<tr>
<td>AJM</td>
</tr>
<tr>
<td>ECM</td>
</tr>
<tr>
<td>CHM</td>
</tr>
<tr>
<td>EDM</td>
</tr>
<tr>
<td>LBM</td>
</tr>
<tr>
<td>PAM</td>
</tr>
</tbody>
</table>

For micro-drilling operation, the only process which has good capability to micro drill is laser beam machining while 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 capability to make pocketing operation (shallow or deep). For surface contouring operation, ECM process is most suitable but other processes except EDM have no application for contouring operation.

**Applicability to materials**

Materials applications of the various machining methods are summarized in the table 1.4 and table 1.5. For the machining of electrically non-conducting materials, both ECM and EDM are unsuitable, whereas the mechanical methods can achieve the desired results.
USM is suitable for machining of refractory type of material while AJM are for super alloys and refractory materials.

Table 1.4

<table>
<thead>
<tr>
<th>Process</th>
<th>Aluminium</th>
<th>Steel</th>
<th>Super alloy</th>
<th>Titanium</th>
<th>Refractory material</th>
</tr>
</thead>
<tbody>
<tr>
<td>USM</td>
<td>Poor</td>
<td>Fair</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>AJM</td>
<td>Fair</td>
<td>Fair</td>
<td>Good</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>ECM</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td>CHM</td>
<td>Good</td>
<td>Good</td>
<td>Fair</td>
<td>Fair</td>
<td>Poor</td>
</tr>
<tr>
<td>EDM</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>EBM</td>
<td>Fair</td>
<td>Fair</td>
<td>Fair</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>LBM</td>
<td>Fair</td>
<td>Fair</td>
<td>Fair</td>
<td>Fair</td>
<td>Poor</td>
</tr>
<tr>
<td>PAM</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
<td>Fair</td>
<td>Poor</td>
</tr>
</tbody>
</table>

Machining characteristics

The machining characteristics of different non-conventional processes can be analyzed with respect to:

(i) Metal removal rate

(ii) Tolerance maintained

(iii) Surface finish obtained

(iv) Depth of surface damage

(v) Power required for machining

The process capabilities of non-conventional manufacturing processes have been compared in table 1.6. The metal removal rates by ECM and PAM are respectively one-fourth and 1.25 times that of conventional whereas others are only small fractions of it. Power requirement of ECM and PAM is also very high when compared with other non-conventional machining processes.
This involves higher capital cost for those processes. ECM has very low tool wear rate but it has certain fairly serious problems regarding the contamination of the electrolyte used and the corrosion of machine parts. The surface finish and tolerance obtained by various processes except PAM is satisfactory.

Table: 1.6

<table>
<thead>
<tr>
<th>Process</th>
<th>MRR (mm³/min)</th>
<th>Tolerance (μm)</th>
<th>Surface (μm) CLA</th>
<th>Depth of surface damage (μm)</th>
<th>Power (watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USM</td>
<td>300</td>
<td>7.5</td>
<td>0.2-0.5</td>
<td>25</td>
<td>2400</td>
</tr>
<tr>
<td>AIM</td>
<td>0.8</td>
<td>50</td>
<td>0.5-1.2</td>
<td>2.5</td>
<td>250</td>
</tr>
<tr>
<td>ECM</td>
<td>15000</td>
<td>50</td>
<td>0.1-2.5</td>
<td>5.0</td>
<td>100000</td>
</tr>
<tr>
<td>CHM</td>
<td>15</td>
<td>50</td>
<td>0.5-2.5</td>
<td>50</td>
<td>—</td>
</tr>
<tr>
<td>EDM</td>
<td>800</td>
<td>15</td>
<td>0.2-1.2</td>
<td>129</td>
<td>2700</td>
</tr>
<tr>
<td>EBm</td>
<td>1.6</td>
<td>25</td>
<td>0.5-2.5</td>
<td>290</td>
<td>150 (average)</td>
</tr>
<tr>
<td>LBM</td>
<td>0.1</td>
<td>25</td>
<td>0.5-1.2</td>
<td>125</td>
<td>2000 (peak)</td>
</tr>
<tr>
<td>PAM</td>
<td>75000</td>
<td>125</td>
<td>Rough</td>
<td>500</td>
<td>50000</td>
</tr>
<tr>
<td>Conventional machining</td>
<td>50000</td>
<td>50</td>
<td>0.5-5.0</td>
<td>25</td>
<td>3000</td>
</tr>
</tbody>
</table>

**Economics of the processes**

The economics of the various processes are analyzed on the basis of following factors and given in Table 1.7.
(i) Capital cost
(ii) Tooling cost
(iii) Consumed power cost
(iv) Metal removal rate efficiency
(v) Tool wear.

Table: 1.7

<table>
<thead>
<tr>
<th>Process</th>
<th>Capital cost</th>
<th>Tooling cost</th>
<th>Power consumption cost</th>
<th>Material removal rate efficiency</th>
<th>Tool wear</th>
</tr>
</thead>
<tbody>
<tr>
<td>USM</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>M</td>
</tr>
<tr>
<td>AIM</td>
<td>VL</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>L</td>
</tr>
<tr>
<td>ECM</td>
<td>VH</td>
<td>M</td>
<td>M</td>
<td>L</td>
<td>VL</td>
</tr>
<tr>
<td>CHM</td>
<td>M</td>
<td>L</td>
<td>H*</td>
<td>M</td>
<td>VL</td>
</tr>
<tr>
<td>EDM</td>
<td>M</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>EBm</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>VH</td>
<td>VL</td>
</tr>
<tr>
<td>LBM</td>
<td>L</td>
<td>L</td>
<td>VL</td>
<td>VH</td>
<td>VL</td>
</tr>
<tr>
<td>PAM</td>
<td>VL</td>
<td>L</td>
<td>VL</td>
<td>VL</td>
<td>VL</td>
</tr>
<tr>
<td>MCG</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>VL</td>
<td>L</td>
</tr>
</tbody>
</table>
The capital cost of ECM is very high when compared with traditional mechanical contour grinding and other non-conventional machining processes 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 case of ECM. The metal removal 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 upon various factors and must be considered all or some of them before applying no conventional processes.
Ultrasonic machining

- Elements of the process
- Mechanics of metal removal process parameters
- Economic considerations
- Applications and limitations
- Recent development.

USM Logic:

- Abrasive slurry flows over top of work piece (loose particles)
- Cutting tool is vibrated by ultrasonic energy
- Abrasive particles between tool and work piece do the machining
- Works well with hard, brittle work pieces

In ultrasonic machining, a liquid filled with abrasive material flows through over the work piece, and the work tool vibrates against the abrasives. The abrasive materials affect the work piece and remove material. Since the tool doesn’t directly touch the work piece, the pressure and tool materials used in ultrasonic machining are often very different from those used in more common machining techniques.

The key to an ultrasonic machining process is the abrasive liquid. This material, called slurry, is a mixture of a free-flowing liquid and one or more types of solid abrasive. The liquid part of the slurry is generally water. For some jobs benzene, glycerol or oil may be used instead, but increasing the viscosity of the liquid will often lead to a slower process. The slurry consists of small abrasive particles mixed with water or oil in the concentration of 30 to 60% by weight.

Since the abrasive used in ultrasonic machining slurry needs to be harder than the machined material, a wide range of abrasives are common. The basic abrasives are often silicon carbide or boron carbide, mostly due to their hardness and low cost. Occasionally, diamond dust is used to work the hardest materials.

The work tool used in ultrasonic machining is different from the ones used in a standard process. The tool is often made of a softer material with a high plasticity. This allows the abrasives to impact the tool, but not damage it the way it does the worked material. These tools are often far too soft for standard machining jobs; they would deform as soon as they touch the work piece.

The process of machining a piece ultrasonically looks similar to a normal process, but is actually quite different. The slurry flows over the work area, creating a connection between the
work piece and work tool. The tool vibrates, which causes the abrasives to bounce back and forth between the piece and tool. Since the tool deforms, it absorbs the impacts of the abrasives while the work piece develops small cracks. The cracks eventually cause small pieces to break off until the machined area of the work piece matches the shape of the work tool.

The slurry is always kept cool by using a refrigerated cooling system at a temp of 5 to 6 degrees centigrade.

The liquid or water or oil should have the following properties:

- Good wetting Characteristics,
- Low Viscosity
- High Thermal Conductivity.
- Anticorrosive property
- Density equal to that of the abrasive
- Low cost.

Grit Size:

Coarse grades are used for roughing ad finer grades for finishing operations.

The most common reason to use ultrasonic machining is when a work piece is very brittle. On a brittle substance, a standard machine process will cause the material to crack and break. This will generally result in a ruined final product. Ultrasonic machining uses thousands of tiny impacts and very little pressure to move material away from a substance. This rarely results in a break, even in very brittle materials, So USM is mainly used for Brittle materials (which are poor conductors of Electricity and cannot be processed using ECM or EDM).

The abrasive particles are propelled or hammered against the work piece by the transmitted vibrations of the tool. The particles then microscopically erode or "chip away" at the work piece. Generally the tool oscillates at a high frequency (about 20,000 cps) in an abrasive slurry. The high speed oscillations of the tool drive the abrasive grain across a small gap of about 0.02-0.10 mm against the work piece.

**Ultrasonic Machining Process:**

- Since the tool doesn’t directly touch the work piece, the pressure and tool materials used in ultrasonic machining are often very different from those used in more common machining techniques. The key to an ultrasonic machining process is the abrasive liquid. This material, called slurry, is a mixture of a free-flowing liquid and one or more types of solid abrasive.

- Additionally, water pressure and type of abrasive must be controlled to achieve the desired cut.
The tool never contacts the work piece and as a result the grinding pressure is rarely more than 2 pounds, which makes this operation perfect for machining extremely hard and brittle materials, such as glass, sapphire, ruby, diamond, and ceramics.

The cutting vibration in the ultrasonic machining process begins with converting a high-frequency electrical signal into an oscillatory mechanical motion. This linear oscillation is typically at a rate of 20,000 times per second, and, when used with an abrasive slurry flowing around the cutting tool, microscopic grinding occurs. The machined area becomes counterpart of the cutting tool used. In ultrasonic machining, the tool, which is shaped conversely to the desired hole or cavity, oscillates at high frequency, typically 20 kHz, and is fed into the work piece by a constant force.

**USM Parts:**

1. Electronic Oscillator and Amplifier: It is also called as a generator, it converts Electrical power of low frequency (50Hz) to a High Frequency power of the order of 20kHz. This is supplied to the transducer,

2. Transducer: It converts electrical energy into Mechanical Motion

The output of the generator is fed into the Transducer that converts electrical energy into vibration energy.

Piezoelectric transducers: Contains Crystals of Polycrystalline material or Quartz, when fed with the electrical output from the generator, causes the crystals to vibrate thus converting electrical energy into vibration energy.
Magnetostrictive Transducer: Here electrical energy supplied into a coil wound around a Magnetostrictive material like Nickel and Nickel alloys results in the generation of a Magnetic field that causes the Magnetostrictive material to contract and elongate thus converting electrical energy into vibration energy.

3. Transformer or Concentrator: Though the vibratory motion signals are generated by the Transducer but the amplitude of those vibrations is not enough for the machining process, so the output from the Transducer is fed into a Transformer which increases the amplitude of the vibrations.

4. Tools holder: The output from the Transformer is fed into the tool holder and thus vibratory motion is fed to the tool.

5. Tool: The shape of the tool is inverse of the cavity to be eroded. Stainless steel, Brass, Mild Steel and other Ductile Materials are used to minimize tool wear. The tools are fastened to tool holder by Brazing to reduce possible fatigue problems.

6. Abrasive Slurry

7. Work Piece.

8. Refrigeration system.

Process variables and their effects:

Machining rate or cutting rate or machining accuracy depends upon certain process variables. The cutting rate depends upon.

1. Grain Size of abrasive

2. Abrasive Material

3. Concentration of Slurry

4. Amplitude of Vibration

5. Frequency.

Machining Rate:

The maximum speed of penetration in soft materials such as ceramics-20mm/min but for hard and tough materials penetration rate is slower.

Effect of Vibration amplitude:
The cutting rate is proportional to the square of the amplitude of vibration for many materials, however it is also dependent upon slurry concentration.

Increase in frequency increases number of blows- thus machining rate is directly proportional to increase in frequency.

Effect of Grit Size: Shape, size, material and hardness of grains affect the material removal rate. Increase in grit size increases machining rate until grit size equals to amplitude of vibration, but as soon as grit size is above amplitude machining rate decreases.

Effect of Slurry Composition: Slurry is composed of abrasive grains and carrier fluid (usually water). The concentration of grain particles in the slurry and the type of abrasive effects the machining rate. The slurry should flow easily. Grits get worn out, so should be replaced periodically.

Viscosity of fluids: - Dampen the oscillations thus reducing machining rates.

Static load on the tools: As we increase the static load on the tool, the machining rate increases until the load reaches a particular value, but after that machining rate reduces with further increase of loads.

Work Piece material: Machining rate depends upon material properties like hardness, toughness and brittleness.

Machining area: Machining rate also depends upon machining area- shape of groove, area of grove and depth of hole.

Accuracy of Machining: Dimensional accuracy of +/-0.005 mm is possible with USM. A mini corner radius of 0.10 mm is possible. Holes as small as 0.076 mm can be drilled, and upper limit on cavity size is approximately 75 mm. Machining depth of 50 mm or more is possible.

Applications:

USM machines are available from a light portable type of 20W rating to heavy machines of 2KW input. The simplicity of the process makes it economical for a wide range of applications. USM has been successfully employed for a wide range of applications. USM has been successfully employed for the following applications.

- Machining of hard and brittle materials. These materials cannot be machined by conventional processes. Examples glass, ceramic, tungsten carbide, diamond, zirconia, graphite, etc.

- Dies of tungsten carbide and diamond for wire drawing, forging and extrusion process.

- Drilling of non-circular holes in glass and similar materials.
• Drilling of holes of any shape in teeth without creating pain. This is a useful practice by dentists.

• Threading in components of hard metals and alloys. This is achieved by rotating and translating the workpiece and translating the workpiece of the tool.

• Machining of holes of various shapes by using appropriate tools. Other types of shapes can be manipulated by giving suitable motion to workpiece during cutting.

• Drilling, grinding, profiling, and milling operations on conducting and non-conducting materials.

• Drilling holes of various shapes with straight or curved axes.

**Limitations:**

The major limitations of USM processes:

• Low machining rates as compared to conventional machining process. The metal removal rate is 3mm³/s.

• Power consumption is very high compared to conventional machining process.

• It is very difficult to machine very deep holes, as the slurry movement is restricted. The depth of cylindrical holes is presently limited to 2.5 times the diameter of the tool.

• It is difficult to design the tool to get the precise dimensions on the workpiece as tool wear is comparable to metal removal rate. Wear of the tool increases the angle of the hole and sharp corners becomes rounded.

• The process is limited to machining of small workpiece.

**Recent Developments:**

In USM processes, slurry has to be continuously fed which limits the machining rate and dimensional tolerance while drilling deep holes. Recently, a new development in ultrasonic machining has taken place where no slurry is used. The tool is impregnated with diamond dust or
other hard abrasive grits. The tool is oscillated at ultrasonic frequencies as well as rotated. If it is not possible to rotate the tool, the workpiece may be rotated.

**The advantages of USM without slurry are:**

- Faster cutting rate of materials such as glass and ceramics.
- Machining of alumina and other difficult to machine materials at economic speeds.
- Higher accuracy in machining compared to conventional USM with slurry. The comparison is shown in the figure 10.12.
- The process is more adaptable for automation.
- The tool can be used as milling cutter for machining different shapes.
- Holes up to 75mm deep have been drilled in ceramics without any fail in machining rates. This was not possible with conventional USM.
- The hole dimensions can be kept within +0.125mm.

Research is being conducted where USM machines are being developed which use ultrasonic vibrations at Kilo Hertz frequency and kilowatt power levels that can be also used for drilling and turning processes.

**SALIENT FEATURES OF THE ULTRASONIC MACHINING SETUP: -**

- The machines have a power rating of 0.2-2.5 kW
- The amplitude of vibration is of the order of 0.01 to 0.06 mm
- Frequency varies from a lower limit of 15,000 Hz (hearing range) to an upper limit of about 25,000 Hz (imposed by the requirement of cooling of the transducer)
- The transducer amplitude is limited by the strength of the magnetostrictive material.
- A refrigerating cooling system is used to cool the abrasive slurry to temperature of 5-60°C
- The tool is smaller than the size of the cavity by a few hundredths of a millimeter and made of low-carbon or stainless steel to the shape of the desired cavity.
- Tool size = Hole size – 2*(Size of the abrasives)
- Grit size 200-400 for roughing & 800-1000 for finishing
- Slenderness ratio of the tool should not exceed 20
Parameters of Ultrasonic Machining:- The ultrasonic vibration machining method is an efficient cutting technique for difficult-to-machine materials. It is found that the USM mechanism is influenced by these important parameters.

- Amplitude of tool oscillation \(a_0\) (15 - 50 μm)
- Frequency of tool oscillation \(f\) (19 – 25 kHz)
- Tool material (Soft steel titanium alloy)
- Type of abrasive (Boron carbide, aluminum oxide and silicon carbide)
- Grain size or grit size of the abrasives – \(d_0\) (100 – 800)
- Feed force - \(F\)
- Contact area of the tool – \(A\)
- Volume concentration of abrasive in water slurry – \(C\)
- Ratio of work piece hardness to tool hardness; \(\lambda = \sigma_w / \sigma_t\)

USM can be applied to machine nearly all materials; however it is not economical to use USM for materials of hardness less than 50 HRC. Generally the workpiece materials are of stainless steel, cobalt-base heat-resistant steels, germanium, glass, ceramic, carbide, quartz and semiconductors.

Advantages:-

USM effectively machines precise features in hard, brittle materials such as

- glass
- engineered ceramics
- CVD SiC- Chemical Vapor Deposition Silicon Carbide
- quartz
- single crystal materials
- PCD - Polycrystalline diamond
- ferrite
- graphite
- glassy carbon
- composites
- composites
- piezo ceramics

- A nearly limitless number of feature shapes—including round, square and odd-shaped thru-holes and cavities of varying depths, as well as OD-ID features—can be machined with high quality and consistency.
• Aspect ratios as high as 25-to-1 are possible, depending on the material type and feature size.
• The machining of parts with preexisting machined features or metallization is possible without affecting the integrity of the preexisting features or surface finish of the workpiece.
• USM machined surfaces exhibit a good surface integrity and the compressive stress induced in the top layer enhances the fatigue strength of the workpiece.
• The quality of an ultrasonic cut provides reduced stress and a lower likelihood of fractures that might lead to device or application failure over the life of the product.
• Unlike other non-traditional processes such as laser beam, and electrical discharge machining, etc., ultrasonic machining does not thermally damage the workpiece or appear to introduce significant levels of residual stress, which is important for the survival of brittle materials in service.
• Unlike conventional machining methods, ultrasonic machining produces little or no subsurface damage and no heat-affected zone.
• This machining process is nonthermal, nonchemical, and nonelectrical. It does not change the metallurgical, chemical or physical properties of the workpiece.

DISADVANTAGES
• Ultrasonic machines have a relatively low MRR. Material removal rates are quite low, usually less than 50 mm3/min.
• The abrasive slurry also "machines" the tool itself, thus causing high rate of tool wear, which in turn makes it very difficult to hold close tolerances.
• The slurry may wear the wall of the machined hole as it passes back towards the surface, which limits the accuracy, particularly for small holes.
• The machining area and the depth of cut are quite restricted

APPLICATIONS
Ultrasonic machining is ideal for certain kinds of materials and applications. Brittle materials, particularly ceramics and glass, are typical candidates for ultrasonic machining. Ultrasonic machining is capable of machining complex, highly detailed shapes and can be machined to very close tolerances (±0.01 mm routinely) with properly designed machines and generators. Complex geometric shapes and 3-D contours can be machined with relative ease in brittle materials. Multiple holes, sometimes hundreds, can be drilled simultaneously into very hard materials with great accuracy. Channels and holes ultrasonically machined in a polycrystalline silicon wafer.
• Coining operations for materials like glass, ceramics, etc.
• Threading by appropriately rotating and translating the workpiece/tool.
• Rotary ultrasonic machining uses an abrasive surfaced tool that is rotated and vibrated simultaneously. The combination of rotating and vibrating action of the tool makes rotary ultrasonic machining ideal for drilling holes and performing ultrasonic profile milling in ceramics and brittle engineered materials that are difficult to machine with traditional processes.

• Ultrasonic machining can be used to form and redress graphite electrodes for electrical discharge machining. It is especially suited to the forming and redressing of intricately shaped and detailed configurations requiring sharp internal corners and excellent surface finishes.

• It is particularly useful in micro drilling holes of upto 0.1 mm.

Summary:

The word **ultrasonics** describes a vibratory wave having a frequency above the hearing range of normal human ear (usually greater than 16 kHz. 1 Hz = 1 c/s.).

For the generation of ultrasonic vibrations, an ultrasonic transducer is employed to convert high frequency electrical signal into high frequency linear mechanical motion (or vibration), which is transmitted to the tool via mechanical amplifier. For achieving maximum
material removal rate (MRR), the tool and tool holder are designed so that the resonance can be achieved.

For ultrasonic machining of a work cavity the tool shape is suitably designed and the tool is made to vibrate at ultrasonic frequency, normal to the work surface. The vibrating tool is brought close to the work surface leaving a small gap in between (of a few microns). Abrasive slurry is circulated through the gap continuously to perform the cutting operation. The individual abrasive grains, on coming into contact with the vibrating tool, acquire high velocity and are propelled towards the work surfaces. High velocity bombardment of the work surface by the abrasive particles gives rise to the formation of a multitude of tiny stressed regions. The stress in these tiny regions is often sufficient to cause cracking, and fracture of the work surface resulting into material removal.

It is considered as a safe process because it does not involve high voltage, chemicals, large mechanical forces and heat. High power sine wave generator converts low frequency (50 Hz) electrical power to high frequency (≈20 kHz) electrical power. This high frequency electrical signal is transmitted to the transducer which converts it into high frequency low amplitude mechanical vibrations. In USM, either of the two types of transducers are used, i.e., piezoelectric type (for low power upto 900W) or magnetostrictive type (for high power, upto 2.4 kW). Piezoelectric crystals (say, quartz) generate a small electric current when compressed. Also, when an electric current is passed through the crystal, it expands; when the current is removed the crystal attains its original size. This effect is known as piezoelectric effect. Magnetostrictive transducer also works on a similar principle. Magnetostrictive transducers are made of nickel, or nickel alloy sheets and their efficiency (20-35%) is much lower than the piezoelectric transducers' (up to 95%), hence their cooling is essential to remove waste heat. The magnetostrictive type transducers are available with power capacity upto 2.4 kW. The US transducers can produce vibrations upto maximum amplitude of 25 μm.

Tool holder holds and connects the tool to the transducer, transmits the energy and, in some cases, amplifies the amplitude of vibration. Amplifying tool holders give as much as 6 times increased tool motion, and yield MRR upto 10 times higher than non-amplifying tool holder. However, amplifying tool holders are more expensive, demand higher operating cost and yield poorer surface quality. Material of the tool should have good acoustic properties, and high resistance to fatigue failure. Due measures should be taken to avoid ultrasonic welding between the transducer and the tool holder [Benedict, 987]. Commonly used materials for the tool holder are Monel metal (for low amplitude applications), titanium and stainless steel.

Tools are usually made of relatively ductile materials (brass, stainless steel, mild steel, etc.) to minimize tool wear rate (TWR). Value of the ratio of TWR and MRR depends upon the type of abrasive, workpiece material, and tool material combination. Surface finish of the tool affects the surface finish obtained on the workpiece. Silver brazing of the tool with tool holder minimizes the fatigue problem associated with screw attachment method.

Abrasive material hardness, particle size, usable life time and cost are used as criteria for selecting the abrasive grains for USM. Commonly used abrasives in the order of increasing hardness, are Al₂O₃, SiC and B₄C (Boron Carbide).
Abrasive hardness should be more than work piece material hardness. MRR and surface finish obtained during USM also depend on the abrasive size. Finer grains result into lower MRR and better surface finish while reverse is true with coarse grains. Mesh sizes of grits generally used range from 240 to 800. Abrasive slurry consists of water and abrasives usually in 1 : 1 (by weight). However, it can vary depending upon type of operation, viz., thinner (or low concentration) mixtures are used while drilling deep holes, or machining complex cavities so that the slurry flow is more efficient. The slurry stored in a reservoir, is pumped to the gap formed by the tool and the work.

Mechanics of Cutting

The mechanism of material removal in USM has been studied by different researchers (Miller, 1957; Shaw, 1956; Kazantsev, 1965; Kainth, et. al, 1979). Theory proposed by M.C. Shaw (1956) is briefly explained below.

Model Proposed by Shaw

The mechanisms that can contribute to material removal in USM are: mechanical erosion, cavitation and chemical corrosion. Material removal due to cavitation under the tool, and chemical corrosion due to slurry medium are however, considered to be insignificant. Hence, material removal due to these two factors can be ignored. Contribution to the material removal by abrasive particle erosion due to throwing and hammering actions has been analyzed by Shaw as below.

Abrasive particles are assumed to be spherical in shape having a uniform diameter of $d$. Abrasive particles suspended in a carrier fluid move under the high frequency vibrating tool. There are two possibilities when the vibrating tool hits the abrasive particles. If the size of the particle is small enough as compared to the gap between the tool and work surface, the particle will be thrown by the tool, to hit the work surface (throwing model). Large size abrasive grains on the other hand are likely to get entrapped between the work surface and the vibrating tool. Such particles would eventually be hammered down on to the work surface by the tool-hammering action. In both cases, it is assumed that a particle after hitting the work surface generates a crater of height $h$ and radius $r$. It is also assumed that volume of the material removed from the workpiece is approximately proportional to the diameter of indentation ($2r$). The volume of material ($V_g$) removed due to fracture per grit per cycle is given by

$$V_g = \frac{1}{2} \left[ \frac{4}{3} \pi r^3 \right] \quad \text{(assuming hemispherical crater)} \quad \text{.....1.1}$$

From the geometry $r^2 = \frac{d}{2}^2 - \left( \frac{d}{2} - h \right)^2$ (neglecting $h^2$ term as $h<<d$) \text{.....1.2}

From equations 1.1 and 1.2 we can write

$$V_g = K_1 (hd)^{3/2}$$

Where $K_1$ is a constant.
Number of impacts (N) on the workpiece by the grits in each cycle will depend upon the number of grits beneath the tool at any time. This is inversely proportional to the diameter of the grit (assumed spherical) as given below:

\[ N = K_2 \cdot \frac{1}{d^2} \]

Where \( k_2 \) is constant of proportionality.

Let \( k_3 \) be the probability of an abrasive particle under the tool being effective. Then volume \( (v_s) \) of the material removed per second will be equal to the frequency \( (f) \) times the amount of material removed per cycle \( (V_c) \)

\[ V_s = v_c \cdot f = K_1 K_2 K_3 \left[ \frac{h^3}{d^4 f} \right]^{1/2} \ldots \ldots 1.3 \]

Where \( v_c = K_1 K_2 K_3 (hd)^{3/2} / d^2 \)

In order to evaluate the depth of penetration \( h \) of an abrasive particle, Shaw (1956) proposed two models: throwing model (Model 1) and hammering model (Model 2). Both these models are discussed below.
Model 1 (Grain Throwing Model)

It is assumed that an abrasive particle on being hit by the vibrating tool accelerates towards the work surface, it can be considered as thrown by the tool onto the workpiece surface. Assuming sinusoidal vibration, the displacement \( Y \) of the tool is given by Eq. (11.6) in which \( 't' \) is time period and \( a/2 \) is amplitude of oscillation.

\[
Y = \frac{a}{2} \sin (2\pi ft).
\]  \( \ldots (11.6) \)

From Eq. (11.6), velocity of the tool is given by

\[
\dot{Y} = \pi a f \cos (2\pi ft).
\]  \( \ldots (11.7) \)

The maximum velocity of the tool \( (\dot{Y}_{\text{max}}) \) is derived as follows:

\[
\dot{Y}_{\text{max}} = \pi a f \quad \text{(for} \cos (2\pi ft) = 1). \]  \( \ldots (11.8) \)

Let us assume that the tool imparts a velocity of \( \dot{Y}_{\text{max}} \) to the grit. The kinetic energy \( (KE) \) of the grit is therefore given by:

\[
KE = \frac{1}{2} m \pi^2 a^2 f^2
\]

\[
= \frac{1}{2} \left( \frac{\pi}{6} \frac{a^3 \rho_a}{\rho} \right) \pi^2 a^2 f^2.
\]  \( \ldots (11.9) \)

Where, \( \rho_a \) is density of the abrasive particles.

It is assumed that when the thrown grit hits the works surface its \( KE \) is absorbed by the work piece before the particle comes to rest after penetrating to a depth equal to \( 'h_{th}' \). The work done by the grit \( (W_g) \) is given by

\[
W_g = \frac{1}{2} \dot{F}_{\text{th}} \cdot \dot{h}_{\text{th}}.
\]  \( \ldots (11.10) \)
Model 2 (Grain Hammering Model)

A situation may arise when an abrasive grain gets entrapped between the vibrating tool and the work piece. Under such a situation, abrasive would be hammered on the work surface. This would lead to partial penetration of the entrapped grain in the tool ($h_t$) as well as the work piece ($h_w$).

The values of $h_w$ and $h_t$ depend on the hardness of the tool as well as work piece material.

The hammering force $F$ acts on the abrasive particle only for a fraction ($\Delta T$) of the cycle time ($T$). During this time period, the abrasive particle is in contact with both the tool and the work piece. The mean force ($F_{\text{avg}}$) on the grit can be expressed by Eq. (11.15),
Here, \( F(t) \) is the force at any instant of time \( t \). The force acting on the grit starts increasing as soon as the grit gets in contact with both the tool and the workpiece. It attains maximum value and then starts decreasing to zero. The momentum equation can be written as

\[
\int_{0}^{T} F(t) \, dt \approx \left( \frac{F}{2} \right) \Delta T. \tag{11.16}
\]

Total penetration of the abrasive due to hammering \( (h_h) \) can be calculated as follows: The mean velocity of the tool during the quarter cycle (from O to B in is given by \((a/2) / (T/4)\). Therefore, approximate time \( (\Delta T) \) is given by the following equation:

\[
\Delta T \approx \frac{h_h}{(a/2)} \left( \frac{T}{4} \right)
\]

\[
= \frac{h_h}{a} \left( \frac{T}{2} \right), \tag{11.17}
\]

where,

\[
h_h = h_w + h_d. \tag{11.18}
\]

From Eqs. (11.15), (11.16), and (11.17), we get;

\[
F = F_{avg} \frac{4a}{h_h}. \tag{11.19}
\]

If \( N \) be the number of grains that are entrapped under the tool, stress acting on the workpiece \( (\sigma_w) \) and the tool \( (\sigma_{tl}) \) can be found as follows:

\[
\sigma_w = \frac{F}{N (\pi h_w d)} \tag{11.20}
\]

\[
\sigma_{tl} = \frac{F}{N (\pi h_d d)}
\]

\[
= -\sigma_w \frac{h_w}{h_{tl}} \quad \text{(from Eq. (11.20)).} \tag{11.21}
\]
From Eqs. (11.4), (11.19) and (11.20),

\[
\sigma_w = F_{avg} \frac{4 \alpha d^2}{h_t K_2 (\pi h_w d)} = \frac{4 F_{avg} \alpha d}{\pi K_2 h_w (h_w + h_t)} = \frac{4 F_{avg} \alpha d}{\pi K_2 h_w^2 \left( \frac{h_t}{h_w} + 1 \right)} \quad \ldots (11.22)
\]

We can define,

\[
h_t / h_w = \sigma_w / \sigma_{tl} = j \quad \ldots (11.23)
\]

where, \(j\) is the ratio of hardness of workpiece material to the hardness of tool material. From Eqs. (11.22) and (11.23),

\[
h_w = \sqrt{\frac{4 F_{avg} \alpha}{\sigma_w \pi K_2 (j+1)}} \quad \ldots (11.24)
\]

Material removal rate from the workpiece due to hammering mechanism \((V_h)\), can be evaluated using Eqs. (11.5) and (11.24) as follows

\[
V_h = K_1 K_2 K_3 \left[ \frac{4 \alpha F_{avg} d}{\sigma_w \pi K_2 (j+1)} \right]^{3/4} d^{1/4} f \quad \ldots (11.25)
\]

From the computational results obtained using Eqs. (11.14) and (11.25), it is observed that

\[V_h >> V_{th} \]

**Process Capabilities and Applications**

USM works satisfactorily only when workpiece hardness is greater than HRC40.

Materials like carbides, ceramics, tungsten, glass, etc., that cannot be easily machined by conventional methods, can be easily machined by this technique.

Tolerances that can be achieved by this process range between 7 \(\mu m\) – 25 \(\mu m\). Holes as small as 0.076 mm have been drilled. Hole depths up to 51 mm have been easily achieved while 152 mm deep holes have also been drilled by using special flushing technique. The aspect ratio of 40 : 1 has been achieved. To drill large diameter hole, it is recommended to use trepanning operation. Linear material removal rate, \((MRR_1)\) – also known as penetration rate) achieved during USM ranges from 0.025-25.0 mm/min, and it depends upon various parameters. Surface finish
achieved during the process varies from 0.25 μm – 0.75 μm. USM results in a non-directional surface texture compared to conventional grinding process.

Accuracy of the machined surface is governed by the size of the abrasive grains, tool wear, transverse vibration and machined depth. Usually overcut (i.e., the clearance between the tool and the workpiece) is used as a measure of accuracy. Radial overcut may be as low as 1.5 to 4.0 times the mean abrasive grain size. Overcut also depends on the other parameters like properties of work piece material and method of tool feed. Out-of-roundness is another criterion used to measure the accuracy of drilled cylindrical holes. Inaccurate setting of the tool during USM is the main source of lateral vibration which results in out-of-roundness in the cavity.

Most successful USM application is machining of cavities (or holes) in electrically non-conductive ceramics. It is quite successful in case of fragile components in which otherwise scrap rate is quite high. To drill multiple numbers of holes at a time, hypodermic needles have been used.

**Economics:** Tool: In order to improve the economics of ultrasonic machining, it is necessary to increase the material removal rate and the tool life. The tool materials, although not given much importance in the theoretical models of material removal rates, have a significant influence on the material removal and tool wear. So, Selection of the right tool material will influence the material removal rates, tool wear and roughness of the machined surfaces.

Try to increase the MRR by optimal selection of parameters that effect the MRR.

Select less expensive abrasive particles.

Less expensive slurry material.

**Problem**

Find the approximate time required to drill a hole of 6 mm diameter in a tungsten carbide plate (fracture hardness = 6900 N/mm² = 6.9 \times 10^9 N/m²) of thickness equal to one and half times the hole diameter. The mean abrasive grain diameter is 0.015 mm. The feed force is equal to 3.5 N. The amplitude of tool oscillation is 25 μm and the frequency is equal to 25 kHz. The tool material used is copper having fracture hardness equal to 1500 N/mm². The slurry contains one part abrasive to one part of water. Take the values of different constants as \( K_1 = 0.3, K_2 = 1.8 \)
$mm^2$, $K_3 = 0.6$ and abrasive density = $3.8 \text{ g/cm}^3$. Also calculate the ratio of volume removed from the work piece by hammering mechanism to the volume removed by throwing mechanism.

**Solution**

In the problem, following data are given:

*For the computation of the time required to machine the hole the following steps be undertaken:*

Calculate the volume ($V$) of material removed during USM using the following relationship:

$$V = K_1 K_2 K_3 \sqrt[3]{\frac{h^3}{d}} \cdot f \quad \ldots (11.5)$$

**Step 1:** Calculate the value of “$h$” which is different for throwing model ($h_{th}$) and for hammering model ($h_w$).

**Step 2:** After computing the values of $h_{th}$ and $h_w$, calculate $V_{th}$ and $V_h$ by substituting these values in the above Eq. (11.5). Find total volume of material removed per unit time ($V_s$) by adding $V_{th}$ and $V_h$.

**Step 3:** Calculate the total amount of material to be removed to make a hole. Divide it by $V_s$ to find the total time required to make the hole.

**Step 4:** Find the ratio of $V_{th} / V_h$.

Following above steps, all calculations are made as given below.

**Step 1**

In Eq. (11.5), except “$h$” all other parameters are known.

Let us calculate $h_{th}$ as given below.
\[ h_{th} = \pi a f d \sqrt{\frac{\rho_a}{6\sigma_w}} \]

\[ = \pi \times (50 \times 10^{-6}) \times (2.5 \times 10^4) \times (1.5 \times 10^{-5}) \sqrt{\frac{3.8 \times 10^3}{6 \times (6.9 \times 10^9)}} \]

\[ h_{th} = 1.78 \times 10^{-4} \text{ mm} . \]

Penetration in the workpiece due to hammering (Eq. (11.24)) is equal to:

\[ h_w = \sqrt{\frac{4 F_{avg} a d}{\pi k_2 \sigma_w (j+1)}} \]

\[ = \sqrt{\frac{4 \times 3.5 \times (2 \times 25 \times 10^{-6}) \times (1.5 \times 10^{-5})}{\pi \times (1.8 \times 10^{-5}) \times (6.9 \times 10^9) \times (1+4.6)}} \]

\[ h_w = 2.192 \times 10^{-4} \text{ mm} . \]

(Here, \( h_w \) is considered in place of \( h_{th} \) because the hole is to be drilled in the workpiece.)

**Step 2**

Calculate the volume of material removed due to throwing action:

\[ V_{th} = K_1 K_2 K_3 \sqrt{\frac{h_{th}^3}{d} \cdot f} \]

\[ - 0.3 \times 1.8 \times 0.6 \sqrt{(1.78 \times 10^{-5})^3} \times 2.5 \times 10^4 \]

\[ V_{th} = 4.97 \times 10^{-3} \text{ mm}^3/\text{s} \]

Volume of material removed from the workpiece due to hammering action:

\[ V_h = K_1 K_2 K_3 \sqrt{\frac{h_{w}^3}{d} \cdot f} \]
\[ V_h = 0.3 \times 1.8 \times 0.6 \sqrt{\frac{(2.192 \times 10^{-4})^3}{1.5 \times 10^{-2}}} \times 2.5 \times 10^4 \]

\[ V_h = 214.6 \times 10^{-3} \text{ mm}^3/s \]

**Step 3**

Time required to drill a hole = \[ \frac{\text{Volume of the hole to be drilled}}{\text{Volumetric MRR (} = V_h + V_{th} \text{)}} \]

\[ = \frac{(\pi/4) \times 6^2 \times 9}{0.219} \]

\[ = 19.366 \text{ min} \]

**Step 4**

Ratio, \[ \frac{V_h}{V_{th}} = \frac{0.21460}{0.00497} \]

\[ = 43.48 \]

It is thus, evident that the material removed in hammering is much more than throwing (approximately 43 times), hence, for approximate calculations, \( V_{th} \) can be ignored compared to \( V_h \).
UNIT – II

Abrasive jet machining, Water jet machining and abrasive water jet machine:

Basic principles,
Equipments, process variables,
Mechanics of metal removal,
MRR, application and limitations.

Abrasive Jet Machining
In Abrasive Jet Machining (AJM), abrasive particles are made to impinge on the work material at a high velocity. The jet of abrasive particles is carried by carrier gas or air. The high velocity stream of abrasive is generated by converting the pressure energy of the carrier gas or air to its kinetic energy and hence high velocity jet. The nozzle directs the abrasive jet in a controlled manner onto the work material, so that the distance between the nozzle and the work piece and the impingement angle can be set desirably. The high velocity abrasive particles remove the material by micro-cutting action as well as brittle fracture of the work material. Fig. 1 schematically shows the material removal process.
AJM is different from standard shot or sand blasting, as in AJM, finer abrasive grits are used and the parameters can be controlled more effectively providing better control over product quality. 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 stand off 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.

The process is used chiefly to cut intricate shapes in hard and brittle materials which are sensitive to heat and have a tendency to chip easily. The process is also used for deburring and cleaning operations. AJM is inherently free from chatter and vibration problems. The cutting action is cool because the carrier gas serves as a coolant.

**Equipment**

In AJM, air is compressed in an air compressor and compressed air at a pressure of around 5 bar is used as the carrier gas as shown in Fig. 2 also shows the other major parts of the AJM system. Gases like CO₂, N₂ can also be used as carrier gas which may directly be issued from a gas cylinder. Generally oxygen is not used as a carrier gas. The carrier gas is first passed through a pressure regulator to obtain the desired working pressure. The gas is then passed through an air dryer to remove any residual water vapour. To remove any oil vapour or particulate contaminant the same is passed through a series of filters. Then the carrier gas enters a closed chamber known as the mixing chamber. The abrasive particles enter the chamber from a hopper through a metallic sieve. The sieve is constantly vibrated by an electromagnetic shaker. The mass flow rate of abrasive (15 gm/min) entering the chamber depends on the amplitude of vibration of the sieve and its frequency. The abrasive particles are then carried by the carrier gas to the machining chamber via an electro-magnetic on-off valve. The machining enclosure is essential to contain the abrasive and machined particles in a safe and eco-friendly manner. The
machining is carried out as high velocity (200 m/s) abrasive particles are issued from the nozzle onto a work piece traversing under the jet.

**ABRASIVE JET MACHINING AJM**

![Diagram of AJM process](image)

A high-velocity jet of dry air, nitrogen, or carbon dioxide containing abrasive particles is aimed at the workpiece surface under controlled conditions. The gas supply pressure is on the order of 850 kPa (125 psi) and the jet velocity can be as high as 300 m/s and is controlled by a valve.

**AJM Process Capability**

**Material removal**

Typical cutting speeds vary between 25 -125 mm/min

**Dimensional Tolerances**

Typical range ±2 - ±5 μm

**Surface Finish**

Typical Ra values vary from 0.3 - 2.3 μm

**AJM Applications and Limitations**

**Applications**

- Can cut traditionally hard to cut materials, e.g., composites, ceramics, glass
- Good for materials that cannot stand high temperatures

**Limitations**

- Expensive process
- Flaring can become large
• Not suitable for mass production because of high maintenance requirements

**Variables in Abrasive Jet Machine:**

The variables that influence the rate of metal removal and accuracy of machining in this process is:

1. Carrier gas (With respect to the needed pressure requirements)
2. Types of abrasive (If harder abrasives are used then MRR is more)
3. Size of abrasive grain
4. Velocity of abrasive jet (AS Velocity increases-MRR also increases)
5. Flow rate of abrasive
6. Work material (AS hardness increases MRR reduces)
7. Geometry, composition and material of nozzle (For Complicate shapes MRR gets slower)
8. Nozzle work distance (stand off distance)
9. Shape of cut and operation type

MRR\(_g\) (material removal rate in mg/min) increases only up to a certain value of abrasive flow rate beyond which it starts decreasing. As abrasive flow rate increases, the number of abrasive-particles cutting the workpiece increases thereby increasing MRR\(_g\). However, with a further increase in abrasive flow rate (other parameters remaining unchanged), the abrasive flow velocity goes down which reduces MRR\(_g\). On the other hand abrasives must impinge the work surface with a certain minimum velocity (say, 150 m/s for machining of glass by SiC particles of 25 μm size) so that the erosion can take place. Kinetic energy (KE) of the abrasive particles is responsible for removal of material by erosion. Mixing ratio (M, i.e., a ratio of volumetric flow rate of abrasive particles and volumetric flow rate of carrier gas) also influences MRR\(_v\). An Increase in the value of ‘M’ increases MRR\(_v\) but a large value of ‘M’ may decrease jet velocity and sometimes may choke the nozzle. Thus, an optimum mixing ratio has been observed that gives maximum MRR.
For brittle materials, normal impingement results maximum MRR and for ductile materials, an impingement angle of 15-20 degrees results in maximum MRR.

The effect of SOD or NTD on material removal rate (MRR) is shown as the NTD increases the diameter of hole increases which is general observation in abrasive jet machining.

The effect of abrasive flow rate on material removal rate (MRR) is shown as the abrasive mass flow rate increases the material removal rate (MRR) increases which is also general observation in abrasive jet machining.

For brittle materials, normal impingement results maximum MRR and for ductile materials, an impingement angle of 15-20 degrees results in maximum MRR.
As the abrasive grit size and mixing ratio increase, the MRR and penetration rate increase but the surfaces finish value which is measured in Ra decreases.

**Effect of pressure on material removal rate (MRR)**

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Gas pressure</th>
<th>Material removal rate (mg/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>18</td>
</tr>
<tr>
<td>2</td>
<td>6</td>
<td>21</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
<td>23</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>26</td>
</tr>
</tbody>
</table>

**Characteristics of different Variables:**

<table>
<thead>
<tr>
<th>Medium</th>
<th>Air, CO₂, N₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrasive</td>
<td>SiC, Al₂O₃ (of size 20μ to 50μ)</td>
</tr>
<tr>
<td>Flow rate of abrasive</td>
<td>3 to 20 gram/min</td>
</tr>
<tr>
<td>Velocity</td>
<td>150 to 300 m/min</td>
</tr>
<tr>
<td>Pressure</td>
<td>2 to 8 kg/cm²</td>
</tr>
<tr>
<td>Nozzle size</td>
<td>0.07 to 0.40 mm</td>
</tr>
<tr>
<td>Material of nozzle</td>
<td>WC, Sapphire</td>
</tr>
<tr>
<td>Nozzle life</td>
<td>12 to 300 hr</td>
</tr>
</tbody>
</table>
**Advantages:**

1. Ability to cut intricate holes shape in materials of any hardness and brittleness.
2. Ability to cut fragile and heat sensitive material without damage.
3. No change in microstructure as no heat is generated in the process.
4. Low capital cost.

**Disadvantages:**

1. Material removal rate is low and hence its application is limited.
2. Stray strings can occur and hence its application is limited.
3. Embedding of the abrasive in the work piece surface may occur while machining softer material.
4. The abrasive material may accumulate at nozzle and fail the process if moisture is present in the air.
5. It cannot be used to drill blind holes.

**Process Capabilities and Applications**

AJM is a low material removal rate process (approx. 0.015 cm³/min) and it can easily produce intricate details on hard and brittle materials. Production of narrow slots (0.12 - 0.25 mm), low tolerance (± 0.12 mm), good surface finish (0.25 - 1.25 μm), and sharp radius (≈ 0.2 mm) are some of the capabilities of the AJM process. AJM can machine without thermal damage to the work because the heat generation during machining is very small.

AJM is useful in the manufacture of electronic devices, deburring, marking on electronic and other products, deflashing small castings, cutting titanium foil, and drilling glass wafers. This process is also used for engraving registration numbers on the toughened glass, frosting glass surfaces, and cutting thin sectioned fragile components. It however, pollutes the working environment.

**PROCESS CAPABILITIES AND LIMITATIONS**

Abrasive Jet Machining utilizes the pressure of fluid stream to remove material from the surface of the job. When using air as a medium the mixture of air and abrasives are allowed to
impinge on the work surface at about 200 to 400m/s through the nozzle and work material is eroded by the high velocity abrasive particles. The inside diameter of the nozzle is about 0.04mm and standoff distance is kept about 0.7 to 1.0mm. The process can be easily controlled to vary the metal removal rate which depends on flow rate and size of abrasive particles. The cutting action is cooled because the carrier gas serves as a coolant.

Gas used are nitrogen or carbon dioxide or even air which are supplied under pressure (2-8 kg/cm^2) filtered through regulator is passed to a mixing chamber (containing abrasive particles) vibrating at 50c/s. From the mixing chamber, the gas along with the entrained abrasives particles of size 10-50 micro meter passes on to nozzle having its tip tungsten carbide and diameter of around 0.45mm, with a velocity of 150 to 300 m/s. The air consumption is of order of 0.6m^3/hr. The nozzle tip distance is of order of 0.81mm. The abrasive powder feed rate is controlled by the amplitude of vibration of mixing chamber. The relative motion between the nozzle and the work piece is obtained by the programmable torch or by cams and pantographs to control the size and shape of the cut. Dust removal equipment is incorporated to protect the environment. The material removal rate, geometry of cut, surface roughness, and nozzle wear rate are influenced by the size and distance of nozzle, composition, strength, size and shape of abrasive flow rate; and composition, pressure and velocity of carrier gas. The abrasive particles should have irregular shape and consist of short edges rather than having rounded shapes. Abrasives generally used are Aluminum Oxide, Silicon Carbide, Sodium bicarbonate, dolomite, glass beads; their selection and their grain size depending on the machining operation.

The material removal rate is mainly dependent on the flow rate and size of the abrasive particles. High grain size will always produce more metal removal. At a particular pressure metal removal rate increases with the abrasive flow rate but after reaching a optimum value, the material removal rate decreases with increase in abrasive flow rate. This is because mass flow rate of the gas decreases with increase of abrasive flow rate and mixing ratio increases causing a decrease in material removal rate because of less energy available for erosion. The abrasive particles are generally not used again and again.

The material removal rate first increases with the increases of tip distance from work up to a certain limit after which it remains unchanged for a certain tip distance and then falls gradually. In this process the limitations are that the material removal rate is low, stray cutting can't be avoided, tapering effect may be found because of unavoidable flaring of the abrasive jets, abrasives may get embedded on the work surface, and suitable dust collecting system has to be provided.

The advantages of this process are that it can be used to cut intricate hole shapes in hard and hard and brittle materials; even fragile and sensitive materials can be cut without damage, and the initial cost is low. It's disadvantages are that it removes material at very low rate, stray cutting can occur resulting in poor accuracy, and soft materials can't be machined by this process.

PROCESS PERFORMANCE

The main aspect of this machining is cornered on mixing tube life and orifice life. Though the orifice life are far greater than mixing tube life but they have a typical life depending upon
material of which they are made. The materials known to me are diamond, ruby and sapphire. The mixing tube generally gets worn down in less than half the time as required by orifice.

1. Although very tight tolerances are achievable by this process but they are dependent on various other parameters of machining that range from feed rate to material thickness to operator experience.
2. Job material- The harder the material the less would be the taper when abrasive jet passes at the bottom of the work piece, since it’s dispersion would be less as compared to softer material.
3. Feed rate-The feed rate also contributes to the tolerance which could be achieved. A slight change in feed could bring about changes in the jet profile and thus tolerance that could be achieved.
4. No initialization of the holes is required for starting of the operation as that is required by EDM.
5. There is almost zero tool setup time involved and almost negligible programming is required for tool motion.
6. Tolerance is also dependent on the material thickness because that only controls the behavior of the jets as it exits out the bottom. This can cause tapering around curves.
7. The jet lag between the points where it first enters and where it exits also has considerable affect on the tolerance of the part machined.
8. Material utilization is very high because no material is wasted in machining of corners and intricate shapes.

**Applications:**

The major field of application of AJM process is in the machining of essentially brittle materials and heat sensitive materials like glass, quartz, sapphire, semiconductor materials, mica and ceramics. It is also used in cutting slot, thin sections, countering, drilling, deburring, for producing integrate shapes in hard and brittle materials. It is often used for cleaning and polishing of plastics nylon and Teflon components. Delicate cleaning, such as removal of smudges from antique documents, is also possible with AJM.

**Process Parameters and Machining Characteristics.**
The process parameters are listed below:

**Abrasive**
- Material – Al$_2$O$_3$ / 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 ~ 1.3 kg/m$^3$
- Velocity – 500 ~ 700 m/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
  \[ \frac{M_{\text{abr}}}{M_{\text{gas}}} \]
- Stand-off distance – 0.5 ~ 5 mm
- Impingement Angle – 60$^\circ$ ~ 90$^\circ$

Nozzle

- Material – WC / sapphire
- Diameter – (Internal) 0.2 ~ 0.8 mm
- Life – 10 ~ 300 hours

The important machining characteristics in AJM are

- The material removal rate (MRR) mm$^3$/min or gm/min
- The machining accuracy
- The life of the nozzle

The below depicts the effect of some process parameters on MRR
Modelling of material removal

As mentioned earlier, material removal in AJM takes place due to brittle fracture of the work material due to impact of high velocity abrasive particles.

Modelling has been done with the following assumptions:

(i) Abrasives are spherical in shape and rigid. The particles are characterised by the mean grit diameter

(ii) The kinetic energy of the abrasives are fully utilised in removing material

(iii) Brittle materials are considered to fail due to brittle fracture and the fracture volume is considered to be hemispherical with diameter equal to chordal

The below figure schematically shows the interaction of the abrasive particle and the work material in AJM.
Interaction of abrasive particles with workpiece
On impact, the work material would be subjected to a maximum force $F$ which would lead to an indentation of $\delta$. Thus the work done during such indentation is given by
\[
W = \frac{1}{2} F \delta
\]
Now considering $H$ as the hardness or the flow strength of the work material, the impact force ($F$) can be expressed as:
\[
F = \text{indentation area} \times \text{hardness} = \pi r^2 H
\]
where, $r$ = the indentation radius
\[
\therefore W = \frac{1}{2} F \delta = \frac{1}{2} \pi r^2 H \delta
\]
Now, as it is assumed that the K.E. of the abrasive is fully used for material removal, then the work done is equated to the energy
\[
W = \text{K.E.} = \frac{1}{2} \pi r^2 \delta H = \frac{\pi}{12} d_{g}^3 \rho_{g} v^2
\]
\[
\delta = \frac{d_{g}^3 \rho_{g} v^2}{6 \pi^2 H}
\]
\[
\delta^2 = \frac{d_{g}^2 \rho_{g} v^2}{6H}
\]
\[
\delta = \sqrt{\frac{d_{g} \rho_{g}}{6H}}^{1/2}
\]
Now MRR in AJM of brittle materials can be expressed as:
\[
MRR_{B} = \Gamma_{B} \times \text{Number of impacts by abrasive grits per second} = \Gamma_{B} N
\]
\[
MRR_{B} = \frac{m_{s}}{\text{mass of a grit}} = \frac{m_{s}}{\frac{\pi}{6} d_{g}^3 \rho_{g}} = \frac{6 \Gamma_{B} m_{s}}{\pi d_{g}^3 \rho_{g}} \quad \text{as } \Gamma_{B} = \frac{2 \pi}{3} (d_{g} \delta)^{3/2}
\]
\[
= \frac{6 \times \frac{2 \pi}{3} (d_{g} \delta)^{3/2} m_{s}}{\pi d_{g}^3 \rho_{g}} = \frac{4 m_{s}}{\rho_{g}} \left( \frac{\delta}{d_{g}} \right)^{3/2}
\]
Applications

- For drilling holes of intricate shapes in hard and brittle materials
- For machining fragile, brittle and heat sensitive materials
- AJM can be used for drilling, cutting, deburring, cleaning and etching.
- Micro-machining of brittle materials

Limitations

- MRR is rather low (around ~ 15 mm$^3$/min for machining glass)
- Abrasive particles tend to get embedded particularly if the work material is ductile
- Tapering occurs due to flaring of the jet
- Environmental load is rather high

Problem

1. Estimate the material removal rate in AJM of a brittle material with flow strength of 4 GPa. The abrasive flow rate is 2 gm/min, velocity is 200 m/s and density of the abrasive is 3 gm/cc.

2. Material removal rate in AJM is 0.5 mm$^3$/s. Calculate material removal per impact if mass flow rate of abrasive is 3 gm/min, density is 3 gm/cc and grit size is 50 μm as well as indentation radius.

Solutions to the Problems

Solution of Prob. 1

\[
MRR_B = \left( \frac{4m_a}{\rho_g} \right) \left( \frac{\delta}{d_g} \right)^{3/2}
\]

\[
\delta = d_g \sqrt{\frac{\rho_g}{6H}}\]

\[
MRR_B = \frac{4m_a}{\rho_g} \left( \frac{d_g \sqrt{\rho_g}}{d_g} \right)^{3/2} \left( \frac{\rho_g}{6H} \right)^{3/4}
\]

\[
MRR_B = \frac{4m_a \sqrt{\rho_g}}{6^{3/4} \rho_g^{1/4} H^{3/4}} \approx \frac{m_a \sqrt{\rho_g}}{\rho_g^{1/4} H^{3/4}}
\]
WATERJET MACHINING

It is important to understand that abrasive jets are not the same thing as the water jet although they are nearly the same. Water Jet technology has been around since the early 1970s or so, and abrasive jets extended the concept about ten years later. Both technologies use the principle of pressuring water to extremely high pressure, and allowing the water to escape through opening typically called the orifice or jewel. Water jets use the beam of water exiting the orifice to cut soft stuffs like candy bars, but are not effective for cutting harder materials. The inlet water is typically pressurized between 20000 and 60000 Pounds per Square Inch (PSI). This is forced through a tiny wall in the jewel which is typically .007” to .015” diameter (0.18 to0.4 mm). This creates a very high velocity beam of water. Abrasive jets use the same beam of water to accelerate abrasive particles to speeds fast enough to cut through much faster material.

High pressure water starts at the pump, and is delivered through special high pressure plumbing to the nozzle. At the nozzle, abrasive is (typically) introduced, and as the abrasive/water mixture exits, cutting is performed. Once the jet has exited the nozzle, the energy is dissipated into the catch tank, which is usually full of water and debris from previous cuts. The motion of the cutting head is typically handled by an X / Y-axis structure. Control of the motion is typically done via a computer following the lines and arcs from a cad drawing.

Introduction to water jet:

It is the fastest growing machining process. One of the most versatile machining proceses.

- Compliments other technologies such as milling laser, EDM, and plasma.
• True cold cutting process-No heat effected zones, mechanical stresses or operator and environment hazards.

• Not limited to machining but also used in food industry applications.

**Evolution of Water jet:**
1930s: Mining Industry to remove stones and coal
1960s: Need to cut advanced materials for aerospace industry
1970s: First attempts were to employ WaterJet to cut advanced composites for aerospace applications.
1980s: First commercial AWJ machines

**Water jet:**
Water jets are used for cutting soft materials
Water Jet Machinable Materials
Like Soft rubber, foam, tin foil, carpet, soft gasket material

**Abrasive water jet**
Abrasive water jets for hard materials
An abrasive element is added to the water beam to assist cutting
Abrasive Water Jet Machinable materials: Titanium, aluminum, stone, hard rubber, hardened tool steel

**Components**
Pump Intensifier
Nozzle
Orifice

**Control System**
Components – Pump & Intensifier:
50 – 100 hp electric driven pump
Hydraulic Based Operation
Pressures Up to 60,000psi (4000 bar)

**Materials:**
The list of materials that a Water jet system could penetrate is significant.
To date, Applications have been used with:
Ceramic Tile, Wood, Rubber, Glass, Marble and Granite, Foam, GIO Phenolic, Steel, Armor plating, Urethane, Titanium, Kevlar, Aluminum, Brass, Copper, Stainless Steel, Spectra, Fiberglass, Corrugated Cardboard, Acrylic.
Surface Characteristics Variables of Cuts are dependent on:

- Water jet Pressure
- Water jet Diameter
- Abrasive Material Type
- Abrasive Material Size
- Abrasive Material Flow Rate
- Traverse Speed
- The cutting angle

Advantages:

- No heat effected zone
- No Stress-free cutting
- No Residual stresses
- Wide range of materials
- Environmentally friendly
- No need for surface finish
- No tool changing
- Minimal Fixturing Required
- Faster than any other technique
- Saves Raw Material
- Flexible Machining Integration
- Does Not Need a Starting Hole
- Ability to Cut in Any Direction

Disadvantages:

- Limited number of materials can be cut economically.
- Very thick parts can not be cut with Water Jet. Cutting and still hold dimensional accuracy.
- Slower cutting rate compared to both plasma and oxyfuel cutting processes.

Comparison to other Methods WaterJet v/s Wire EDM

**Water JET:** Can Cut through any material
- No Need for a Starting Hole
- No Heat Affected Zone

**EDM:** Limited to Conducting Materials
- A Starting Hole is Needed for the Wire
- Heat Affected Zone

**Water Jet v/s Laser**
- Water Jet: No Heat Affected Zone
- Can Cut Through Reflective Materials
- Can Cut Uneven Surfaces Smoothly
- Environmentally friendly
Can Cut Up to 12” in hard materials (Ti, SS) & 24” in Rubber

Laser: Minimal Heat Affected Zone
Reflects on Shiny Surfaces
Laser Defracts and Looses its Focu
Produces Toxic Fumes
Max. Depth 0.5 – 0.75”

**Water Jet v/s Milling**

**Water Jet:** Excellent Use of Raw Material
No Tool Changing
No Fixturing Required
No Cleanup is Required
Faster, No HAZ

**Milling:**

Large Amounts of Waste of Raw Material
Frequent Tool Changing
Fixturing is essential
Requires Periodical Cleanup
Slow & HAZ

**Variables to be considered when making a decision on the right cutting system to use:**

Cutting speed
Edge cleanliness
Degree of tolerance required
Number and types of metal to be cut
Capital investment
Operating costs
Size of heat affected zone
Access to secondary machining processes

**Conclusion:**

It is relatively a new technology which has caught on quickly and is replacing century-old methods used for manufacturing
Used not only in typical machining applications, but food and soft-goods industries
As material and pump technology advances faster cutting rates, longer component life and tighter tolerances will be achievable
Paves the way for new machining processes that embrace simplicity and have a small environmental impact
WATER JET MACHINING:

Also called as hydrodynamic machining.

WJM is a form of micro erosion. It works by forcing a large volume of water through a small orifice in the nozzle. The extreme pressure of the accelerated water particles contacts a small area of the workpiece and acts like a saw and cuts a narrow groove in the material.

- **Pros:** no need for predrilled holes, no heat, no workpiece deflection (hence suitable for flexible materials), minimal burr, environmentally friendly.
- **Cons:** limited to material with naturally occurring small cracks or softer material.
- **Applications:**
  - Mostly used to cut lower strength materials such as wood, plastics, rubber, paper, leather, composite, etc.
  - Food preparation
  - Good for materials that cannot withstand high temperatures of other methods for stress distortion or metallurgical reasons.
WJM Examples

A abrasive Water-Jet Machining
(AWJM)

The water jet contains abrasive particles such as silicon carbide, thus increasing MRR.

Metallic materials can be cut. Particularly suitable for heat-sensitive materials.
Water Jet & Abrasive Water Jet MRR Calculations:

Velocity of water Jet:

\[ v_{wj} = \Psi \sqrt{\frac{2 P_w}{\rho_w}} \]

- \( \Psi \) = Velocity coefficient of the orifice.
- \( P_w \) = Pressure of the Jet
- \( \rho_w \) = Density of water

The volume flow rate of water may be expressed as

\[ q_w = \phi \times v_{wj} \times A_{orifice} \]

\[ q_w = \phi \times v_{wj} \times \frac{\Pi}{4} d_o^2 \]

\[ q_w = \phi \times \frac{\Pi}{4} d_o^2 \times \Psi \sqrt{\frac{2 P_w}{\rho_w}} \]

\[ q_w = c_d \times \frac{\Pi}{4} d_o^2 \times \sqrt{2 \frac{P_w}{\rho_w}} \]

where,

- \( \phi \) = Coefficient of “vena-contracta”
- \( c_d \) = Discharge coefficient of the orifice

Thus, the total power of the water jet can be given as

\[ P_{wj} = P_w \times q_w \]

\[ P_{wj} = P_w \times c_d \times \frac{\Pi}{4} d_o^2 \times \sqrt{2 \frac{P_w}{\rho_w}} \]

\[ P_{wj} = c_d \times \frac{\Pi}{4} d_o^2 \times \sqrt{\frac{2 P_w^3}{\rho_w}} \]

Mass Flow rate:

\[ m_w = \text{Density of Water} \times \text{Volume Flow rate} \]
In water jet machining, the material removal rate may be assumed to be proportional to the power of the water jet.

\[ MRR \propto P_{awj} \propto c_d \frac{\Pi}{4} d_o^2 \times \frac{2p_{aw}^3}{\rho_w} \]

\[ MRR = u \times c_d \frac{\Pi}{4} d_o^2 \times \frac{2p_{aw}^3}{\rho_w} \]

The proportionality constant \( u \) is the specific energy requirement and would be a property of the work material.

Velocity of Abrasive Water Jet:

\[ v_{awj} = \frac{1}{1 + R} v_{awj} \]

where, \( \eta = \) momentum loss factor.

\( R = \) loading factor \( = \frac{m_{abr}}{m_w} \)

The power of the abrasive phase of the abrasive water jet can be estimated as,

\[ P_{abr} = \frac{1}{2} m_{abr} v_{awj}^2 \]

\[ P_{abr} = c_d \frac{\Pi}{4} d_o^2 R \left( \frac{\eta}{1+R} \right)^2 \frac{p_{aw}}{\rho_w} \frac{2}{\rho_w} \]

MRR abrasive water Jet:

\[ MRR = \xi \frac{P_{abr}}{n_{job}} \]

where \( \xi \) is a coefficient which takes into account several factors like sharpness or dullness of the abrasive, friability of the abrasives, stand off distance, process inhomogeneities etc
where,

\( u_{job} \) = specific energy requirement in machining a material in AWJM

Now

\( MRR = h_tv_f \)

Where,

\( h_t \) = depth of penetration

\( w \) = width of the kerf

\( \approx d_i \), the diameter of the focusing tube or nozzle or the insert

\( v_f \) = traverse speed of the AWJ or cutting speed

\[
\therefore h_t = \frac{2E_c d_i}{4} \left( \frac{\eta}{1 + R} \right)^2 \frac{p_w^{3/2}}{u_{job} d_i v_f} \sqrt{\frac{2}{\rho_w}}
\]

Problems

1. Assuming no losses, determine water jet velocity, when the water pressure is 4000 bar, being issued from an orifice of diameter 0.3 mm

Ans:

\[
v_w = \sqrt{\frac{2p}{\rho_w}} = \sqrt{\frac{2 \times 4000 \times 10^5}{1000}} = 894 \text{ m/s}
\]

2. Determine the mass flow rate of water for the given problem assuming all related coefficients to be 1.

Ans:

\[
m_w = \rho_w Q_w = \rho_w \frac{\pi}{4} d_o^2 v_w
\]

\[
= 1000 \times \frac{\pi}{4} \times (0.3 \times 10^{-3})^2 \times 894
\]

\[
= 0.0631 \text{ kg/s}
\]

\[
= 0.0631 \times 60 = 3.79 \text{ kg/min}
\]
If the mass flow rate of abrasive is 1 kg/min, determine the abrasive water jet velocity assuming no loss during mixing process using the above data (data of Question 1, 2 and 3)

Ans:

\[ V_{awj} = \left( \frac{1}{1 + R} \right) V_{wj} = \left( \frac{1}{1 + \frac{m_{air}}{m_w}} \right) V_{wj} = \left( \frac{1}{1 + \frac{1}{3.79}} \right) \times 894 = 707 \text{ m/s} \]

4. Determine depth of penetration, if a steel plate is AWJ machined at a traverse speed of 300 mm/min with an insert diameter of 1 mm. The specific energy of steel is 13.6 J/mm².

Ans:

\[ h_t = \frac{\pi d^2 R}{4} \left( \frac{1}{1 + R} \right) \left( \frac{\rho^{3/2}}{\mu_{Job} d / V_f} \right) \sqrt{\frac{2}{\rho_w}} \]

\[ h_t = \frac{\pi}{4} (0.3 \times 10^{-3})^2 \left( \frac{1}{3.8} \right) \left( \frac{13.6 \times 10^9 \times 1 \times 10^{-3} \times 300}{60 \times 10^{-3}} \right) \sqrt{\frac{2}{1000}} \]

\[ h_t = 77.66 \text{ mm} \]

**Application**

The applications and materials, which are generally machined using WJM and AWJ, are given below:

- Paint removal
- Cleaning
- Cutting soft materials
- Cutting frozen meat
- Textile, Leather industry
- Mass Immunization
- Surgery
- Peening
- Cutting
- Pocket Milling
- Drilling
- Turning
- Nuclear Plant Dismantling

**Materials**

- Steels
- Non-ferrous alloys
- Ti alloys, Ni-alloys
- Polymers
- Honeycombs
- Metal Matrix Composite
- Ceramic Matrix Composite
- Concrete
- Stone – Granite
- Wood
- Reinforced plastics
- Metal Polymer Laminates
- Glass Fibre Metal Laminates

The cutting ability of water jet machining can be improved drastically by adding hard and sharp abrasive particles into the water jet. Thus, WJM is typically used to cut so called “softer” and “easy-to-machine” materials like thin sheets and foils, non-ferrous metallic alloys, wood, textiles, honeycomb, polymers, frozen meat, leather etc, but the domain of “harder and “difficult-to-machine” materials like thick plates of steels, aluminium and other commercial materials, metal matrix and ceramic matrix composites, reinforced plastics, layered composites etc are reserved for AWJM.

WJM and AWJM have certain advantageous characteristics, which helped to achieve significant penetration into manufacturing industries.

- Extremely fast set-up and programming
- Very little Fixturing for most parts
- Machine virtually any 2D shape on any material
- Very low side forces during the machining
- Almost no heat generated on the part
- Machine thick plates
Unit III

Electro chemical machining


Electrochemical machining (ECM) has been developed initially to machine these hard to machine alloys, although any metal can so be machined. ECM is an electrolytic process and its basis is the phenomenon of electrolysis, whose laws were established by Faraday in 1833. The first significant developments occurred in the 1950s, when ECM was investigated as a method for shaping high strength alloys. As of the 1990s, ECM is employed in many ways, for example, by automotive, offshore petroleum, and medical engineering industries, as well as by aerospace firms, which are its principal user.

Metal removal is achieved by electrochemical dissolution of an anodically polarized workpiece which is one part of an electrolytic cell in ECM. Hard metals can be shaped electrolytically by using ECM and the rate of machining does not depend on their hardness. The tool electrode used in the process does not wear, and therefore soft metals can be used as tools to form shapes on harder workpieces, unlike conventional machining methods. The process is used to smooth surfaces, drill holes, form complex shapes, and remove fatigue cracks in steel structures. Its combination with other techniques yields fresh applications in diverse industries. Recent advances lie in computer-aided tool design, and the use of pulsed power, which has led to greater accuracy for ECM-produced components.

Electrolysis is the name given to the chemical process which occurs, for example, when an electric current is passed between two conductors dipped into a liquid solution. A typical example is that of two copper wires connected to a source of direct current and immersed in a solution of copper sulphate in water, as shown in Figure 1. An ammeter, placed in the circuit, will register a flow of current; from this indication, the electric circuit can be deduced to be complete. A significant conclusion that can be made from an experiment of this sort is that the copper sulphate solution obviously has the property that it could conduct electricity. Such solution is termed an electrolyte. The wires are called electrodes, the one with positive polarity being the anode, and the one with negative polarity the cathode. The system of electrodes and electrolyte is referred to as the electrolytic cell, whilst the chemical reactions which occur at the electrodes are called the anodic or cathodic reactions or processes.

Electrolytes are different from metallic conductors of electricity in that the current is carried not by electrons but by atoms, or group of atoms, which have either lost or gained electrons, thus acquiring either positive or negative charges. Such atoms are called ions. Ions which carry positive charges move through the electrolyte in the direction of the positive current,
that is, toward the cathode, and are called cations. Similarly, the negatively charged ions travel toward the anode and are called anions. The movement of the ions is accompanied by the flow of electrons, in the opposite sense to the positive current in the electrolyte, outside the cell, as shown also in Figure 2 and both reactions are a consequence of the applied potential difference, that is, voltage, from the electric source.

A cation reaching the cathode is neutralized, or discharged, by the negative electrons on the cathode. Since the cation is usually the positively charged atom of a metal, the result of this reaction is the deposition of metal atoms.

To maintain the cathodic reaction, electrons are required to pass around the external circuit. These are obtained from the atoms of the metal anode, and these atoms thus become the positively charged cations which pass into solution. In this case, the reaction is the reverse of the cathodic reaction.

The electrolyte in its bulk must be electrically neutral; that is, there must be equal numbers of opposite charges within it, and thus there must be equal amounts of reaction at both electrodes. Therefore, in the electrolysis of copper sulphate solution with copper electrodes, the overall cell reaction is simply the transfer of copper metal from the anode to the cathode. When the wires are weighted at the end of the experiment, the anodic wire will be found to have lost weight, whilst the cathodic wire will have increased in weight by an amount equal to that lost by the other wire.

Fig 1. Electrolysis of copper sulphate solution.  Fig 2. Electrolytic dissolution of iron.

These results are embodied in Faraday’s two laws of electrolysis:

1. The amount of any substance dissolved or deposited is directly proportional to the amount of electricity which has flowed.
2. The amounts of different substances deposited or dissolved by the same quantity of electricity are proportional to their chemical equivalent weights.

A popular application of electrolysis is the electroplating process in which metal coatings are deposited upon the surface of a cathodically polarized metal. An example of an anodic dissolution operation is electropolishing. Here, the item which is to be polished is made the
anode in an electrolytic cell. Irregularities on its surface are dissolved preferentially so that, on their removal, the surface becomes flat and polished.

ECM is similar to electropolishing in that it also is an anodic dissolution process. But the rates of metal removal offered by the polishing process are considerably less than those needed in metal machining practice.

Some observations relevant to ECM can be made:

- Since the anode metal dissolves electrochemically, its rate of dissolution depends only upon the atomic weight and the ionic charge, the current which is passed, and the time for which the current passes. The dissolution rate is not influenced by the hardness or other characteristics of the metal.
- Since only hydrogen gas is evolved at the cathode, the shape that electrode remains unaltered during the electrolysis. This feature is perhaps the most relevant in the use of ECM as a metal shaping process.

**Electrolysis process:-**

During ECM, there will be reactions occurring at the electrodes i.e. at the anode or workpiece and at the cathode or the tool along with within the electrolyte. Let us take an example of machining of low carbon steel which is primarily a ferrous alloy mainly containing iron. For electrochemical machining of steel, generally a neutral salt solution of sodium chloride (NaCl) is taken as the electrolyte. The electrolyte and water undergoes ionic dissociation as shown below as potential difference is applied

\[ \text{NaCl} \leftrightarrow \text{Na}^+ + \text{Cl}^- \]

\[ \text{H}_2\text{O} \leftrightarrow \text{H}^+ + (\text{OH})^- \]

As the potential difference is applied between the work piece (anode) and the tool (cathode), the positive ions move towards the tool and negative ions move towards the workpiece. Thus the hydrogen ions will take away electrons from the cathode (tool) and from hydrogen gas as:

\[ 2\text{H}^+ + 2e^- = \text{H}_2 \uparrow \text{ at cathode} \]

Similarly, the iron atoms will come out of the anode (work piece) as:

\[ \text{Fe} = \text{Fe}^{2+} + 2e^- \]

Within the electrolyte iron ions would combine with chloride ions to form iron chloride and similarly sodium ions would combine with hydroxyl ions to form sodium hydroxide

\[ \text{Na}^+ + \text{OH}^- = \text{NaOH} \]

In practice \( \text{FeCl}_2 \) and \( \text{Fe(OH)}_2 \) would form and get precipitated in the form of sludge. In this manner it can be noted that the work piece gets gradually machined and gets precipitated as the
sludge. Moreover there is not coating on the tool, only hydrogen gas evolves at the tool or cathode. Fig. 2 depicts the electro-chemical reactions schematically. As the material removal takes place due to atomic level dissociation, the machined surface is of excellent surface finish and stress free.

![Schematic representation of electro-chemical reactions](image)

**Characteristics of ECM**

1. Tool and workpiece electrodes should be conductors of electricity.
2. Atomic level of dissolution happens
3. Surface finish is excellent
4. Almost stress free i.e., machined surface is free from residual stresses
5. No thermal damage
6. Cam machine hard materials with softer tools

**Electrochemical Machine components**

![Fig. 4. Electrochemical Machine.](image)
Industrial electrochemical machines work on the principles outlined. Particular attention has to be paid to the stability of the electrochemical machine tool frame, and to the machining table which should also be stable and firm. The electrolyte has to be filtered carefully to remove the products of machining and often has to be heated in its reservoir to a fixed temperature, for instance 30°C (86°F), before entering the machining apparatus. This procedure is used to provide constant operating conditions. During machining the electrolyte heats up from the passage of current. Precautions must be taken to avoid a high electrolyte temperature which can cause changes in the electrolyte specific conductivity and subsequent undesirable effects on machining accuracy.

**Rates of machining**

The rates at which metals can be electrochemically machined is in proportion to the current passed through the electrolyte and the elapsed time for that operation, and is in inverse proportion to the electrochemical equivalent of the anode-metal which corresponds to the atomic weight of the dissolving ions over the ionic charge times the Faraday’s constant. See the Appendix for more details.

Many factors other than current influence the rate of machining. These involve electrolyte type, rate of electrolyte flow, and some other process conditions. For example, current efficiency decreases when current density is increased for a certain metal, for example, for nickel.

If the ECM of titanium is attempted in sodium chloride electrolyte, usually very low (10–20%) current efficiencies are obtained. When this solution is replaced by some mixture of fluoride-based electrolytes, to achieve greater efficiencies (>60%), a higher voltage is used.

If the rates of the flow are kept too low, the current efficiency of even the most easily electrochemically machined metal is reduced. Insufficient flow does not allow the products of machining to be so readily flushed from the machining gap. When complex shapes have to be produced the design of tooling incorporating the right kind of flow ports becomes a considerable problem.

**Surface finish**

Type of electrolytes used in the process affects the quality of surface finish obtained in ECM. Depending on the material, some electrolytes leave an etched finish. This finish results from the non specular reflection of light from crystal faces electrochemically dissolved at different rates. Sodium chloride electrolyte tends to produce an etched, matte finish with steels and nickel alloys.

The production of an electrochemically-polished surface is usually associated with the random removal of atoms from the anode workpiece, whose surface has become covered with an oxide film. This is governed by the metal-electrolyte combination used. Nonetheless, the mechanisms controlling high-current density electropolishing in ECM are still not completely understood. For example, with nickel-based alloys, the formation of a nickel oxide film seems to
be a prerequisite for obtaining a polished surface; a finish of this quality, of 0.2 µm, has been claimed for Nimonic (a nickel alloy) machined in saturated sodium chloride solution. Surface finishes as fine as 0.1 µm have been reported when nickel-chromium steels are machined in sodium chlorate solution. The formation of an oxide film on the metal surface is considered the key to these conditions of polishing.

Sometimes the formation of oxide film on the metal surface hinders efficient ECM and leads to poor surface finish. For example, the ECM of titanium is rendered difficult in chloride and nitrate electrolytes because the oxide film formed is so passive. Even when higher voltages about 50 V are applied to break the oxide film, its disruption is so non-uniform that deep grain boundary attack of the metal surface can occur.

Occasionally, metals that have undergone ECM have a pitted surface while the remaining area is polished or matte. Pitting normally stems from gas evolution at the anode; the gas bubbles rupture the oxide film.

Process variables also affect surface finish. For example, as the current density is raised the finish generally becomes smoother on the workpiece surface. A similar effect is achieved when the electrolyte velocity is increased. In tests with nickel machined in hydrochloric acid solution the surface finish has been noted to improve from an etched to a polished appearance when the current density is increased from about 8 to 19 A/square centimeter with constant flow velocity.

**Accuracy and dimensional control**

Electrolyte selection plays an important role in ECM. Sodium chloride, for example, yields much less accurate components than sodium nitrate. The latter electrolyte has far better dimensional control owing to its current efficiency - current density characteristics. Using sodium nitrate electrolyte, the current efficiency is greatest at the highest current densities. In hole drilling these high current densities occur between the leading edge of the drilling tool and the workpiece. In the side gap there is no direct movement between the tool and workpiece surface, so the gap widens and the current densities are lower. The current efficiencies are consequently lower in the side gap and much less metal than predicted from Faraday’s law is removed. Thus the over cut in the side gap is reduced with this type of electrolyte. If another electrolyte such as sodium chloride solution was used instead, then the overcut could be much greater. Using sodium chloride solutions, its current efficiency remains steady at almost 100% for a wide range of current densities. Thus, even in the side gap, metal removal proceeds at a rate which is mainly determined by current density, in accordance with Faraday’s law. A wider overcut then ensues.

**Modeling of material removal rate:**

Material removal rate (MRR) is an important characteristic to evaluate efficiency of a non-traditional machining process. In ECM, material removal takes place due to atomic dissolution of work material. Electrochemical dissolution is governed by Faraday’s laws. The
first law states that the amount of electrochemical dissolution or deposition is proportional to amount of charge passed through the electrochemical cell, which may be expressed as:

\[ m \propto Q, \]

Where \( m = \) mass of material dissolved or deposited
\( Q = \) amount of charge passed

The second law states that the amount of material deposited or dissolved further depends on Electrochemical Equivalence (ECE) of the material that is again the ratio atomic weigh and valency. Thus

\[ m \propto ECE \frac{A}{\nu}, \]

Thus \( m \propto \frac{QA}{\nu} \)

where \( F = \) Faraday's constant
\[ = 96500 \text{ coulombs} \]

\[ \therefore m = \frac{tA}{F \nu} \]

\[ \therefore \text{MRR} = \frac{m}{t \rho} = \frac{tA}{F \rho \nu} \]

Where \( I = \) current
\( \rho = \) density of the material

The engineering materials are quite often alloys rather than element consisting of different elements in a given proportion.

Let us assume there are ‘n’ elements in an alloy. The atomic weights are given as \( A_1, A_2, \ldots, A_n \) with valency during electrochemical dissolution as \( \nu_1, \nu_2, \ldots, \nu_n \). The weight percentages of different elements are \( \alpha_1, \alpha_2, \ldots, \alpha_n \) (in decimal fraction)

Now for passing a current of \( I \) for a time \( t \), the mass of material dissolved for any element ‘i’ is given by

\[ m_i = \Gamma_a \rho \alpha_i \]

Where \( \Gamma_a \) is the total volume of alloy dissolved. Each element present in the alloy takes a certain amount of charge to dissolve.

\[ m_i = \frac{Q_i A_i}{F \nu_i} \]

\[ \Rightarrow Q_i = \frac{F m_i \nu_i}{A_i} \]

\[ \Rightarrow Q_i = \frac{F \Gamma_a \rho \alpha_i \nu_i}{A_i} \]

\[ \therefore Q_T = It = \sum Q_i \]

\[ \therefore Q_T = It = \frac{F \Gamma_a \rho \sum \alpha_i \nu_i}{A_i} \]

Now

\[ \text{MRR} = \frac{\Gamma_a}{t} = \frac{1}{F \rho \sum \alpha_i \nu_i} \]
Dynamics of Electrochemical Machining

ECM can be undertaken without any feed to the tool or with a feed to the tool so that a steady machining gap is maintained. Let us first analyse the dynamics with NO FEED to the tool. Fig. 5 schematically shows the machining (ECM) with no feed to the tool and an instantaneous gap between the tool and workpiece of ‘h’.

Now over a small time period ‘dt’ a current of I is passed through the electrolyte and that leads to a electrochemical dissolution of the material of amount ‘dh’ over an area of S

\[
\begin{align*}
I &= \frac{V}{R} = \frac{V}{\frac{m}{s}} = \frac{Vs}{rh} \\
\text{then } \frac{dh}{dt} &= \frac{1}{F} \frac{A_x}{\rho v_x} \left( \frac{Vs}{rh} \right) \\
&= \frac{1}{F} \frac{A_x}{\rho v_x} \frac{V}{rh} \\
\text{for a given potential difference and alloy} \\
\frac{dh}{dt} &= \frac{A_x V}{F \rho v_x r} \cdot \frac{1}{h} = \frac{c}{h}
\end{align*}
\]

where \( c = \text{constant} \)

\[
\begin{align*}
\frac{A_x V}{F \rho v_x r} &= V \\
\frac{c}{h} &= \frac{A_x V}{F \rho v_x r} \\
\therefore \frac{dh}{dt} &= \frac{c}{h} \\
h dh = c dt
\end{align*}
\]
At \( t = 0 \), \( h = h_o \) and at \( t = t_1 \) and \( h = h_1 \)

\[
\frac{h_1 - h_0}{h_o} = c \int_0^{t_1} dt
\]

\[
\Rightarrow h_1^2 - h_0^2 = 2ct
\]

That is the tool–workpiece gap under zero feed condition grows gradually following a parabolic curve as shown in Fig 111.

![Figure 111: Variation of tool-workpiece gap under zero feed condition](image)

Thus dissolution would gradually decrease with increase in gap as the potential drop across the electrolyte would increase.

Now generally in ECM a feed \( (f) \) is given to the tool

\[
\Rightarrow \frac{dh}{dt} = \frac{c}{h} - f
\]

Now if the feed rate is high as compared to rate of dissolution, then after sometime the gap would diminish and may even lead to short circuiting. Under steady state condition the gap is uniform i.e. the approach of the tool is compensated by dissolution of the work material. Thus with respect to the tool, the workpiece is not moving

\[
\text{Thus} \quad \frac{dh}{dt} = 0 \Rightarrow \frac{c}{h} = f
\]

\[
\Rightarrow f = \frac{c}{h} \quad \text{or} \quad h^* = \text{steady state gap} = \frac{cf}{c}
\]

Now under practical ECM condition it is not possible to set exactly the value of \( h^* \) as the initial gap. Thus it is required to be analysed if the initial gap value would have any effect on progress of the process

Now

\[
\frac{dh}{dt} = \frac{c}{h} - f
\]

\[
\text{Now} \quad h^* = \frac{h}{h^*} = \frac{hf}{c}
\]
Now integrating between \( t' = 0 \) to \( t' = t' \) when \( h' \) changes from \( h_0' \) to \( h_1' \):

\[
\int_0^{t'} dt' = \int_{h_0'}^{h_1'} \frac{h'}{1-h'} dh'
\]

\[
\Rightarrow t' = \int_{h_0'}^{h_1'} \frac{d(1-h')}{1-h'} + \int_{h_0'}^{h_1'} \frac{h'}{h_0'} dh'
\]

\[
\Rightarrow t' = h_0' - h_1' + \ln \frac{h_0' - 1}{h_1' - 1}
\]

Now for different values of \( h_0' \), \( h_1' \) seems to approach 1 as shown in Fig. below.

*Fig. Variation in steady state gap with time for different initial gap*
Thus it seems from the above equation that ECM is self regulating as MRR is equal to feed rate.

**Advantage of Electrochemical Machining:**
- No mechanical force
- There is no cutting forces therefore clamping is not required except for controlled motion of the work piece.
- There is no heat affected zone.
- Very accurate.
- Relatively fast
- Can machine harder metals than the tool
- No material corrosion
- Provides smooth surfaces
- No need of harder material that is used in processing.
- More sensitive and repeatable
- Provides of processing complex

**Disadvantages**
1. Solution usage Pump, tank, pipe, filter and sink usage.
2. Keeping the solution conductivity constant.
3. More expensive than conventional machining.
4. Need more area for installation.
5. Electrolytes may destroy the equipment.
6. Not environmentally friendly (sludge and other waste)
7. High energy consumption
8. The effect of the toxic gases and aerosols
9. produced in the course of ECM.
10. Chemical attack by electrolytes.
11. The risk of an electric shock.
12. The danger of a burn in the case of a short circuit between the positive and negative leads.
13. Mechanical factors.
14. The danger of a fire damp explosion.
15. The effects of the electromagnetic field.
16. Material has to be electrically conductive

**Applications**

ECM technique removes material by atomic level dissolution of the same by electrochemical action. Thus the material removal rate or machining is not dependent on the mechanical or physical properties of the work material. It only depends on the atomic weight and valency of the work material and the condition that it should be electrically conductive. Thus ECM can machine any electrically conductive work material irrespective of their hardness, strength or even thermal properties. Moreover as ECM leads to atomic level dissolution, the surface finish is excellent with almost stress free machined surface and without any thermal damage.

ECM is used for
- Die sinking
- Drilling
- Profiling and contouring
- Trepnning
- Grinding
- Micro-machining

Duplicating, drilling and sinking operations in the manufacture of dies, press and glass-making moulds, the manufacture of turbine and compressor blades for gas-turbine engine, the generation of passages, cavities, holes and slots in parts, and the like
ELECTRO CHEMICAL GRINDING

Electro chemical grinding is one of the latest methods of grinding. This method is introduced in early 1970’s. In this process a grinding wheel in which an insulating abrasive is set in a conducting bonding material is employed. The D.C power required here is 5-15V. So for obtaining a voltage between 5 to 15V a step down transformer is used. The metal bonded abrasive wheel (or) the grinding wheel acts as a cathode. The work piece acts as anode. Very small distance between cathode and anode.

An electrolyte is allowed to pass through the gap between the electrodes. The insulating abrasive particles get spread over the surface of the wheel. The height of the abrasive particles over the wheel in the gap between the electrodes indicates effective gap between the electrodes. The electrolysis can take place effectively in between this gap only. The current densities used are 2A/cm² to 3A/cm². The electrolyte that can be employed here should satisfy the following properties.
1) High electrical conductivity
2) Low viscosity and high specific heat chemical stability.
3) Resistance to formation of passive film on work surface.
4) Non-corrosive and non-toxic in nature
5) Readily available and inexpensive.

**Functions of Electrolyte:**
1) These should complete the electrical circuit between tool and work piece.
2) Electrolyte must allow all the desirable machining processes to occur.
3) It should function as a coolant by carrying away the heat generated during the chemical reactions.
4) Electrolyte should be effective in carrying away the products obtained by reactions in machining zone.

**Removal of metal in ECG**
Most of metal removal is done by electrochemical action. But some of the metal is also removed by the contact of abrasive particles to work piece. The abrasive particles have two main functions in electro chemical grinding.
1) To find the effective gap between the anode and cathode
2) To remove any passive layer formed over the work piece.

The metal removal rates in electro chemical grinding are of order 1.0m3/min/100A. But in general it is estimated as 0.5m3/min/100A.

Surface finish obtained by Electro chemical grinding 0.2 to 0.4 microns of plunge grinding can be expected for tungsten carbide tools. It is 0.4 to 0.5 microns in traverse grinding. For various alloys the surface finish is up to 0.4 to 0.6 microns can be easily obtained. If the alloy is hard then the surface finish will be high.

**Accuracy of surface finish**
Tolerances of order 0.01 mm can be easily obtained by employing electro chemical grinding. Even high accuracy can be obtained by removing required machining material in a single pass. If even high accuracies are required then most of metal should be removed in final pass with the same wheel by merely turning off the power supply.

**Advantages of electro chemical grinding**

1. Metal removal rate is very high.
2. Though the machine requires very high investment increased metal removal rate and less abrasive consumption acts as more than compensate for extra capital cost. On large scale production the cost per piece gets highly reduced.
3. Less risk of thermal damage as the heat generated is very low.
4. No presence of burrs on the finished surface.
5. High surface finish and no grinding scratches are present on the finish surface.
6. Pressure over the wheel due to work gets minimized.
Applications of electro chemical grinding

1) This process is extensively used for grinding carbide tools. Electro chemical grinding provides a savage of 75% in wheel cost and 50% in labor cost
2) Electro chemical grinding is also used for grinding fragile (or) very hard and tough materials

Process Parameters
Power Supply
Type direct current
Voltage 2 to 35 V
Current 50 to 40,000 A
Current density \(0.1 \text{ A/mm}^2\) to \(5 \text{ A/mm}^2\)
Electrolyte Material NaCl and NaNO₃
Temperature \(20^\circ \text{C} – 50^\circ \text{C}\)
Flow rate 20 lpm per 100 A current
Pressure 0.5 to 20 bar
Dilution 100 g/l to 500 g/l
Working gap 0.1 mm to 2 mm
Overcut 0.2 mm to 3 mm
Feed rate 0.5 mm/min to 15 mm/min
Electrode material copper, brass, bronze
Surface roughness, \(R_a 0.2 \text{ to } 1.5 \mu \text{m}\)

Shaping

Most metal-shaping operations in ECM utilize the same inherent feature of the process whereby one electrode, generally the cathode tool, is driven toward the other at a constant rate when a fixed voltage is applied between them. Under these conditions, the gap width between the tool and the workpiece becomes constant. The rate of forward movement between the tool and the workpiece becomes constant. The rate of forward movement of the tool is matched by the rate of recession of the workpiece surface resulting from electrochemical dissolution.

Three practical cases are of interest in considering some equations derived for the variation of the interelectrode gap width:

1. When there is no tool movement, the gap width increases indefinitely with the square root of machining time. This condition is often used in deburring by ECM when surface irregularities are removed from components in a few seconds, without the need for mechanical movement of the electrode.
2. When the tool is moved mechanically at a fixed rate toward the workpiece, the gap width tends to a steady value. This inherent feature of ECM, whereby an equilibrium gap width is obtained, is used widely in ECM for reproducing the shape of the cathode tool on the workpiece.

3. Under short-circuit conditions the gap width goes to zero. If some process conditions, such as too small equilibrium gap width caused by too high movement of the tool toward the workpiece, occur, contact between the two electrodes ensues. This causes a short circuit between the electrodes and hence premature termination of machining.

The equilibrium gap is applied widely in the shaping process. Studies of ECM shaping are usually concerned with three distinct problems:

1. The design of the cathode tool shape needed to produce required profile geometry of the anode workpiece.
2. For a given cathode tool shape, prediction of the resultant anode workpiece geometry, for example, hole drilling by ECM.
3. Specification of the shape of the anode workpiece, as machining proceeds. This is most readily predicted for smoothing of surfaces, although for actual shaping of components by ECM, estimates of the machining times as the shape develops provide useful information about the process.

Problems:

1. In electrochemical machining of pure iron a material removal rate of $600 \text{ mm}^3/\text{min}$ is required. Estimate current requirement.

Solution

\[
\text{MRR} = \frac{m}{t} = \frac{Al}{Fv}
\]

\[
\therefore \text{MRR} = \frac{m}{F} = \frac{Al}{Fv} = \frac{600 \text{ mm}^3/\text{min}}{600/60 \text{ mm}^3/\text{s}} = 10 \text{ mm}^3/\text{s} = 10 \times 10^{-3} \text{ cc/s}
\]

\[
\therefore 10 \times 10^{-3} = \frac{56 \times l}{96500 \times 7.8 \times 2}
\]

As
\[
A_{Fe} = 56
\]
\[
\nu_{Fe} = 2
\]
\[
F = 96500 \text{ coulomb}
\]
\[
\rho = 7.8 \text{ gm/cc}
\]

\[
\therefore I = \frac{96500 \times 10 \times 10^{-3} \times 7.8 \times 2}{56}
\]

\[
I = 268.8 \text{ A} \quad \text{Answer}
\]
2. Composition of a Nickel super alloy is as follows: Ni = 70.0%, Cr = 20.0%, Fe = 5.0% and rest Titanium

Calculate rate of dissolution if the area of the tool is 1500 mm$^2$ and a current of 2000 A is being passed through the cell. Assume dissolution to take place at lowest valency of the elements.

$A_{Ni} = 58.71, \rho_{Ni} = 8.9, v_{Ni} = 2$
$A_{Cr} = 51.99, \rho_{Cr} = 7.19, v_{Cr} = 2$
$A_{Fe} = 55.85, \rho_{Fe} = 7.86, v_{Fe} = 2$
$A_{Ti} = 47.9, \rho_{Ti} = 4.51, v_{Ti} = 3$

\[
\rho_{alloy} = \frac{1}{\sum \frac{\alpha_i}{\rho_i}} = \frac{1}{\frac{\alpha_{Ni}}{\rho_{Ni}} + \frac{\alpha_{Cr}}{\rho_{Cr}} + \frac{\alpha_{Fe}}{\rho_{Fe}} + \frac{\alpha_{Ti}}{\rho_{Ti}}} = \frac{1}{0.7 + 0.2 + 0.05 + 0.05 \frac{8.9}{7.19} + \frac{7.86}{7.86} + \frac{4.51}{4.51}} = 8.07 \text{ gm/cc}
\]

Now, MRR = \[
\frac{m}{\rho F} = \frac{1}{F \rho \sum \frac{\alpha_i v_i}{A_i}} = \frac{1000}{96500 \times 8.07 \times \left[ \frac{0.75 \times 2}{58.71} + \frac{0.2 \times 2}{51.99} + \frac{0.05 \times 2}{55.85} + \frac{0.05 \times 3}{47.9} \right]} = 0.0356 \text{ cc/sec} = 2.14 \text{ cc/min} = 2140 \text{ mm}^3/\text{min}
\]

\[
\text{Rate of dissolution} = \frac{\text{MRR}}{\text{Area}} = \frac{2140}{1500} = 1.43 \text{ mm/min} \quad \text{answer}
\]

3. In ECM operation of pure iron an equilibrium gap of 2 mm is to be kept. Determine supply voltage, if the total over voltage is 2.5 V. The resistively of the electrolyte is 50 $\Omega$-mm and the set feed rate is 0.25 mm/min.
\[ h^* = \frac{c}{f} \]

where \( c = \frac{V A_{Fe}}{\mu_0 \rho_{Fe} r_{Fe}} \)

\[
C = \frac{(V - 2.5) \times 55.85}{96600 \times 7.8 \times 10^{-3} \times 60 \times 2}
\]

\[
= \frac{(V - 2.5)}{1347.7}
\]

\[ h^* = 2 = \frac{c}{f} = \frac{(V - 2.5)}{1347 \times \frac{0.25}{60}} \]

\[ 2 - \frac{V - 2.5}{5.615} \]

\[ \therefore V = 8.73 \text{ Volt.} \quad \text{Answer} \]
UNIT IV

THERMAL METAL REMOVAL PROCESSES:


INTRODUCTION

Electro Discharge Machining (EDM) is an electro-thermal non-traditional machining process, where electrical energy is used to generate electrical spark and material removal mainly occurs due to thermal energy of the spark. EDM is mainly used to machine difficult-to-machine materials and high strength temperature resistant alloys. EDM can be used to machine difficult geometries in small batches or even on job-shop basis. Work material to be machined by EDM has to be electrically conductive.

HISTORY

The history of EDM itself begins in 1943, with the invention of its principle by Russian Scientists Boris and Natalya Lazarenko in Moscow. The Soviet government assigned them to investigate the wear caused by sparking between tungsten electrical contacts, a problem which was particularly critical for maintenance of automotive engines during the Second World War. Putting the electrodes in oil, they found that the sparks were more uniform and predictable than in air. They had then the idea to reverse the phenomenon, and to use controlled sparking as an erosion method [9]. Though they could not solve the original wear problem, the Lazarenkos developed during the war the first EDM machines, which were very useful to erode hard metals such as tungsten or tungsten carbide. The “Lazarenko circuit” remained the standard EDM generator for years.

In the 1950’s, progress was made on understanding the erosion phenomenon [10–12]. It is also during this period that industries produced the first EDM machines. Swiss industries were involved very early in this market, and still remain leaders nowadays. Agie was founded in 1954, and les Ateliers des Charmilles produced their first machine in 1955. Due to the poor quality of electronic components, the performances of the machines were limited at this time.
PRINCIPLE AND MECHANISM

Fig. 5.1 shows schematically the basic working principle of EDM process.

In EDM, a potential difference is applied between the tool and workpiece. Both the tool and the work material are to be conductors of electricity. The tool and the work material are immersed in a dielectric medium. Generally kerosene or deionised water is used as the dielectric medium. A gap is maintained between the tool and the workpiece. Depending upon the applied potential difference and the gap between the tool and workpiece, an electric field would be established. Generally the tool is connected to the negative terminal of the generator and the workpiece is connected to positive terminal. As the electric field is established between the tool and the job, the free electrons on the tool are subjected to electrostatic forces. If the work function or the bonding energy of the electrons is less, electrons would be emitted from the tool (assuming it to be connected to the negative terminal). Such emission of electrons are called or termed as cold emission. The “cold emitted” electrons are then accelerated towards the job through the dielectric medium. As they gain velocity and energy, and start moving towards the job, there would be collisions between the electrons and dielectric molecules. Such collision may result in ionisation of the dielectric molecule depending upon the work function or ionisation energy of the dielectric molecule and the energy of the electron. Thus, as the electrons get accelerated, more positive ions and electrons would get generated due to collisions. This cyclic process would increase the concentration of electrons and ions in the dielectric medium between the tool and the job at the spark gap. The concentration would be so high that the matter existing in that channel could be characterised as “plasma”. The electrical resistance of such plasma channel would be very less. Thus all of a sudden, a large number of electrons will flow from the tool to the job and ions from the job to the tool. This is called avalanche motion of electrons. Such movement of electrons and ions can be visually seen as a spark. Thus the electrical energy is dissipated as the thermal energy of the spark.

The high speed electrons then impinge on the job and ions on the tool. The kinetic energy of the electrons and ions on impact with the surface of the job and tool respectively would be converted
into thermal energy or heat flux. Such intense localised heat flux leads to extreme instantaneous confined rise in temperature which would be in excess of 10,000 °C.

Such localised extreme rise in temperature leads to material removal. Material removal occurs due to instant vapourisation of the material as well as due to melting. The molten metal is not removed completely but only partially.

As the potential difference is withdrawn as shown in Fig. 1, the plasma channel is no longer sustained. As the plasma channel collapse, it generates pressure or shock waves, which evacuates the molten material forming a crater of removed material around the site of the spark.

Thus to summarise, the material removal in EDM mainly occurs due to formation of shock waves as the plasma channel collapse owing to discontinuation of applied potential difference.

Generally the workpiece is made positive and the tool negative. Hence, the electrons strike the job leading to crater formation due to high temperature and melting and material removal. Similarly, the positive ions impinge on the tool leading to tool wear.

In EDM, the generator is used to apply voltage pulses between the tool and the job. A constant voltage is not applied. Only sparking is desired in EDM rather than arcing. Arcing leads to localised material removal at a particular point whereas sparks get distributed all over the tool surface leading to uniformly distributed material removal under the tool.

![Electric Discharge Machine](image)

**Fig.5.2 Electric Discharge Machine**
EDM Process

EDM spark erosion is the same as having an electrical short that burns a small hole in a piece of metal it contacts. With the EDM process both the workpiece material and the electrode material must be conductors of electricity.

The EDM process can be used in two different ways:

1. A preshaped or formed electrode (tool), usually made from graphite or copper, is shaped to the form of the cavity it is to reproduce. The formed electrode is fed vertically down and the reverse shape of the electrode is eroded (burned) into the solid workpiece.

2. A continuous-travelling vertical-wire electrode, the diameter of a small needle or less, is controlled by the computer to follow a programmed path to erode or cut a narrow slot through the workpiece to produce the required shape.

Basic parts of EDM:

1. **Base and container:**
   It should be made of non-conducting and transparent material. The container is filled with the dielectric solution.
A base to hold the work piece is installed at the bottom of the container, the base is made of conductive material

2. **Tool**
   It is given negative polarity. It is made of copper, brass and tungsten. It is pre-shaped, so that a reverse shape is coded into the work piece. Even the tool can be made of non-metals like graphite.

3. **Dielectric**
   Dielectric fluid plays an important role in the EDM process. Because of a high dielectric strength, the dielectric medium prevents premature discharge between the electrodes until a low discharge gap is established between them. Continuous dielectric flow in the discharge gap helps in carrying away the debris formed during the discharge and ensures a proper flushing. Also, dielectric medium cools the machining zone by carrying away excess heat from the tool electrode and the work piece.

4. **Tool feed mechanism—servo mechanism**
   It can be achieved by gear, rack and pinion arrangement. The servo mechanism compares the gap voltage to a reference value and it ensures that the needed spark gap is maintained by providing the needed tool feed movement. The servo control can be achieved by electro hydraulic.

5. **Dc power supply**
   Pulsating dc power supply with high voltages needed

   Ac power supply is converted into dc power supply by means of rectifiers (that employ diode—which enable current to flow in a single direction). Step up transformers are also used to get the needed voltage levels.

   MRR and Surface finish depends on the spark energy. Spark is controlled by dc power supply. The power supply works by pulsing (on or off). The current at frequencies of 200-500kHz.

**Process Parameters**

The process parameters in EDM are mainly related to the waveform characteristics. Fig.5.4. below shows a general waveform used in EDM.
The waveform is characterised by the
- The open circuit voltage - $V_o$
- The working voltage - $V_w$
- The maximum current - $I_o$
- The pulse on time – the duration for which the voltage pulse is applied - $t_{on}$
- The pulse off time - $t_{off}$
- The gap between the workpiece and the tool – spark gap - $\delta$
- The polarity – straight polarity – tool (-ve)
- The dielectric medium
- External flushing through the spark gap.

**Characteristics of EDM**

(a) The process can be used to machine any work material if it is electrically conductive
(b) Material removal depends on mainly thermal properties of the work material rather than its strength, hardness etc
(c) In EDM there is a physical tool and geometry of the tool is the positive impression of the hole or geometric feature machined
(d) The tool has to be electrically conductive as well. The tool wear once again depends on the thermal properties of the tool material
(e) Though the local temperature rise is rather high, still due to very small pulse on time, there is not enough time for the heat to diffuse and thus almost no increase in bulk temperature takes place. Thus the heat affected zone is limited to $2 – 4 \mu m$ of the spark crater.
(f) However rapid heating and cooling and local high temperature leads to surface hardening which may be desirable in some applications
(g) Though there is a possibility of taper cut and overcut in EDM, they can be controlled and compensated.
Electric Discharge Machine (EDM) Capabilities:

There are a lot of benefits when using electrical discharge machine (EDM) when machining. This is due to its capabilities and advantage. To summarize, these are the electric discharge machine (EDM) capabilities compare to other method.

- Material of any hardness can be cut
- High accuracy and good surface finish are possible
- No cutting forces involved
- Intricate-shaped cavities can be cut with modest tooling costs
- Holes completed in one “pass”

Modelling of Material Removal and Product Quality

Material removal in EDM mainly occurs due to intense localised heating almost by point heat source for a rather small time frame. Such heating leads to melting and crater formation as shown in Fig.

![Schematic representation of crater formation in EDM process.](image)

The molten crater can be assumed to be hemispherical in nature with a radius \( r \) which forms due to a single pulse or spark. Hence material removal in a single spark can be expressed as

\[
\Gamma_s = \frac{2}{3}\pi r^3
\]

Now as per Fig. 2, the energy content of a single spark is given as

\[
E_s = VI_{on}
\]

A part of this spark energy gets lost in heating the dielectric, and rest is distributed between the impinging electrons and ions. Thus the energy available as heat at the workpiece is given by
Now it can be logically assumed that material removal in a single spark would be proportional to the spark energy. Thus

\[ E_v \propto E_s \]
\[ E_w = kE_s \]

Now material removal rate is the ratio of material removed in a single spark to cycle time.

Thus

\[ \Gamma_s = \frac{E_s}{t_{c}} \]
\[ \therefore \Gamma_s = gE_s \]

The model presented above is a very simplified one and linear relationship is not observed in practice. But even then such simplified model captures the complexity of EDM in a very efficient manner. MRR in practice does increase with increase in working voltage, current, pulse on time and decreases with increase in pulse off time.

Product quality is a very important characteristic of a manufacturing process along with MRR. The followings are the product quality issues in EDM

- Surface finish
- Overcut
- Tapercut

No two sparks take place side by side. They occur completely randomly so that over time one gets uniform average material removal over the whole tool cross section. But for the sake of simplicity, it is assumed that sparks occur side by side as shown in Fig. 5.6

**Fig. 5.6** Schematic representation of the sparks in EDM process.
Thus it may be noted that surface roughness in EDM would increase with increase in spark energy and surface finish can be improved by decreasing working voltage, working current and pulse on time.

In EDM, the spark occurs between the two nearest point on the tool and workpiece. Thus machining may occur on the side surface as well leading to overcut and taper cut as depicted in Fig. 5.7. Taper cut can be prevented by suitable insulation of the tool. Overcut cannot be prevented as it is inherent to the EDM process. But the tool design can be done in such a way so that same gets compensated.

![Fig. 5.7 Schematic depiction of taper cut and over cut and control of taper cut](image)

**Power supply parameters:**

Fig.5.4 depicted general nature of voltage pulses used in electro-discharge machining. Different power generators are used in EDM and some are listed below:

- Resistance-capacitance type (RC type) Relaxation generator
• Rotary impulse type generator
• Electronic pulse generator
• Hybrid EDM generator

Analysis of RC type Relaxation EDM Generator

In RC type generator, the capacitor is charged from a DC source. As long as the voltage in the capacitor is not reaching the breakdown voltage of the dielectric medium under the
prevailing machining condition, capacitor would continue to charge. Once the breakdown voltage is reached the capacitor would start discharging and a spark would be established between the tool and workpiece leading to machining. Such discharging would continue as long as the spark can be sustained. Once the voltage becomes too low to sustain the spark, the charging of the capacitor would continue. Fig. 5.9 shows the working of RC type EDM relaxation.

![Fig. 5.9 Schematic of the working principle of RC type EDM relaxation circuit.](image)

During charging, at any instant, from circuit theory,

\[
\frac{dV}{V_o - V_c} = \frac{1}{CR_c} \frac{dt}{dt}
\]

At \( t = 0 \), \( V_c = 0 \) and \( t = t_c \), \( V_c = V_c^* \)

\[
\frac{V_c^*}{V_o - V_c} = \frac{1}{CR_c} \int_0^{t_c} dt
\]

\[
\Rightarrow -\frac{t_c}{R_c} = \ln(V_o - V_c) V_c^*
\]

\[
V_c^* = V_o \left(1 - e^{-\frac{t_c}{R_c C}} \right)
\]

or \( V_c = V_o \left(1 - e^{\frac{t}{R_c C}} \right) \)

where,

\( I_c \) = charging current

\( V_o \) = open circuit voltage

\( R_c \) = charging resistance
\[ C = \text{capacitance} \]
\[ V_c = \text{instantaneous capacitor voltage during charging} \]

Thus at any instant charging current, \( i_c \), can be given as:

\[
i_c = \frac{V_o - V_c}{R_c} = \frac{V_o - V_c \left(1 - e^{-\frac{t}{R_cC}}\right)}{R_c}
\]

\[
i_c = \frac{V_o e^{-\frac{t}{R_cC}}}{R_c} - i_0 e^{-\frac{t}{R_cC}}
\]

During discharging, the electrical load coming from the EDM may be assumed a totally resistive and is characterised by a machine resistance of \( R_m \). Then the current passing through the EDM machine is given by

\[
i_d = \frac{V_c}{R_m} = -C \frac{dV_c}{dt}
\]

Where, \( I_d = \text{discharge current or current flowing through the machine} \)
\[ V_c = \text{instantaneous capacitor voltage during discharging} \]
\[ R_m = \text{machine resistance} \]

The negative sign in front of the derivative of the voltage represents that the \( V_c \) is gradually decreasing during discharging.

Now at \( t = 0 \) (i.e. at the start of discharging, i.e. initiation of the spark), \( V_c = V_c^* \) and at \( t = t_d \), \( V_c = V_d^* \)

\[
\frac{V_c^*}{V_c} - \frac{1}{CR_m} \int_0^{t_d} dt
\]

\[
\therefore \quad \frac{t_d}{CR_m} = \ln \frac{V_d^*}{V_c}
\]

\[
\therefore \quad V_d^* = \frac{V_c^*}{R_m} e^{-\frac{t_d}{R_m C}}
\]
The discharging or the machining current \( I_d \) is given by

\[
I_d = \frac{V_d}{R_m} = \frac{V_c^*}{R_m} e^{\frac{t}{R_mC}}
\]

Thus the voltage and the current pulses during charging and discharging is given in Fig. 5.10.

Fig. 5.10. Schematic representation of the current pulses during charging and discharging in EDM process.

For maximum power dissipation in RC type EDM generator \( V_c^* = 0.716 \ V_o \).

The charging time or idle time or off time, \( t_c \), can be expressed as

\[
t_c = -\frac{R_mC}{\ln\left(\frac{V_c^*}{V_c}\right)}
\]

The discharging time or machining time or on time can be expressed as

\[
t_d = -\frac{R_dC}{\ln\left(\frac{V_d}{V_o}\right)}
\]

:: Frequency of operation, \( f \)
Total energy discharged through spark gap

\[
I = \frac{1}{t_e + t_a} = \frac{1}{\frac{R_c C}{\ln \left(1 - \frac{V_e}{V_c}\right)} + \frac{R_m C}{\ln \left(1 - \frac{V_d}{V_c}\right)}}
\]

\[
\begin{align*}
&= \int_{0}^{2t} \sqrt{\frac{2}{R_m}} \; dt = \left[ \sqrt{\frac{2}{R_m}} \right]_0^{2t} R_m e^{-\frac{2t}{R_m C}} dt \\
&= \frac{V_c}{R_m} \left[ 1 - e^{-\frac{2t}{R_m C}} \right]_0^{2t} \\
&\approx \frac{1}{2} CV_c^2
\end{align*}
\]

**EDM Process Capability**

**MRR**

Range from 2 to 400 mm³/min. High rates produce rough finish, having a molten and recast structure with poor surface integrity and low fatigue properties.

**Dimensional Tolerances**

Function of the material being processed

Typically between ±0.005 - ±0.125 mm

**Surface Finish**

Depends on current density and material being machined

Ra varies from 0.05 – 12.5 μm

New techniques use an oscillating electrode, providing very fine surface finishes.

\[
MRR = 4 \times 10^4 I T_w^{-1.23}
\]

MRR=mm³/min
I = current in amperes
Tw = melting point of workpiece (°C)

**Wear rate of electrode (TOOL):**

\[ W_t = 11 \times 10^3 I T_t^{2.38} \]

Wt = mm³/min
Tt = melting point of electrode material (°C)

**Wear ratio of workpiece to electrode:**

\[ R = 2.25 T_r^{-2.3} \]

Tr = ratio of workpiece to electrode melting points (°C)

**Experimental Approach:**

\[ MRR = Vc f \dot{\eta} \]

Where f = frequency of operation and
\[ \dot{\eta} = \text{efficiency} \]

Metal removal is function of pulse energy and frequency:

\[ h = K1 W_n \]
\[ D = K2 W_n \]

Where
W = Pulse energy, J
h = height of crater, mm
D = diameter of crater, mm
K1, K2 = constants depending on electrode materials and dielectric
n = constant depending on work tool combination

The crater volume from geometry,

\[ V_c = \frac{\pi}{6} h \left( \frac{3}{4} D^2 + h^2 \right) \]
\[ V_c = \frac{\pi}{6} K_1 \left( \frac{3}{4} K_2^2 + K_1^2 \right) W^{3n} \]

Advantages of EDM are:
- By this process, materials of any hardness can be machined;
- No burrs are left in machined surface;
- One of the main advantages of this process is that thin and fragile/fragile components can be machined without distortion;
- Complex internal shapes can be machined

ELECTRIC DISCHARGE MACHINE (EDM) LIMITATIONS:

But, when using electric discharge machine (EDM) when machining there are a few limitation. These are electric discharge machine (EDM) limitation
- Limited to electrically conductive materials
- Slow process, particularly if good surface finish and high accuracy are required
- Dielectric vapour can be dangerous
- Heat Affected Zone (HAZ) near cutting edges
- Die sinking tool life is limited.

Improving the MRR (Metal removal rate) and TWR (Tool wear rate):

MRR and TWR can be increased by using suitable electrode design and by using powder mixed dielectric
DIELECTRIC FLUID IN EDM:

FUNCTIONS OF DIELECTRIC FLUID

Dielectric fluid plays an important role in the EDM process. Because of a high dielectric strength, the dielectric medium prevents premature discharge between the electrodes until a low discharge gap is established between them. Continuous dielectric flow in the discharge gap helps in carrying away the debris formed during the discharge and ensures a proper flushing. Also, dielectric medium cools the machining zone by carrying away excess heat from the tool electrode and the work piece.

PROPERTIES OF DIELECTRIC FLUID

The most important properties of dielectric are its dielectric strength, viscosity, thermal conductivity and thermal capacity. Dielectric strength characterizes the fluid’s ability to maintain high resistivity before spark discharge and the ability to recover rapidly after the discharge. High dielectric strength leads to a lower discharge gap which in turn leads to a low gap resistance. Hence, high discharge currents may flow leading to a higher material removal rate. Also, fluids with high dielectric strength need lower time for the recovery of dielectric strength. Thus, low pulse-off times are sufficient. This not only improves the MRR but also provides better cutting efficiency because of a reduced probability of arcing. Liquids with low viscosity generally provide better accuracies because of a better flow ability of the oil leading to improved flushing. Also, the sideward expansion of the discharge plasma channel is restricted by high viscosity fluids. This focuses the discharge energy over a small region and leads to a deeper crater which reduces the surface finish. Dielectric fluids with high thermal conductivity and thermal heat capacity can easily carry away excess heat from the discharge spot and lead to a lower thermal damage.

TYPES OF DIELECTRIC

Selection of dielectric medium is an important consideration for EDM performance. Mineral oils are commonly used as the dielectric medium for die sinking EDM operations. Mineral oils exhibiting high dielectric strength and a low viscosity are preferred because of their higher performance. For safety reasons oils with a high flash point are usually used. Kerosene is one such oil which is used commonly for EDM. Water based dielectrics are used almost extensively for wire EDM operations. Water has a high specific heat capacity which leads to a better cooling effect required for wire cut operations. To prevent chemical reactions, deionized water is used in such applications.
**Table 5.1: Comparison of electrical, thermal and mechanical properties of mineral oil, deionized water and air**

<table>
<thead>
<tr>
<th>Medium</th>
<th>Dielectric Strength (MV/m)</th>
<th>Dynamic Viscosity (g/m-s)</th>
<th>Thermal Conductivity (W/m-K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kerosene</td>
<td>14-22</td>
<td>1.64</td>
<td>0.149</td>
</tr>
<tr>
<td>Deionized water</td>
<td>13</td>
<td>0.92</td>
<td>0.606</td>
</tr>
<tr>
<td>Air</td>
<td>3</td>
<td>0.019</td>
<td>0.026</td>
</tr>
</tbody>
</table>

In comparison to mineral oils and water, air has the lowest dielectric strength, viscosity, thermal conductivity and thermal capacity as shown in Table. Low viscosity air medium favors higher cutting accuracy and better surface finish. However, low dielectric constant suggests a lower MRR with air medium. Low thermal capacity and thermal conductivity suggests higher thermal damage of work piece. However, for a complete analysis of the thermal damage an opposing effect caused by the expansion of plasma channel due to low viscosity must also be accounted. Thus, overall it seems that using air as dielectric may be a better alternative for improving some of the process performance such as surface finish and accuracy at the expense of the MRR.

**POWDER MIXED EDM (PMEDM)**

Powder mixed electric discharge machining (PMEDM) is one of the new innovations for the enhancement of capabilities of electric discharge machining process. In this process, a suitable material in fine powder is properly mixed into the dielectric fluid. The added powder improves the breakdown characteristics of the dielectric fluid. The insulating strength of the dielectric fluid decreases and as a result, the spark gap distance between the electrode and work piece increases. Enlarged spark gap distance makes the flushing of debris uniform. This results in much stable process thereby improving material removal rate and surface finish. Fig. below shows the principle of powder mixed EDM.
When voltage is applied the powder particles become energized and behave in a zigzag fashion. These charged particles are accelerated due to the electric field and act as conductors promoting breakdown in the gap. This increases the spark gap between tool and the work piece. Under the sparking area, these particles come close to each other and arrange themselves in the form of chain like structures. The interlocking between the powder particles occurs in the direction of flow of current. The chain formation helps in bridging the discharge gap between the electrodes. Because of bridging effect, the insulating strength of the dielectric fluid decreases resulting in easy short circuit. This causes early explosion in the gap and series discharge’ starts under the electrode area. The faster sparking within a discharge causes faster erosion from the work piece surface and hence the material removal rate increases.

**VARIOUS POWDERS USED IN PMEDM ARE**

- Silicon carbide
- Boric acid
- Graphite
- Chromium powder
- Aluminium etc.

**PROPERTIES OF POWDER AFFECTING MRR AND TWR**

- Concentration
- Size
- Electrical and thermal conductivity.

A number of research works have been reported for different combinations of materials, powders and operating conditions. Erden and Bilgin [1] investigated mixing of copper, aluminum, iron and carbon powders in kerosene oil as dielectric for machining of brass–steel and copper–steel pairs. The machining rate was found to increase with powder particle concentration
obtained due to the decrease in time lag at high impurity concentrations. It was found that the concentration, size, density, electrical resistivity and thermal conductivity of powders significantly affect the machining performance. Addition of appropriate amount of powders to the dielectric fluid resulted in increased MRR and decreased TWR. For a fixed concentration of particles, the smallest size of the particle led to highest MRR and lowest TWR.

Jeswani investigated the effect of the addition of fine graphite powder into kerosene oil as dielectric. The experimentation resulted in 60% increase in MRR and 28% reduction in wear ratio. The results indicate that Al and Cr mixture in kerosene fluid reduces the isolation and increases the spark gap. With this, the process gets stabilized and the MRR is enhanced considerably.

**Tool Steels**

Tool steels as work pieces are steels that are primarily used to make tools used in manufacturing processes as well as for machining metals, woods, and plastics. Tool steels are generally ingot-cast wrought products, and must be able to withstand high specific loads as well as be stable at elevated temperatures. The tool steels that used in this experiment is high speed tools steel (XW42 Tool Steel). High-Speed Tool Steels: High-speed alloys include all molybdenum (M1 to M52) and tungsten (T1 to T15) class alloys. High-speed tools steels can be hardened to 62-67 HRC and can maintain this hardness in service temperatures as high as 540 °C (1004°F), making them very useful in high-speed machinery. Typical applications are end mills, drills, lathe tools, planar tools, punches, reamers, routers, taps, saws, broaches, chasers, and hobs.

**Electrode design**

The electrode has to be designed to reduce the tool wear and to improve the MRR. When selecting an electrode material for using in machining in electric discharge machine (EDM), several factors must be considered, including the cost, strength, resistance to wear, and

<table>
<thead>
<tr>
<th>FORMULAS:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MATERIAL REMOVAL RATE (MRR):</strong></td>
</tr>
</tbody>
</table>
| \[
\text{MRR} = \frac{\text{Work piece weight loss (g)}}{\text{Machining time (sec)}}
\] |
| **TOOL WEAR RATE:** |
| \[
\text{TWR} = \frac{\text{Electrode weight loss (g)}}{\text{Machining time (sec)}}
\] |
The machinability of a material is difficult to quantify, but can be said to possess the following characteristics:

1. Provides faster rate for production; higher material removal rate (MRR)
2. Promotes long tool life; less electrode wear ratio (EWR)
3. Easy to find, lower cost and available.
4. Results in a good surface finish; (finishing surface free from electrode that have wear)

**Wire EDM:**

EDM, primarily, exists commercially in the form of die-sinking machines and wire-cutting machines (Wire EDM). This process introduced to avoid the effects of distortion of tool due to erosion. 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 removed particles are flushed away by the flowing dielectric fluids.

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.
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 possess 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

Wire diameters range from 0.08 to 0.30 mm, depending on required kerf width. Materials used for the wire include brass, copper, tungsten, and molybdenum. Dielectric fluids include deionized water or oil. As in EDM, an overcut in the range from 0.02 to 0.05 mm exists in wire EDM that makes the kerf larger than the wire diameter.

**MRR in Wire EDM**

\[
MRR = V_f \cdot h \cdot b
\]

*where, \( b = d_w + 2s \)*

MRR = mm³/min

\( V_f \) = feed rate of wire into the

Workpiece in mm/min

\( h \) = workpiece thickness or height in mm

\( d_w \) = wire diameter in mm

\( s \) = gap between wire and workpiece in mm

**Advantages of EDM**

The main advantages of EDM are:

- By this process, materials of any hardness can be machined;
- No burrs are left in machined surface;
- One of the main advantages of this process is that thin and fragile/brittle components can be machined without distortion;
- Complex internal shapes can be machined
Limitations of EDM

The main limitations of this process are:

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

EDM Applications:

Widely used in aerospace, mold making, and die casting to produce die cavities, small deep holes, narrow slots, turbine blades, and intricate shapes

![Stepped cavities](image1)

![cavities produced](image2)

Difficult internal parts made by EDM process
UNIT-V

Generation and control of electron beam for machining, theory of electron beam machining, comparison of thermal and non-thermal processes – General Principle and application of laser beam machining – thermal features, cutting speed and accuracy of cut.

Electron-Beam Machining (EBM)

How it Works

- A stream of electrons is started by a voltage differential at the cathode. The concave shape of the cathode grid concentrates the stream through the anode.

- The anode applies a potential field that accelerates the electrons.

- The electron stream is then forced through a valve in the electron beam machine.

- The beam is focused onto the surface of the work material, heating, melting, and vaporizing the material.

Schematic Illustration of Electron-Beam Machining Process
The entire process occurs in a vacuum chamber because a collision between an electron and an air molecule causes the electrons to veer off course. LBM doesn’t need vacuum because the size and mass of a photon is numerous times smaller than the size of an electron.

**EBM CHARACTERISTICS:**

- Mechanics of material removal – melting, vaporization
- Medium – vacuum
- Tool-Beam of electrons moving at very high velocity
- Maximum MRR = 10 mm³/min
- Specific power consumption = 450 W/mm³/min
- Critical parameters – accelerating voltage, beam diameter, work speed, melting temperature.
- Material applications – all materials
- Shape applications – Drilling fine holes, cutting contours in sheets, cutting narrow slots.
- Limitations – very high specific consumption, necessity of vacuum, expensive machine.
Electron beam machining (EBM)

Electron beam machining (EBM) is one of several industrial processes that use electron beams. Electron beam machining uses a high-velocity stream of electrons focused on the workpiece surface to remove material by melting and vaporization. A schematic of the EBM process is illustrated in the figure:

The setup of electron beam machining process.

An 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 approx. 150,000 V to create velocities over 200,000 km/s. The lens is capable of reducing the area of the beam to a diameter as small as 0.025 mm. 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 very localized area. EBM must be carried out in a vacuum chamber to eliminate collision of the electrons with gas molecules.

The process of Electron Beam Machining (EBM) can be divided into two categories: ‘Thermal type’ and ‘Non-thermal type’. In non-thermal EBM process, the electron beam is used to cause a chemical reaction. In the thermal type EBM process, a thermo-electronic cathode is heated to a very high temperature resulting into the release of electrons from the cathode surface. The free electrons are made to travel towards the anode at high speed in the form of a very small diameter electron stream. Thus, a large number of free electrons travel towards the anode per unit time. The velocity of the electrons stream is closer to the velocity of light. The work piece is heated in a localized area by the bombardment of high velocity electrons beam, to such a high temperature that it melts and, in some cases, and it vaporizes also.

The kinetic energy of the striking electrons is converted into heat which is responsible for melting and vaporization of work piece material. This process can machine both electrically conducting as well as non-conducting materials like metals, ceramics, plastics, etc. Before
machining starts, vacuum is created in the machining chamber. However, with present day configuration of the EBM machine, the vacuum is not essential. The diameter or the size of the hole machined in this case is slightly larger than the diameter of the electron beam focused onto the work piece surface. The properties of the work piece surface like strength and hardness do not affect the EBM performance. On the exit side of the hole or cavity being made, the synthetic or organic backing material is placed. The electron beam after complete penetration into the work piece, partly penetrates into the auxiliary backing material, which vaporizes and flows out of drilled hole at a high pressure. This helps in expulsion of the molten material out of the cavity along with the vaporized backing material. This process can be used to make circular as well as non-circular holes. The electron beam can be deflected with the help of the computer control, along the perimeter of the hole to be produced. However, usually, the beam is kept stationary but the work-table is moved in the desired path with the help of computer numerical control (CNC).

**Equipment**

There are three important elements of EBM equipment, viz., vacuum system, electron beam gun and the DC power supply.

**Electron Beam Gun** is used to produce electrons beam of the desired size, and to focus at the predetermined location. EBM gun is operated in the pulsed mode. A superheated cathode (tungsten filament type) generates the electrons cloud. Sometimes cathode may be used as a solid block indirectly heated by radiation emitted from a filament. Due to the force of repulsion from the cathode, electrons move at a very high acceleration towards the anode, which attracts them. The velocity with which electrons pass through the anode is approximately 66% that of light. On the path of electrons, there is a kind of switch (bias electrode), which generates pulses. A magnetic lens is used to shape the electrons beam into a converging beam. This beam is passed through a variable aperture to reduce the diameter of the focused beam by removing the stray electrons. Deflection coils are used to pinpoint the location of the beam. The electric power supply generates a voltage as high as 150 kV in order to help accelerate the electrons. The system usually operates at about 12 kW and individual pulse energy as high as 120 J/pulse. The power density at the work surface is very high which is capable to melt and vaporize any work piece material. The electrons beam generation and the machining take place in a vacuum chamber. The vacuum of the order of $10^{-4} - 10^{-5}$ torr helps in two ways: it does not allow rapid oxidation of incandescent filament and also there is no loss of energy of electrons as a result of collision with air or neutral gas molecules.

**Process Parameters and Characteristics**

- The important parameters in EBM process are the beam current, duration of pulse, lens current and signals for the deflection of beam. The values of these parameters during EBM are controlled with the help of a computer.

- Power density is the main factor that influences material removal. Power density is affected by how efficiently a beam is focused. For an unfocused beam power density is around 1 watt/mm² & for a highly focused beam the power density is around tens of KW/mm².
• Power density enables the W/P melting and Vaporization.

• The other factors that influence Material removal are Beam current & Pulse Duration.

• Beam current & Pulse Duration determine the energy/pulse- it ranges around 120J/Sec & if energy/pulse increases the hole can be drilled faster.

• Spot sizes determine the hole diameter-100μm to 1mm & the hole depth can be as deep as 15 mm. The depth to diameter ration is high in EBM.

• Beam current varies from 100 μA to 1A and it governs the rate at which a hole can be drilled. Pulse duration ranges from 50μs to 10 ms and it depends upon the depth and diameter of the hole to be drilled. If longer Pulse duration is used- it results in deeper and wider drilled holes but It also affects the HAZ as well as thickness of the recast layer which is normally 25 μm or less. HAZ should be kept as small as possible. Thus multiple pulses are to be used to drill a hole in a thicker material. The working distance is defined as the distance between the electron beam gun and the focal point. The working distance and the focused beam size (diameter) are determined by the magnitude of the lens current. It is always desirable to have the focal point of the electron beam lying on the work piece surface being machined. Hence, in case of deep holes, the linear material removal rate and feed rate should always be equal. The shape of the hole along its axis (straight, tapered, etc.) is determined by the location of the focal point above or below the top surface of the work piece. To obtain a hole shape other than circular the relative movement between the electrons beam and work piece has be programmed on a CNC-EBM machine. Also the deflection coils in EBM help in machining non-circular contours.

• It is experimentally found that hole drilling rate decreases as the diameter of the hole increases.

• The work piece has no electric polarity. Hence, this process can be used to machine both electrically conductive as well as non-conductive materials, viz. Ni, Cu, Al, ceramics, leather, plastics, etc. Material removal rate of the EBM process is not influenced significantly by the physical, mechanical and metallurgical properties of work piece material.

• The geometry of the hole and the depth of the hole to be drilled determine the average machining rate (or penetration rate). Fragile (or brittle), thin, and low strength work pieces can be easily machined by this process because no mechanical force is exerted on to the work. Further, by tilting the work piece appropriately, off-the-axis holes and inclined holes can also be machined. However, very high temperature gradient produced during the process may result into the generation of residual thermal stresses.

• The EBM equipment cost is very high. The operator should be skilled one. Thermal properties of the work piece material and the pulse energy determine the quality of the edges of a hole produced. The heat-affected zone (HAZ) depends upon beam current, feed rate and the diameter of the hole being drilled.
Applications
To make complex shape accurate workpieces, the EBM machine parameters like beam power, focus, and mechanical motions are numerically controlled. This process is commonly used for making fine gas orifices in space nuclear reactors, very fine holes in dies, metering holes in injector nozzles, etc. It is being used for pattern generation in case of integrated circuit fabrication. This process is used for making thousands of holes (dia. < 1 mm) in very thin plates used for turbine engine combustor dome, filters used in textile and food processing industries and similar other applications. This process is also used in industries like aerospace, insulation, chemical and others.

Disadvantages: High investment cost, high maintenance & energy costs. Maintaining the needed vacuum conditions is very difficult. Needs a skilled operator. This process should be enclosed as it might result in emission of harmful X rays.

Non-Thermal EBM- The main application is EBM curing. Curing is a term in Polymer chemistry where in polymers when exposed to Electron Beams get toughened or Hardened due to cross linking of Polymer Chains.

These polymers or Resins that need to be cured by EBM should be Radiation Sensitive. These resins after the curing process due to good cross linking can provide greater stability at higher temperatures, so these can be used to insulate Spark plug wires (Automotive Applications).

The curing process using EBM is faster compared to the normal curing methods. Also multiple materials can be cured concurrently.

This process can be also used for curing of inks & paints as well.

LASER BEAM MACHINING (LBM)

• Laser beam have wide industrial applications including some of the machining processes. A laser is an optical transducer that converts electrical energy into a highly coherent light beam. One must know the full name of laser, it stands for “light amplification of stimulated emission of radiation”. Laser being coherent in nature has a specific property, if it is focused by conventional optical lenses can generate high power density. Outside energy source is used to trigger the stimulated emission.

• Light packets are called as photons.

• In LBM the external energy source should be efficient enough to stimulate the atoms in a Lasing medium (Solid- Ruby or gas-Co2, He or N2) to higher energy levels. Thus the generation of a photon from a single atom results in stimulated emission of photons from all the stimulated atoms. The light energy gets multiplied as the # of photons increase. The generated photons are made to reciprocate in the lasing medium using reflectors thus helping the generation of multiple photons.

• Laser is produced by population inversion-it is a stage where the # of excited atoms or molecules in a system are more than the # of atoms or molecules in a non excited state.
• Light energy of a particular frequency can be used to stimulate the emission of photons from atoms in a lasing medium. The photons emitted are of the same characteristics (wave length, phase, direction and energy) as the stimulating light source.

• Laser light is mono-chromatic in nature- i.e. the wave length occupies a very narrow portion of the spectrum- Wave lengthy of a laser ranges from 0.21μm to 11 μm. Since Laser beam is mono-chromatic a simple lens can be used to converge & focus the beam to drill small holes.

• Laser light is coherent in nature (i.e. it travels in a phase), because of which we can get highly focused intensities.

• Laser light is Mono-chromatic, it has high degree of coherence, it has high pulse energy and it can be focused as a spot of very small size.

• For Machining- Laser power densities of $1.5 \times 10^6$ to $1.5 \times 10^8$ w/cm$^2$ are needed and the work piece should be close to the prime focus, for welding low densities -$1.5 \times 10^4$ to $1.5 \times 10^5$ w/cm$^2$ are adequate.

• Power density as informed in EBM increases with Focus & a laser beam should be focused using an optical lens.

• Laser beam is less powerful than normal light but a highly powerful laser beam is achievable as the laser can be highly focused compared to the normal light.

**Laser – Beam Machining (LBM)**

**Laser concept**

• Add energy to make electrons “jump to higher energy orbit.
• Electron “relaxes” and moves to equilibrium at ground state energy level
• Emits a photon in this process.(key laser components)
• Two mirrors reflects the photon back and forth and “excite” more electrons
• One mirror is partially reflective to allow some light to pass through: creates narrow laser beam
Working Principle of LBM
LBM uses the light energy of a laser beam to remove material by vaporization and ablation. The working principle and the process details (setup) are indicated in Figure below. In this process the energy of coherent light beam is focused optically for pre-decided longer period of time. The beam is pulsed so that the released energy results in an impulse against the work surface that does melting and evaporation. Here the way of metal removing is same as that of EDM process.
but method of generation of heat is different. The application of heat is very finely focused in case of LBM as compared to EDM.

**Process Details of LBM**

Process details of LBM are shown in line diagram shown in Figure description of the details is given below.

Laser Tube and Lamp Assembly
This is the main part of LBM setup. It consists of a laser tube, a pair of reflectors, one at each end of the tube, a flash tube or lamp, an amplification source, a power supply unit and a cooling system. This whole setup is fitted inside a enclosure, which carries good quality reflecting surfaces inside. In this setup the flash lamp goes to laser tube, that excites the atoms of the inside media, which absorb the radiation of incoming light energy. This enables the light to travel to and fro between two reflecting mirrors. The partial reflecting mirror does not reflect the total light back and apart of it goes out in the form of a coherent stream of monochromatic light. This highly amplified stream of light is focused on the workpiece with the help of converging lens. The converging lens is also the part of this assembly.

**Workpiece:**
The range of workpiece material that can be machined by LBM includes high hardness and strength materials like ceramics, glass to softer materials like plastics, rubber wood, etc. A good workpiece material high light energy absorption power, poor reflectivity, poor thermal conductivity, low specific heat, low melting point and low latent heat.

**Feed back Mechanism:**
The reflecting mirrors act as a feedback mechanism that help generated photons to reciprocate in the lasing medium thus helping the generation of multiple photons.

**Cooling Mechanism**
A cooling mechanism circulates coolant in the laser tube assembly to avoid its over heating in long continuous operation.
Tool Feed Mechanism

- There is no tool used in the LBM process. Focusing laser beam at a pre-decided point in the workpiece serve the purpose of tool. As the requirement of being focused shifts during the operation, its focus point can also be shifted gradually and accordingly by moving the converging lens in a controlled manner. This movement of the converging lens is the tool feed mechanism in LBM process.

- As the laser beam falls on the work piece surface it results in reflection & transmission of electromagnetic waves. If the beam is of low intensity- no changes are observed with respect to the work piece, but if the intensity is high it results in increase of work piece surface temperature and resulting in vaporization.

- Solid state lasers because of their poor thermal properties, it cannot be used for heavy duty works- it can be only used for minor works like spot welding.

- For heavy duty works Gas lasers like CO2 are used- in which the external energy can be supplied by direct connection to an external power source. In Co2 laser the power output is around 100 watt for 1 meter length of the lasing tube, so to increase the power output the lasing tube length has be increased or a folded lasing tube has to be used. If the lasing medium is “Gas” then it needs to be maintained at low pressure.

LBM Capability

- **MRR**
  - Cutting speed can be as high as 4 m/min.
  - Typical material removal rate is 5 mm³/min.

- **Dimensional Tolerance**
  - Typical ranges from ±0.015 - ±0.125 mm

- **Surface Finish**
  - $R_a$ varies between 0.4 – 6.3 μm

- LBM can be used for wide variety of operations- heat treatment, welding, drilling, slotting & trimming, scribing and engraving of hard materials.
- It can drill holes as small as 0.025 mm, for drilling large sized holes- the beam has to be focused to cut the outline of the hole.
- It can be used to drill fine & precise holes and cavities, it provides smooth clean cuts.
- It can be used for machining 2D or 3D work spaces.
Applications

- Multiple holes in very thin and thick materials
- Non-standard shaped holes and slots
- Prototype parts
- Trimming, scribing and engraving of hard materials
- Small diameter lubrication holes

Limitations

- Localized thermal stresses, heat affected zones, recast layer and thermal distribution in thin parts
- Difficulty of material processing depends on how close materials boiling and melting points are
- Hole wall geometry can be irregular
- The cutting of flammable materials is usually inert gas assisted

Applications of LBM

- LBM is used to perform different machining operations like drilling, slitting, slotting, scribing operations. It is used for drilling holes of small diameter of the order of 0.025 mm. It is used for very thin stocks. Other applications are listed below:
  - Making complex profiles in thin and hard materials like integrated circuits and printed circuit boards (PCBS).
  - Smaller machining of very hard material parts.

Advantages of LBM

(a) Materials which cannot be machined by conventional methods are machined by LBM.

(b) There is no tool so no tool wear.

(c) Application of heat is very much focused so rest of the workpiece is least affected by the heat.

(d) Drills very fine and precise holes and cavities.
• More precise
• Useful with a variety of materials: metals, composites, plastics, and ceramics
• Smooth, Clean cuts.
• Faster process.
• Decreased heat affected zone.

Disadvantages of LBM

Major disadvantages of LBM process are given below:

(a) High capital investment is involved. Operating cost is also high.

(b) Recommended for some specific operations only as production rate is very slow.

(c) Cannot be used comfortably for high heat conductivity materials light reflecting materials.

(d) Skilled operators are required
UNIT -VI

Application of plasma for machining, metal removal mechanism, process parameters, accuracy and surface finish and other applications of plasma in manufacturing industries. Chemical machining-principle-maskants –etchants-applications.

Chemical machining is one of the non-conventional machining processes where material is removed by bringing it in contact of a strong chemical enchant. There are different chemical machining methods base on this like chemical milling, chemical blanking, photochemical machining, etc.

Working Principle of CHM
The main working principle of chemical machining is chemical etching. The part of the work piece whose material is to be removed, is brought into the contact of chemical called enchant. The metal is removed by the chemical attack of enchant. The portion of work piece where no material is to be removed is masked before chemical etching.

Process Details of CHM
Following steps are normally followed in the process of CHM :

Cleaning
The first step of the process is a cleaning of work piece, this is required to ensure that material will be removed uniformly from the surfaces to be processed. Can be cleaned with alkaline solutions and fresh water.

Masking
Masking is similar to masking action is any machining operation. This is the action of selecting material that is to be removed and another that is not to be removed. The material which is not to be removed is applied with a protective coating called maskant. This is made of a materials are neoprene, polyvinylchloride, polyethylene or any other polymer. Thinkers of maskent is maintained upto 0.125 mm. The portion of workpiece having no application of maskent is etched during the process of etching.

Etching
In this step the material is finally removed. The workpiece is immersed in the enchant where the material of workpiece having no protective coating is removed by the chemical action of enchant. Enchant is selected depending on the workpiece material and rate of material removal; and surface finish required. There is a necessity to ensure that maskant and enchant should be chemically in active. Common enchants are H2SO4, FeCL3, HNO3. Selection of enchant also affects MRR. As in CHM process, MRR is indicated as penetration rates (mm/min).

Demasking
After the process is completed demasking is done. Demasking is an act of removing maskent after machining. Can be done with the help of fresh water.
Maskant can be applied to the Work piece by Cut & peel method, Screen Printing method or by Photo Resist Method

**Cut & Peel:** Maskants like Butyl & Vinyl Based materials are sprayed or the material is dipped in the maskant, so that the thickness of the maskant is around 0.025 to 0.13mm. Here the areas to be etched are cut and peeled away before applying the etchant.

**Screen Printing:** Before applying a Maskant a Screen which blocks the areas to be etched is held on the top of the work piece and then the maskant is applied.

**Photo Resist Method:** An enlarged diagram of the contour to be produced is prepared, a picture of the same is taken and the art work features from the picture are transferred on to a photo master film.

The work piece is coated with photo resist (light activated etchant resistant material) & dried for baking.

Then UV light is passed on the work piece after covering it with the photo master film. This process helps in the removal of maskant after development from the areas that needs to be etched.

**Etchants:** Dissolve the work piece to form metallic salts, FeCl₃ is used for Al, Cu & Ni; Fe(No₃)₃ for Ag. The depth of cut can be increased by increasing the etching time.

**Application of CHM**

The application and working of CHM process are indicated in Figure 5.4, various applications of CHM are discussed below.

*Chemical Milling*

It is widely used in aircraft industry. It is the preparation of complicated geometry on the workpiece using CHM process.
Chemical Blanking
In this application cutting is done on sheet metal workpieces. Metal blanks can be cut from very thin sheet metal, this cutting may not be possible by conventional methods.

Photochemical Machining
It is used in metal working when close (tight) tolerances and intricate patterns are to be made. This is used to produce intricate circuit designs on semiconductor wafers.

Advantages of CHM process are listed below:

(a) Low tooling cost.
(b) Multiple machining can be done on a workpiece simultaneously.
(c) No application of force so on risk of damage to delicate or low strength workpiece.
(d) Complicated shapes/patterns can be machined.
(e) Machining of hard and brittle material is possible.

Disadvantages and Limitations of CHM

(a) Slower process, very low MRR so high cost of operation.
(b) Small thickness of metal can be removed.
(c) Sharp corners cannot be prepared.
(d) Requires skilled operators.

Plasma Arc Machining:
It is one of the Thermal Machining Processes:

- Plasma is a stream of ionized gas
- Typical temperatures are very high
- Torch movement is controlled by computer
- Power requirements depend on material being cut, plus depth of cut

Working Principle of PAM
In this process gases are heated and charged to plasma state. Plasma state is the superheated and electrically ionized gases at approximately 5000oC. These gases are directed on the work piece in the form of high velocity stream. Working principle and process details are shown in Figure below
Process Details of PAM
Details of PAM are described below.

Plasma Gun
Gases are used to create plasma like, nitrogen, argon, hydrogen or mixture of these gases. The plasma gun consists of a tungsten electrode fitted in the chamber. The electrode is given negative polarity and nozzle of the gun is given positive polarity. Supply of gases moving at high velocities is maintained into the gun. A strong arc is established between the two terminals anode and cathode. There is a collision between molecules of gas and electrons of the established arc. As a result of this collision gas molecules get ionized and heat is evolved. The temperatures needed for the gases to go into plasma state is around 5000 to 6000°C. This hot and ionized gas called “plasma” impinges the work piece at high velocities & the nozzle helps in focusing & directing the Plasma beam. The established arc is controlled by the supply rate of gases.

Power Supply and Terminals
Power supply (DC) is used to develop two terminals in the plasma gun. A tungsten electrode is inserted to the gun and made cathode and nozzle of the gun is made anode. Heavy potential difference is applied across the electrodes to develop plasma state of gases.

Cooling Mechanism
As we know that hot gases continuously comes out of nozzle so there are chances of its overheating. A water jacket is used to surround the nozzle to avoid its overheating.

Tooling
There is no direct visible tool used in PAM. Focused spray of hot, plasma state gases works as a cutting tool.

Work piece
Work piece of different materials can be processed by PAM process. These materials are aluminum, magnesium, stainless steels and carbon and alloy steels. All those materials which can be processed by LBM can also be processed by PAM process.
Applications of PAM
The chief application of this process is profile cutting as controlling movement of spray focus point is easy in case of PAM process. This is also recommended for smaller machining of difficult to machining materials.

Advantages of PAM Process
Advantages of PAM are given below:

(a) It gives faster production rate.

(b) Very hard and brittle metals can be machined.

(c) Small cavities can be machined with good dimensional accuracy.

Disadvantages of PAM Process

(a) Its initial cost is very high.

(b) The process requires over safety precautions which further enhance the initial cost of the setup.

(c) Some of the work piece materials are very much prone to metallurgical changes on excessive heating so this fact imposes limitations to this process.

(d) It is uneconomical for bigger cavities to be machined.

(e) The surface finish obtained is rough compared to other Unconventional methods.

Plasma cutting process does not cut metal by using a flame similar to the oxy acetylene. The cutters used under the procedure utilize a high voltage charge to energize a high velocity stream of inert gas that is converted into the plasma as soon as it reaches at the high temperatures. There is a little impact on the surrounding metal when plasma cuts through metal, so that you can use this method for a précised metal cutting.

A variety of materials can be cut by plasma cutting technique. Metals related to the weapons, construction, ornaments, motor, packing material and others can be molten and given the desired shape and size. The metal cutting equipments required to cut materials depend upon the type, size and thickness of material.

PAM is a process used as an alternative to oxyfuel-gas cutting, employing an electric arc at temperatures as high as 27,800°C to melt and vaporize the metal.

The temperatures near the Work piece surface in PAM range from 15,000 to 30,000°C.
Magnetic abrasive finishing, Abrasive flow finishing, Electro stream drilling, Shaped tube electrolytic machining.

Magnetic abrasive finishing (MAF) process is the one in which material is removed in such a way that surface finishing and deburring are performed simultaneously with the applied magnetic field in the finishing zone. The mechanism of super finishing in any finishing process is widely focused by the knowledge of forces involved in the process.

The technology for super finishing needs ultra clean machining of advanced engineering materials such as silicon nitride, silicon carbide, and aluminum oxide which are used in high-technology industries and are difficult to finish by conventional grinding and polishing techniques with high accuracy, and minimal surface defects, such as micro cracks. Therefore, magnetic abrasive finishing (MAF) process has been recently developed for efficient and precision finishing of internal and flat surfaces. This process can produce surface finish of the order of few nanometers. The method was originally introduced in Soviet Union, with further fundamental research in various countries including Japan [1-2]. An attempt has been made to measure forces acting on the work piece and to evolve correlation between the surface finish and forces.

In MAF, two types of forces generated by flexible magnetic abrasive brush (FMAB) are responsible for finishing:

(i) Normal magnetic force responsible for packing the magnetic abrasive particles and providing micro indentations into the work piece, and (ii) Tangential cutting force responsible for micro chipping due to rotation of the FMAB. The FAMB pushes abrasive particles downward against the work piece surface. The relative motion between the FMAB and the work piece is provided by rotating the magnet. As a result, the abrasive particles remove the surface material circumferentially resulting in the finished surface. The schematic diagram of the plane magnetic abrasive super finishing apparatus is shown in Fig.1. In this process, the magnetic flux density of 0-0.44 T is used in the working gap of 1.00–2.00 mm. Both magnetic as well tangential cutting forces are varied by changing the magnetic flux density and the working gap. The magnetic flux density is varied by changing input current to the electromagnet. On the supply of current to the magnet, the work piece gets magnetized and magnetic lines of force emanate from the north pole of the magnet and terminate at the south pole via magnetic abrasive particles and work piece, completing magnetic circuit (Fig.1). The space between the flat work piece and flat-faced pole (also known as working gap/finishing gap) is filled with a mechanically made homogeneous mixture of silicon carbide abrasives (mesh no. 600) and ferromagnetic iron particles (mesh no. 300), known as unbounded magnetic abrasive particles (UMAPs) in 25:75 ratio by weight. In UMAPs, silicon carbide particles are not physically bonded to ferromagnetic iron powder. In the magnetic field, the abrasive particles can freely move around within the constraint of the adjacent ferromagnetic particles. The UMAPs are joined to each other along the magnetic lines of force and form FMAB (Fig. 2) between magnetic north pole and work piece. This brush
behaves like a multi point cutting tool. When the magnet north pole rotates, the FMAB also rotates concomitantly with the same rotational speed resulting in relative motion between the brush and the workpiece leading to finished workpiece surface. Here, cutting speed is continuously varying from the center to the periphery of FMAB.

The equipment needed for deburring with MAF depends on part geometry. For example, a small lathe can typically be used for MAF of cylindrical surfaces, while a milling machine performs MAF on flat surfaces, recessed pockets, rectangular parts and parts with both flat and cylindrical surfaces. In MAF, a magnetic field is created by rotating the part opposite a fixed magnet or rotating the magnet around a fixed part. These magnets attract abrasive grains of different sizes and materials, such as silicon carbide, which come into contact with and finish the part’s surface. The abrasive grains are mixed with small amounts of metalworking fluid, such as distilled water, SAE30 motor oil or kerosene. The fluid helps retain the abrasive, adds lubricity and cools the parts. It also reduces abrasive impregnation and improves finishes. Some abrasives have metal cores that respond to the magnetic field. If abrasives without this core are used, loose magnetic grit (such as iron filings) is added to create a medium that responds to the magnetic field. The magnetized grit and coolant medium carries the abrasive particles along with it.

An MAF setup for deburring does not need to be precise or rigid to produce mirror finishes because the magnetic field directs the loose abrasive grains. These grains act as self-sharpening tools because different edges rotate to make tiny cuts in the workpiece. The magnetic field orients the abrasive/magnetic grit mixture into long strings, producing a brush-like tool. Since the field constantly exerts a force attracting the abrasive medium, this “brush” does not need
compensation. Real brushes wear and their length must constantly be adjusted in CNC machines. Grinding and honing require dressing of their tools, but MAF does not. Figures 2a and 2b show two typical MAF setups. In a milling machine (2a), the magnetic tool is chucked in the spindle and rotated. Cylindrical parts are typically chucked in a small lathe (2b).

Figure 2a: Milling machine-based MAF (conventional MAF uses coolant rather than the electrolyte shown here).

Figure 2b: Lathe-based magnetic abrasive finishing for cylindrical workpieces.

Abrasive flow machining (AFM), is a very precise and economical method of smoothing and polishing internal surfaces and producing controlled radii. The process is particularly useful for difficult to reach internal passages, bends, cavities, and edges. The AFM process uses a specially formulated abrasive laden polymer, hydraulically forced over, or through, areas requiring finishing. AFM differs from others finishing’s in that the unique properties of the polymer (called media) permit it to floe through passages and confirm to the shape requiring finishing.

Media viscosity and flow rates are controlled by pressure and temperature settings engineered for maximum efficiency and effective results. The ability of AFM to polish difficult to reach internal passages and bends ensure that it is a crucial part of the modern surface finishing plant.

The typical AFM process (two-way flow) uses two vertically opposed cylinders which extrude an abrasive media back and forth through passages formed by the workpiece and tooling. Abrasive action occurs wherever the media enters and passes through the most restrictive passages. The extrusion pressure is controlled between 7-200 bar (100-3,000 psi), as well as the displacement per stroke and the number of reciprocating cycles.

One-way AFM systems flow the abrasive media through the workpiece in only one direction, allowing the media to exit freely from the part for fast processing, easy cleaning and simple quick-exchange tooling.
Versatility

AFM is used in a wide range of finishing operations. It can simultaneously process multiple parts or many areas of a single work piece. Inaccessible areas and complex internal passages can be finished economically and effectively. Automatic AFM systems are capable of handling thousands of parts per day, greatly reducing labor costs by eliminating tedious handwork. By understanding and controlling the process parameters, AFM can be applied to an impressive range of finishing operations that provide uniform, repeatable, predictable results. Anywhere that the media can be forced to flow represents a practical application.

**Electro Stream Drilling:**

Standard ElectroChemical Drilling process uses a hollow metal tube as cathode through which electrolyte flows at high velocity. This tube moves in the hole as it is drilled hence, the hole diameter is always bigger than the outside diameter of the cathode tube. There are certain practical limitations because of which the cathode tube diameter cannot be reduced below a certain value. To drill a hole of diameter smaller than this value, a process named Electrostream drilling was invented. This process was employed for drilling thousands of small cooling holes in nickel and cobalt superalloys.

In electrostream drilling, electrically negatively charged, high velocity, acid electrolyte stream is passed through electrically non conducting nozzle (fig 1) This stream strikes +vly charged workpiece and removes material in the same way as in conventional ECM. This dissolved material (the sludge dissolved in the acid electrolyte) is flushed out from the machining zone in the form of metal ions in the solution. Since there is no sludge to restrict the flow of electrolyte, the limit on the minimum diameter of the hole at steep angles or curved holes (FIG 2) By this
method it has been possible to drill holes of diameter as small as 0.127 mm to as large as 0.89 mm. But the voltage used during ESD is very high (say, 150-850 V).

**Schematic of Electro Stream Drilling (Fig-1)**

In ESD, a dilute solution of H₂SO₄ or HCL is used as an electrolyte. Hydrochloric acid has proved to be a better electrolyte for drilling materials like aluminium, titanium, etc. Sulfuric acid is the electrolyte preferred for drilling in carbon steel, cobalt alloys and stainless steels.

ESD can be performed in two ways, by giving no feed (or zero feed rate) and by providing finite feed rate to the nozzle. The first one is known as “Dwell Drilling” which is used when shallow and less accurate holes are required. This technique is also required under circumstances when workpiece configurations or machine capabilities do not permit the movement of the nozzle. Nozzle tip is fixed at predetermined distance from the work surface, and drilling is done by the electrolyte stream, but it limits the depth of the drilled hole and obtainable accuracy.

(fig 3)
A gap sensing device is used to monitor the current being drawn, to slow down the feed, and trigger and full power when the proper nozzle-workpiece gap is detected.

The second kind of ESD is known as “penetration drilling” and is used for deep and accurate hole drilling (fig 4). During ESD, the nozzle is fed towards the workpiece with a finite feed rate to maintain a constant inter-electrode gap.
Components of m/c and fixtures must be made of acid resistant materials. Nozzles designed for drilling round holes are made of glass tubing that is drawn to a small diameter, thus forming a capillary at one end. If a hole in the cavity is to be drilled at such an angle that the line of sight access is not available, a tool with a right angle bend at the tip is used.

The outside diameter of the nozzle tip should be such that it fits within hole being drilled as well as allows room for the repeatable escape of the used electrolyte. The length of the small diameter part of the tube should always be greater than the depth of the hole to be drilled.

Charging of electrolyte can be done in two ways, either by the use of a metallic sleeve or by a small titanium wire which is placed inside the large diameter section of the ES nozzle. Metallic sleeve or titanium wire is kept as close to the throat as possible. Multiple nozzle applications require the use of a junction manifold with individual wires running from the electrolyte manifold to each nozzle.

**Shaped-tube electrolytic machining process**

A process of electrolytic machining holes of uniform diameter in a conductive workpiece, particularly one having a slotted lower portion. Drilling is accomplished electrochemically by providing a conductive tube, passing an electrolytic fluid through the tube to the workpiece, and passing a DC current between the tube and the workpiece through the electrolyte. The DC current causes material from the workpiece to "deplate" into the electrolyte, resulting in the formation of the hole. Hole diameter is made uniform by maintaining the supplied DC current constant, despite sudden changes in the conductivity of the electrolyte, the work piece or both.
STEM:

For drilling smaller diameter but deep holes in electrically conductive materials, shaped-tube electrolytic machining (STEM) process is used. Shaped-tube electrolytic machining is quite commonly done in aerospace industries and difficult to machine super alloys. It was developed primarily for drilling high aspect ratio (up to 300:1) round and shaped holes in turbine engine airfoils. It uses acid based electrolyte which ensures that the reaction products formed during electrolytic deplating are dissolved and carried away as metal ions. It eliminates clogging of the electrolyte flow path around the electrode. STEM uses an electrode as a hollow, shaped tube covered with insulating coating on all exterior surfaces except at the tip. Fig. 1 shows the different elements of a STEM system. STEM is a low voltage process (5-15 V DC). At higher voltages, drilling rates can be increased but boiling of electrolyte, plating of electrodes, and damage to the electrodes coating may lead to serious problems. Feed rate depends on the machining parameters; however it can be as high as 5 mm/min against a normal feed rate of 1.5 mm/min. For clarity, magnified view of overcut is shown in figure 1. Value of the cut can be changed by varying the applied voltage and electrolyte flow velocity with the help of computer control. During STEM, taper obtained is 0.015 mm/cm and surface finish achieved is 0.8 to 3.1 μm. Surface finish depends upon work material and machining parameters.

Electrolyte normally used is 10% concentration of sulphuric acid or hydrochloric acid in water. Temperature of electrolyte is maintained between 37-40°C. To maintain a constant gap between tool and work piece, a servo system is used. After drilling is over, the work piece should be thoroughly washed by water to neutralize and remove residual acid. Tube material is pure titanium to resist acidic action of the electrolyte. Coating on the tube serves dual purpose, e.g., it saves from the attack of the electrolyte as well as eliminates stray cutting at the walls of the hole. Best results are obtained if the tip is dressed at an angle of 10°. Pinhole scratches and delaminations in the coating would result in stray cutting (i.e., non-uniform cutting). Multiple electrodes even with varying shapes and sizes, would be able to produce as many as 100 holes simultaneously. The components of the machine which are likely to come in contact with electrolyte, should be made of corrosion resistant materials like titanium stainless steel plastics and ceramics. Proper ventilation of machining chamber must be provided to extract corrosive electrolyte mist and hydrogen gas by products of the process.

Material removal is performed basically by the foot (or tip) of the tube, hence by changing its shape, the holes of different shapes can be obtained without changing the shape of the full tube. To increase productivity and to make the process more versatile, these tips may be made of different shapes and sizes even in multiple hole machining. An alternative method is to make these tips as independent, separate, bit type of tube of the desired shape and size, and then fasten them to the bit holder (or electrode). Electrolyte mist and hydrogen gas by products of the process should be properly removed from the machining chamber.
Fig. 1 Schematic diagram of a shaped-tube electrolytic machining system.