PDHonline Course M500 (5 PDH)

Non-Conventional Machining Technology Fundamentals

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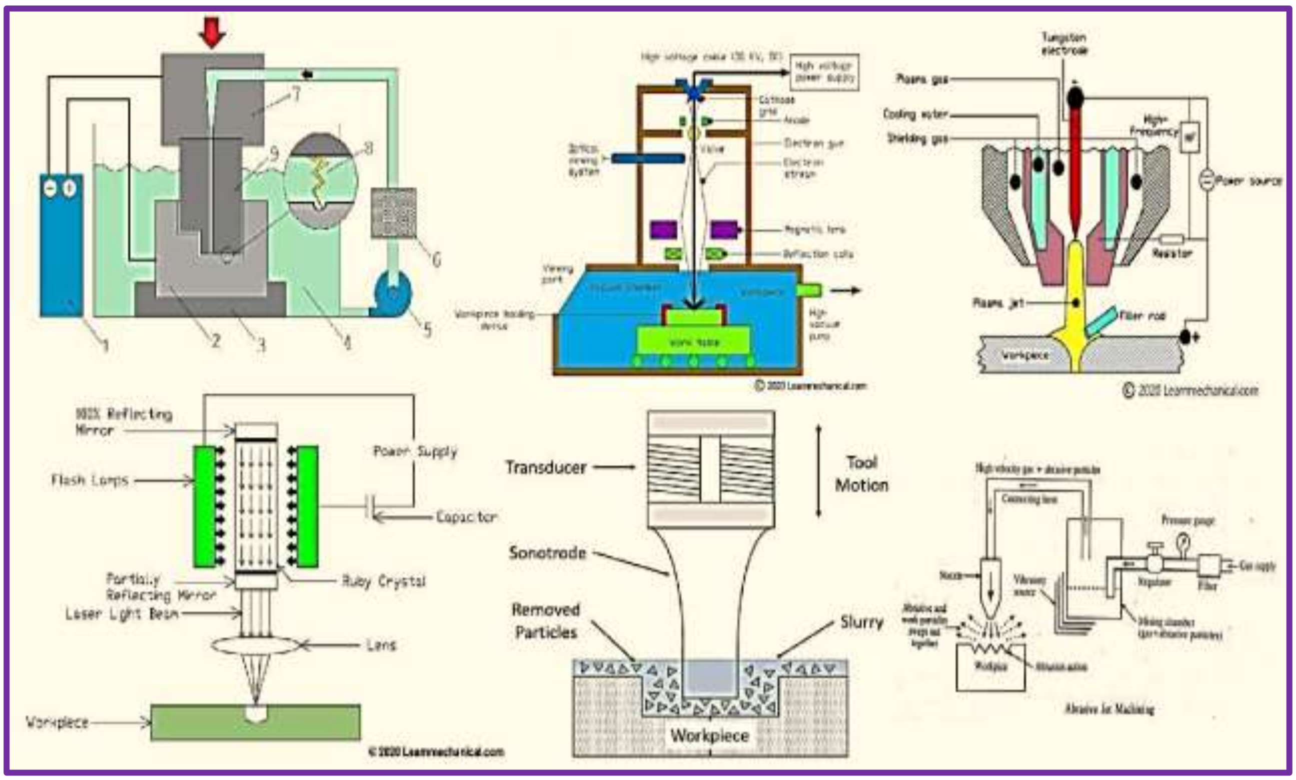

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NON-CONVENTIONAL MACHINING TECHNOLOGY – FUNDAMENTALS

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OBS.: This is a professional didactic manual. It´s highly recommended to download and print the course content for your study, before answering the quiz questions.

INTRODUCTION:

Manufacturing processes can be broadly divided into **two groups: primary** manufacturing processes and **secondary** manufacturing processes. The former one, provide basic shape and size to the material as per designer's requirement. Casting, forming, powder metallurgy are such processes to name a few. Secondary manufacturing processes provide the final shape and size with tighter control on dimension, surface characteristics, etc.

Material removal processes once again can be divided into two groups:

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

The most important examples of conventional machining processes are: Turning, boring, milling, shaping, broaching, slotting, grinding, etc.

b. **Non-Traditional Machining Processes:** Also called non-conventional machining processes, is defined as a group of processes that removes the excess of material by various techniques involving mechanical, thermal, electrical or chemical energy or combinations of these energies, but do not use a sharp cutting tools as it needs to be used for traditional manufacturing processes.

Classification of NTM processes is carried out depending on the nature of energy used for material removal. The main broad classification is given as follows:

1. Mechanical Processes:

- Abrasive Jet Machining (AJM)
- Ultrasonic Machining (USM)
- Water Jet Machining (WJM)
- Abrasive Water Jet Machining (AWJM)

2. Electrochemical Processes:

- Electrochemical Machining (ECM)
- Electrochemical Grinding (ECG)
- Electro Jet Drilling (EJD)

3. Electro-Thermal Processes:

- Electro Discharge Machining (EDM)
- Laser Jet Machining (LJM)
- Electron Beam Machining (EBM)

4. Chemical Processes:

- Chemical Machining (CHM)
- Photochemical Machining (PCM)

Non-traditional machining needs:

Conventional machining sufficed the requirement of the industries over the decades. However, new exotic work materials, as well as, **innovative geometric design** of products and components put a lot of pressure on capabilities of the conventional machining processes to manufacture the components, with desired tolerances economically.

The major characteristics of non-conventional machining are:

- Material removal may occur even no chip formation may take place. For example in AJM, chips are of microscopic size and in case of ECM material removal occurs due to electrochemical dissolution at atomic level.
- There may not be a physical tool present. For example in LJM, machining is carried out by laser beam; however, in ECM there are tools very much required for machining.
- The tool needs not be harder than the work piece material. For example, in EDM, copper is used as the tool material, to machine hardened steels.
- Mostly NTM processes do not necessarily use mechanical energy to provide material removal. For example, in USM, AJM, WJM mechanical energy is used to machine material, whereas in ECM electrochemical dissolution constitutes the material removal.

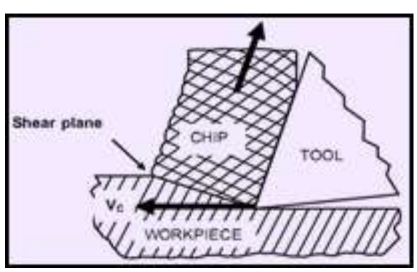
The following examples below show where the NTM processes are preferred, over the conventional machining process:

- Intricate shaped blind hole – e.g., square holes of 15 mm x 15 mm with a depth of 30 mm;
- Difficult to machine material – such as Inconel, Ti-alloys or carbides;
- Low stress grinding – Electrochemical grinding is preferred, when compared to conventional grinding;
- Deep holes with small hole diameters;
- Machining of composites.

This led to the development and establishment of the NTM processes in industry, as efficient and economic alternatives to conventional ones. With development of the NTM processes, currently there are many choices, and not only the alternative to conventional processes for certain technical requirements.

Processes of non-traditional machining (NTM):

It is necessary to understand and analyze the differences and similar characteristics between conventional machining operations and NTM processes. Conventional or traditional machining operations mostly remove material in the form of chips, by applying forces on the work material with a wedge shaped cutting tool that is harder than the work material under machining condition. Such forces induce plastic deformation within the work piece leading to shear deformation along the shear plane and chip formation. The figure below, shows the chip formation by shear deformation in conventional machining.



The major characteristics of conventional (or traditional) machining are:

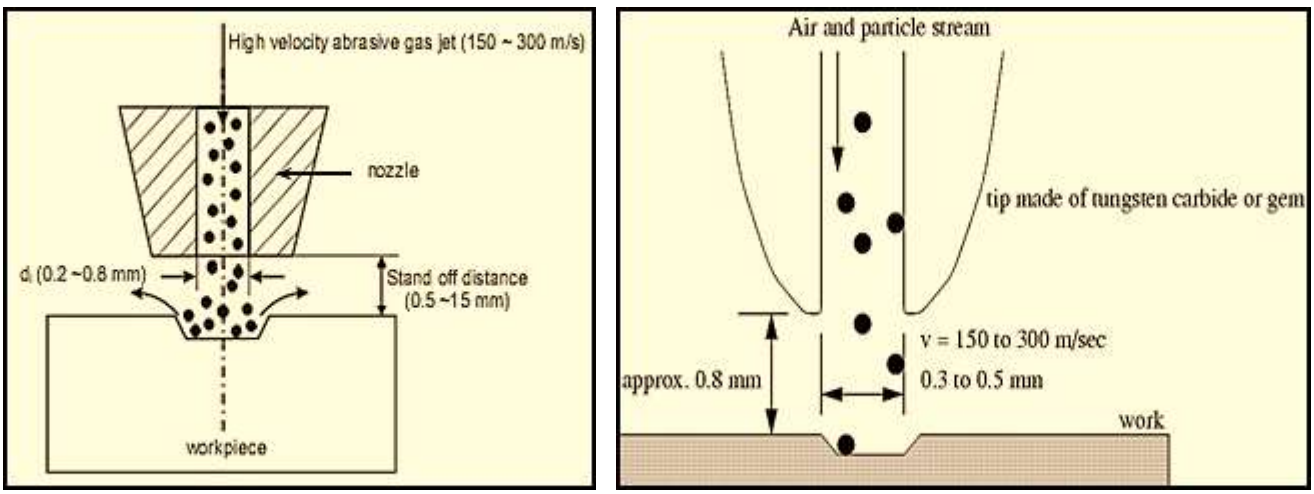
- Generally macroscopic chip formation by shear deformation;
- Material removal takes place due to application of cutting forces;
- Cutting tool is harder than work piece at room temperature as well as under machining conditions.

I. ABRASIVE JET MACHINING (AJM):

Abrasive Jet Machining (AJM), also known as micro-abrasive blasting, is a mechanical energy based - unconventional machining process, used to remove unwanted material from a given workpiece. The process makes use of an **abrasive jet with high velocity**, to remove material and provide smooth surface finish to hard metallic workpieces. It is similar to Water Jet Machining (WJM).

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. The figure below shows the material removal process.

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 a kinetic energy and hence to a high velocity jet. Fine particles **(0.025 mm)** are accelerated in a gas stream (commonly air at a few times atmospheric pressure). The particles are directed towards the focus of machining (less than **1.0 mm** from the tip). As the particles impact the surface, they fracture off other particles.

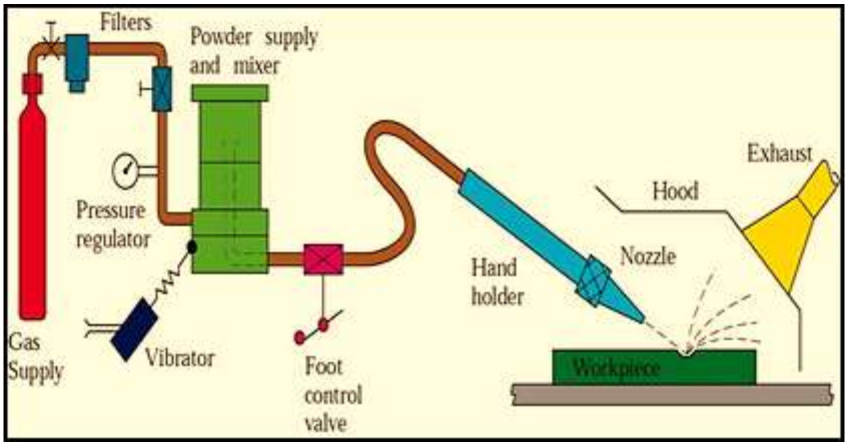


The AJM is different from standard shot or sand blasting, as finer abrasive grits are used and the parameters can be controlled more effectively providing better control over product quality. In AJM, generally, the abrasive particles of around **25 µm** grit size would impinge on the work material a velocity of **150 to 300 m/s**, from a nozzle of I.D. of **0.3~0.5 mm** with a standoff distance of around **2 mm**. The kinetic energy of the abrasive particles would be sufficient to provide material removal due to brittle fracture of the work piece or even micro cutting by the abrasives.

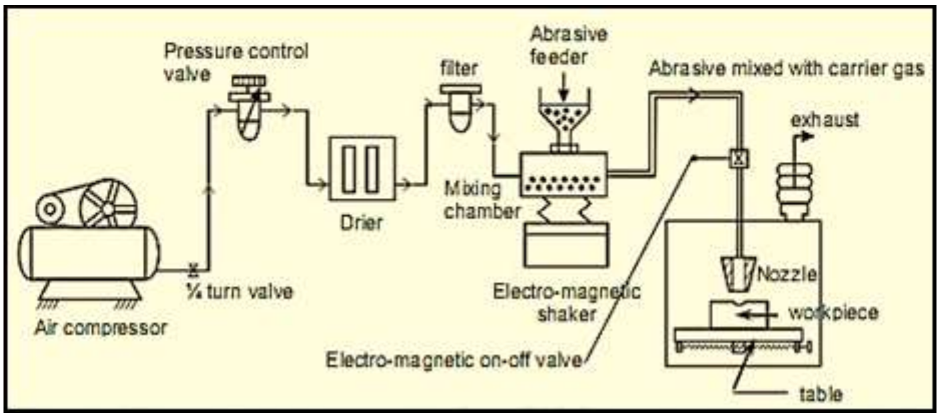
Equipment:

In AJM, the air is compressed in an air compressor at a pressure of around **5 bar,** used as the carrier gas as shown below, which 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, then is passed through an air dryer to remove any residual water vapor. To remove the oil vapor 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 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 electromagnetic 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 **(150~300 m/s)** abrasive particles are issued from the nozzle onto a work piece traversing under the jet.



Dry air or gas is filtered and compressed by passing it through the filter and compressor. A pressure gauge and a flow regulator are used to control the pressure and regulate the flow rate of the compressed air. Compressed air is then passed into the mixing chamber. In the mixing chamber, abrasive powder is fed. A vibrator is used to control the feed of the abrasive powder.

Abrasive Jet Machine

The abrasive powder and the compressed air are thoroughly mixed in the chamber. The pressure of this mixture is regulated and sent to nozzle. The nozzle increases the velocity of the mixture at the expense of its pressure. A fine abrasive jet is rendered by the nozzle. This jet is used to remove unwanted material from the workpiece.

The process parameters and machining characteristics, are listed below:

Abrasive:

- ✓ Material: Aluminum Oxide - Al_2O_3; Silicon Carbide (Carborundum) - 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/m³;
- ✓ Velocity – 500 ~ 700 m/s;
- ✓ Pressure – 2 ~ 10 bar;
- ✓ Flow rate – 5 ~ 30 l/min;

Abrasive Jet:

- ✓ Velocity – 150 ~ 300 m/s;
- ✓ Mixing ratio – mass flow ratio of abrasive to gas;
- ✓ Standoff distance – 0.5 ~ 5 mm;
- ✓ Impingement Angle – 60 ~ 90°;

Nozzle:

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

The most important machining characteristics in AJM are:

- ✓ The material removal rate (MRR) mm³/min or gm/min;
- ✓ The machining accuracy;
- ✓ The life of the nozzle.

The following are some of the operations that can be performed using Abrasive Jet Machining:

Drilling; boring; surface finishing; cutting; cleaning; deburring; etching; trimming and milling.

Modeling of material removal:

Material removal in AJM takes place due to brittle fracture of the work material due to impact of high velocity abrasive particles. Modeling has been done with the following assumptions:

- ✓ Abrasives are spherical and rigid. The particles are characterized by the mean grit diameter;
- ✓ The kinetic energy of the abrasives is fully utilized in removing material;
- ✓ Brittle materials are considered to fail due to brittle fracture and the fracture volume is considered to be hemispherical with diameter equal to chordal length of the indentation;

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

See figure below, the interaction of the abrasive particle and the work material in AJM.

The kinetic energy of a single abrasive particle is given by:

$$K.E._g = \frac{1}{2} m_g v^2 = \frac{1}{2}\left\{\frac{\pi}{6} d_g^{\,3} \rho_g\right\} v^2 = \frac{\pi}{12} d_g^{\,3} \rho_g v^2$$

Where:

v = velocity of the abrasive particle;
mg = mass of a single abrasive grit;
dg = diameter of the grit;
pg = density of the grit.
On impact, the work material would be subjected to a maximum force **F** which would lead to an indentation of ′ δ', the work to be 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:

$$F = \pi r^2 H$$

Where:

F = indentation hardness x area
r = is the indentation radius.

$$W = \frac{1}{2} F\delta = \frac{1}{2}\pi r^2 H \delta$$

MRR for brittle materials can be expressed as:

$$MRR_B = \frac{4\,\dot{m}_a v^{3/2}}{6^{3/4}\rho_g^{\;1/4} H^{3/4}} \approx \frac{\dot{m}_a v^{3/2}}{\rho_g^{\;1/4} H^{3/4}}$$

MRR for ductile materials can be expressed as:

$$MRR_D = \frac{1}{2}\frac{\dot{m}_a v^2}{H}$$

Where:

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.

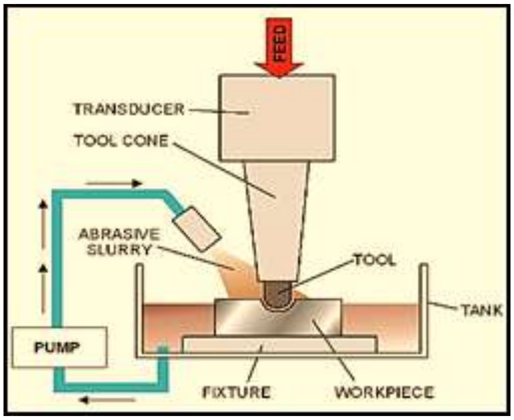
Limitations:

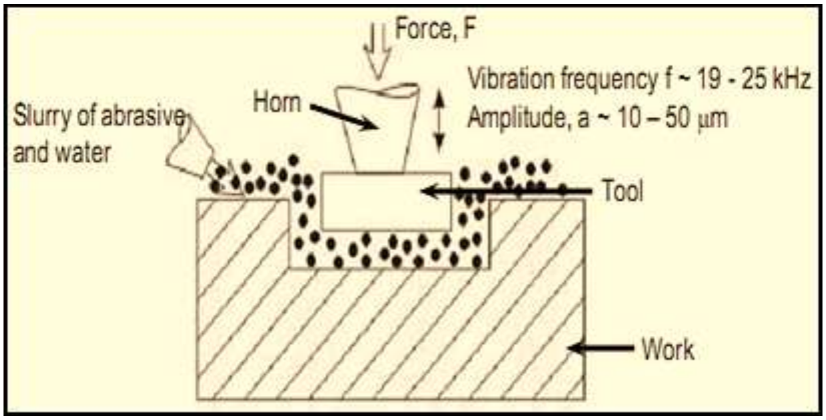
- MRR is low (~15 mm³/min for machining glasses);
- Abrasive particles tend to get embedded particularly if the work material is ductile;
- Tapering occurs due to flaring of the jet;
- Environmental load is rather high.

An EDM pallet generally is useful for small parts for two reasons. First, it is convenient to be able to insert and remove parts outside the machine. Second, the parts can be left within the fixture and moved to an EDM machine for final ultra-precise finishing without having to repeat the setup procedure. This involves centering the nozzle over a reference location on the part and either noting the coordinates or zeroing the coordinates at that point.

II. ULTRASONIC MACHINING (USM):

In Ultrasonic Machining (USM), a tool of desired shape vibrates at an **ultrasonic frequency (19~25kHz)** with an amplitude of around **15 - 50 μm** over the workpiece. The tool is pressed downward with a feed force, between the tool and workpiece. The machining zone **is flooded with hard abrasive particles** generally in the **form of water based slurry**, as shown below:





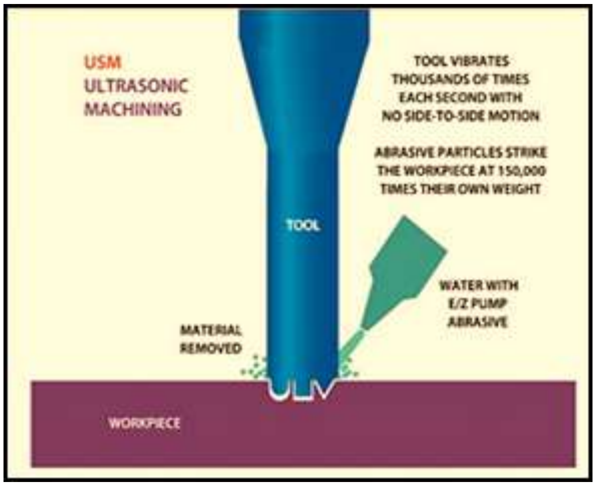
As the **tool vibrates** over the workpiece, the **abrasive particles act as the indenters** and indent both the work material and the tool. The abrasive particles indent the workpiece, particularly if the work material is brittle, due to crack initiation, propagation and brittle fracture of the material. Hence, the **USM** is mainly used for **machining brittle materials** (as poor conductors of electricity cannot be processed by Electro-chemical and Electro-discharge machining (ECM or ED).

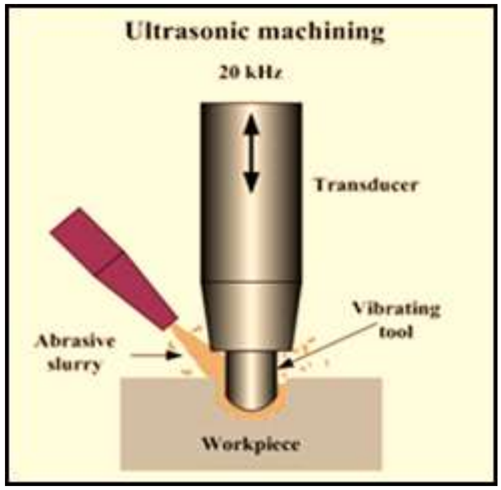
Material removal is by 3 mechanisms:

- ✓ Hammering of grit against the surface by the tool;
- ✓ Impact of free abrasive grit particles (erosion);
- ✓ Micro-cavitation.

USM modeling:

USM is generally used for machining brittle work material. The material removal primarily occurs due to the indentation of the hard abrasive grits on the brittle work material. As the tool vibrates, it leads to indentation of the abrasive grits.





The tool material should be modeled the way that indentation by the abrasive grits does not lead to brittle failure. The tools have to be tough, strong and ductile materials like steel, stainless steel and other ductile metallic alloys. Some material removal may occur due to free flowing impact of the abrasives against the work material and related solid-solid impact erosion, but it is estimated to be rather insignificant.

The material removal would be assumed to take place only due to impact of abrasives between tool and workpiece, followed by indentation and brittle fracture of the workpiece. The model considers the deformation of the tool. All abrasives are considered to be identical in shape and size. An abrasive particle is considered to be spherical but with local spherical bulges as shown below.

Process Parameters:

The process parameters governing the USM process are listed below:

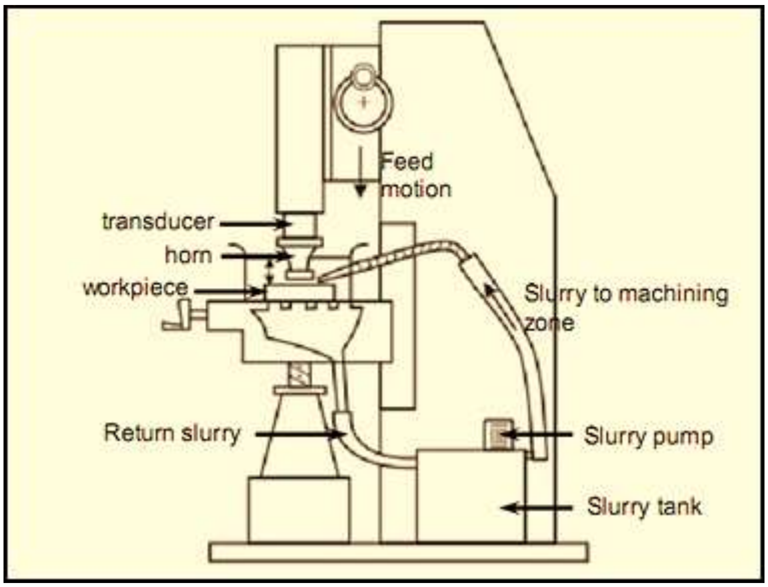
- ✓ Amplitude of vibration (a) – 15 – 50 μm;
- ✓ Frequency of vibration (f) – 19 – 25 kHz;
- ✓ Feed force (F) – related to tool dimensions;
- ✓ Feed pressure (p);
- ✓ Abrasive size – 15 – 150 μm.

Abrasive material:

- ✓ Al2O3;
- ✓ SiC;
- ✓ B4C;
- ✓ Boronsilicarbide;
- ✓ Diamond.

Machine structure:

The basic mechanical structure of an USM is **very similar to a drill press**. However, it has additional features to carry out USM of brittle work material. The workpiece is mounted on a vice, which can be located at the desired position under the tool using a 2 axis table. The table can further be lowered or raised to accommodate work of different thickness. The typical elements of an USM are:



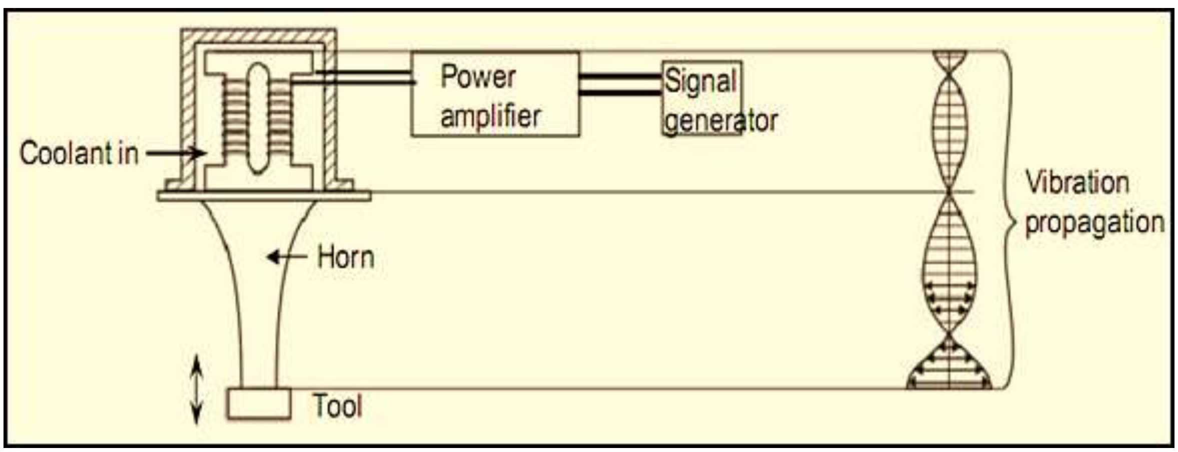
- ✓ Slurry delivery and return system;
- ✓ Feed mechanism to provide a downward feed force on the tool during machining;
- ✓ The transducer, which generates the ultrasonic vibration;
- ✓ The horn or concentrator, mechanically amplifies the vibration to the required amplitude of 15 to 50 µm and accommodates the tool, as schematically shown below:

In the 1940′s and 1950′s, the technology expanded into the ultrasonic frequency range in response to a need for ultrasonic devices that were more robust than those using the (then) fragile crystal compositions that were used in piezoelectric ultrasonic transducers of the day. Figure below shows a typical magnetostrictive transducer with a horn. The **horn or concentrator** is a wave-guide, which **amplifies and concentrates the vibration** to the tool from the transducer.

The **ultrasonic vibrations** are produced by the **transducer**. The transducer is driven by a suitable signal generator followed by the power amplifier. The transducer works on the following principle:

- Piezoelectric effect;
- Magnetostrictive effect;
- Electrostrictive effect.

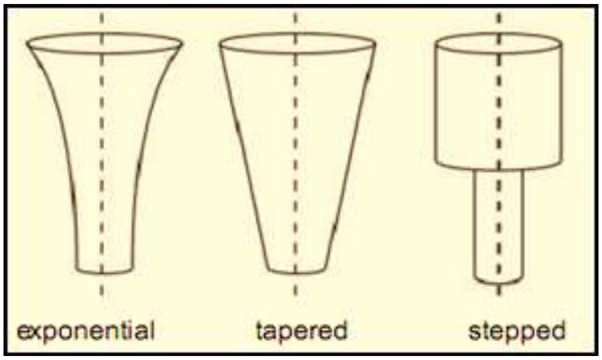
The Magnetostrictive transducers are the most popular and more robust among all. Magnetostrictive ultrasonic transducers utilize the principle of magneto-striction exhibited by “ferromagnetic” materials which include iron, nickel and cobalt as well as many alloys of these three elements to create ultrasonic waves in a liquid. USM offers a solution for machining brittle materials such as single crystals, glasses and polycrystalline ceramics, and complex operations or intricate shapes and workpiece profiles.

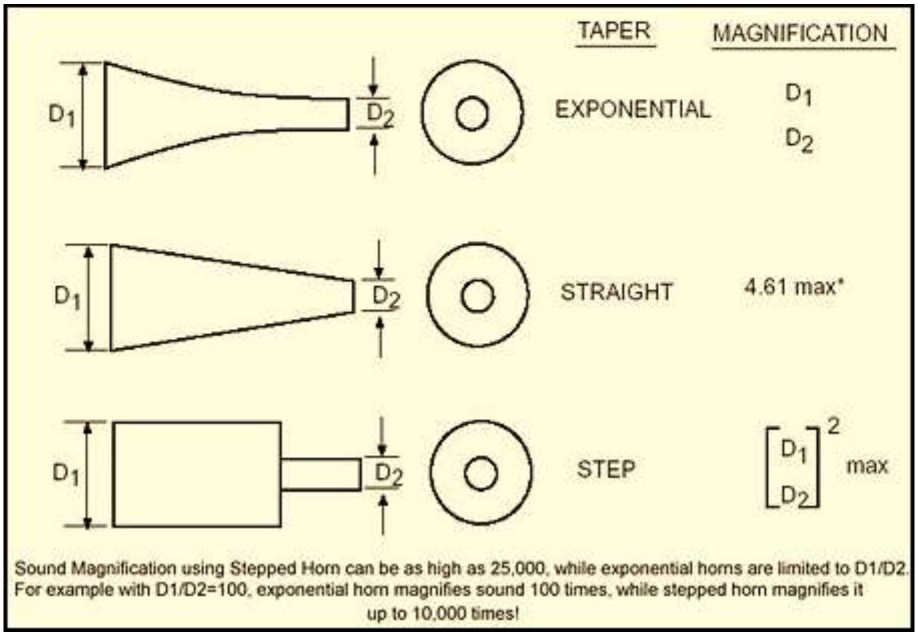


An ultrasonic horn (also known as acoustic horn, sonotrode, acoustic waveguide, ultrasonic probe) is a tapering metal bar commonly used for augmenting the oscillation displacement amplitude provided by an ultrasonic transducer operating at the low end of the ultrasonic frequency spectrum (commonly between 15 and 100 kHz). The horn or concentrator can be of different shape like:

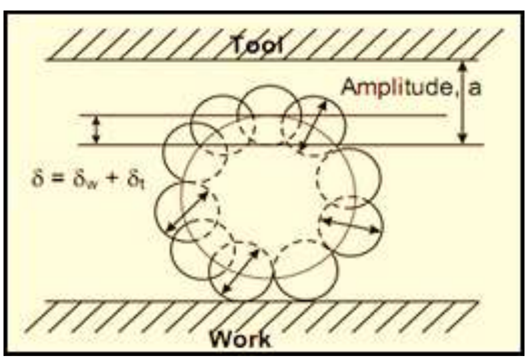
- ✓ Tapered or conical;
- ✓ Exponential;
- ✓ Stepped.

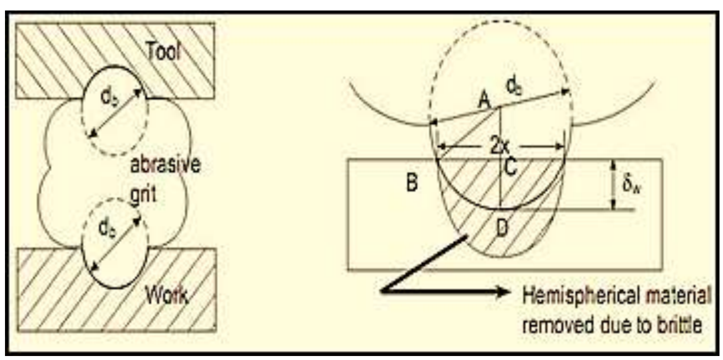
The tapered and stepped horns are much easier, in machining, compared to the exponential one. The figure below shows the different horns used in USM:



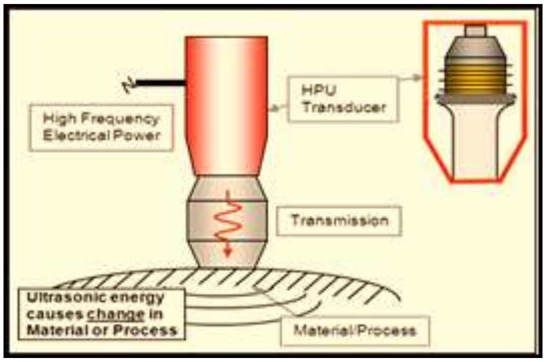


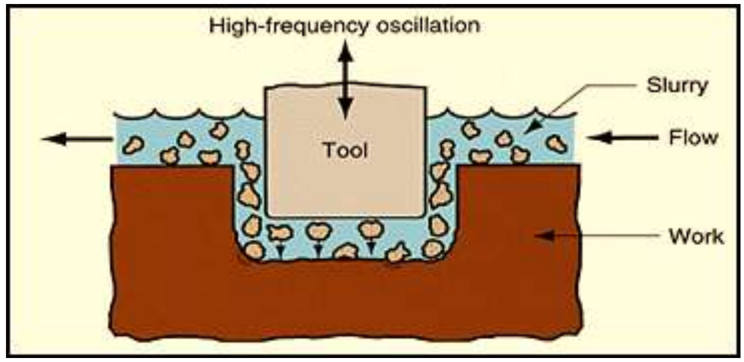
Now as the tool and workpiece would be pressing against each other, contact being established via the abrasive grit, both of them would deform or wear out. As the **tool vibrates**, for some time, it vibrates freely; then it comes in contact with the abrasive, which is already in contact with the job. The tool vibrates in a harmonic motion. Thus, only during its first quarter of its cycle it can derive an abrasive towards interaction with the tool and workpiece, as shown below:





Thus, it is used extensively in machining hard and brittle materials that are difficult to machine by traditional manufacturing processes. The hard particles in slurry are accelerated toward the surface of the workpiece by a tool oscillating at a frequency up to 100 KHz - through repeated abrasions, the tool machines a cavity of a cross section identical to its own.





The contact zone between the abrasive grit and workpiece is established. The contact zone is circular in nature and is characterized by its diameter ‘2x’. At full indentation, the indentation depth in the work material is characterized by δw. Due to the indentation, as the work material is brittle, brittle fracture takes place leading to hemi-spherical fracture of diameter ‘2x’ under the contact zone. Therefore material removal per abrasive grit is given as:

$$MRR_w = \Gamma_w . n . f$$
$$= \frac{2}{3}\pi\left(\delta_w d_b\right)^{3/2} nf$$

Applications:

- Machining hard and brittle metallic alloys, semiconductors, glass, ceramics, carbides, etc;
- Machining round, square, irregular shaped holes and surface impressions;
- Machining, wire drawing, punching or small blanking dies.

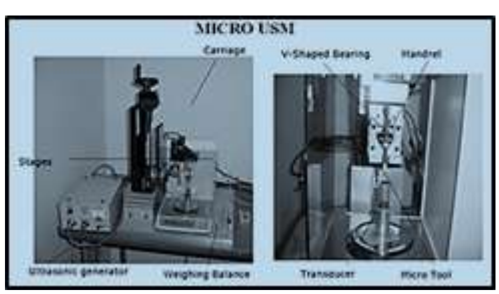
Limitations:

- Low MRR;
- Rather high tool wear;
- Low depth of hole.

Micro USM:

Micro Rotary Ultrasonic Machining (MRUM) is a hybrid machining process which combines the mechanism of material removal of conventional grinding and ultrasonic machining for applications in fields such as biotechnology, medical devices, aerospace, optics and communications.

In micro USM the workpiece table vibrates at ultrasonic frequency (40 KHz) and abrasive slurry is injected on the top. There is a rotating tool which hits the abrasive particles in the slurry and chips away the work piece material. The vibrations given to the workpiece aid in refreshing the slurry so that fresh abrasive particles are in contact with the workpiece and also in removing the debris from the tool workpiece gap.



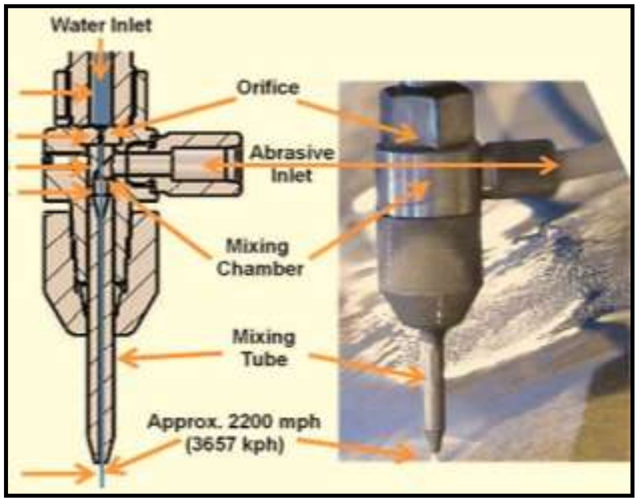
III. WATER JET MACHINING (WJM):

Water Jet Machining (WJM) is a mechanical energy based non-traditional machining process used to cut and machine soft and non-metallic materials. It involves the use of high velocity water jet to smoothly cut a soft workpiece. It is similar to **Abrasive Water Jet Machining** (AWJM). In these processes (WJM and AJWM), the mechanical energy of water and abrasive phases are used to achieve either material removal or machining. The general grouping of some of the typical non-traditional processes are shown below:

Mechanical Processes
- USM
- AJM
- WJM and AWJM

Thermal Processes
- EBM
- LBM
- PAM
- EDM and WEDM

Electrical Processes
- ECM
- ECG
- EJD



WJM and AWJ can be achieved using different approaches and methodologies as enumerated below:

Water Jet Machining (WJM):
- WJM – pure water;
- WJM – water with stabilizer;

Abrasive Water Jet (AWJ):
- AWJM – entrained abrasive, water and air – three phase;
- AWJM – suspended abrasive and water – two phase;

In WJM – pure water, commercially pure water (tap water) is used. In WJM – with stabilizer, water soluble stabilizers are named by how can be removed after the machining is complete. Stabilisers are **long chain polymers** that hinder the fragmentation of water jet, added to the water. When water at such pressure is issued through a suitable orifice, the potential energy is converted into kinetic energy at a high velocity jet (1000 m/s). Such high velocity water jet, can machine thin sheets/foils of aluminium, leather, textile, frozen food, etc.

Abrasive Water Jet (AWJ):

AWJ are mainly of two types – **entrained and suspended type**. In entrained type the **Abrasive Water Jet Machining** (AWJM), the abrasive particles are allowed to entrain in water jet to form abrasive water jet with significant velocity of 800 m/s. Such high velocity abrasive jet can machine almost any material, as can be seen below, the photographic view of a commercial CNC water jet machining system.

In AWJM, the **abrasive particles** like sand (SiO2), glass beads are added to the water jet to enhance its cutting ability by many folds. However as the high velocity water jet is discharged from the orifice, the jet tends to entrain atmospheric air and flares out decreasing its cutting ability. In all variants of the processes, the basic methodology remains the same. Water is pumped at a suf-ficiently high pressure, 200 - 400 MPa

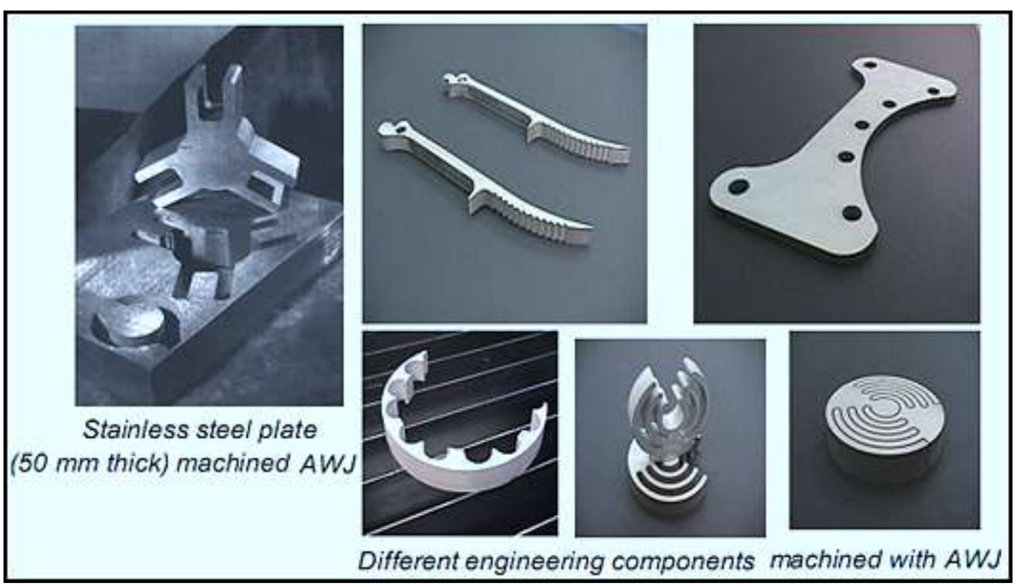
(2000 - 4000 bar) using intensifier technology. An intensifier works on the simple principle of pressure amplification using hydraulic cylinders of different cross-sections.

WJM and AWJM application:

The processes, using WJM and AWJM are for applications such as, paint removal, cleaning, cutting soft materials, cutting frozen meat, textile, leather industry, mass immunization, surgery, peening, pocket milling, drilling, turning, plant dismantling and useful for machining the following 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, etc.

The cutting ability of water jet machining can be improved 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.



Stainless steel plate (50 mm thick) machined AWJ

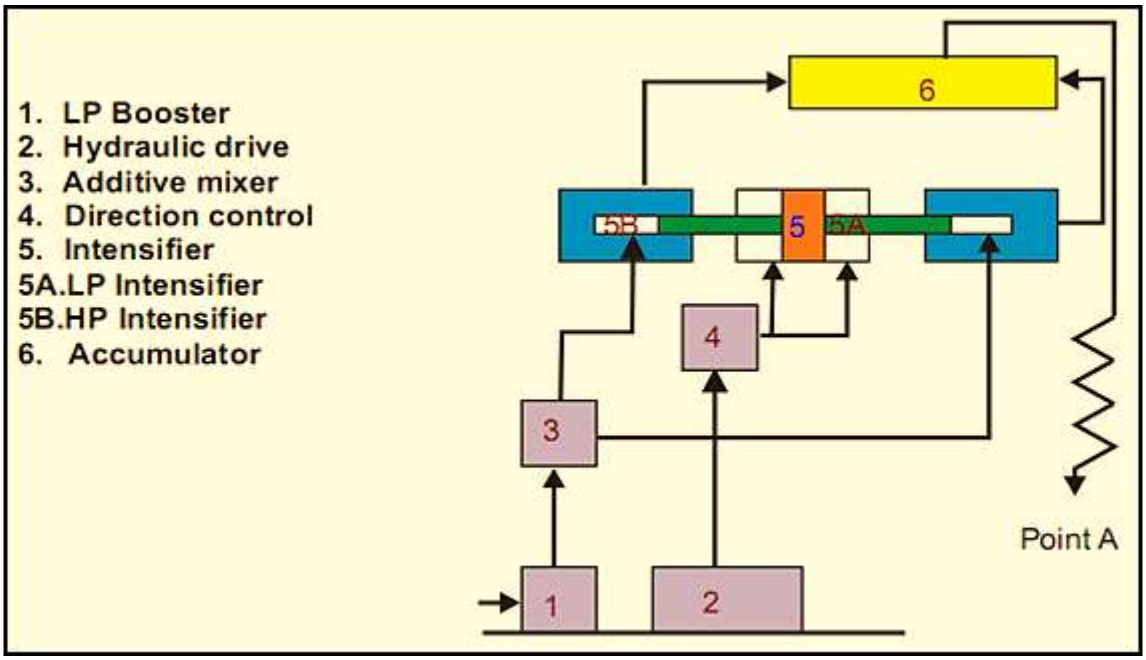
Different engineering components machined with AWJ

The figure above shows a typical example of WJM, where a 50 mm thick stainless steel can be machined and after the obtainable accuracy and precision with AWJM. Some of the job shop industries and manufacturers claim to have successfully used AWJM in free form surface generation by milling. 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

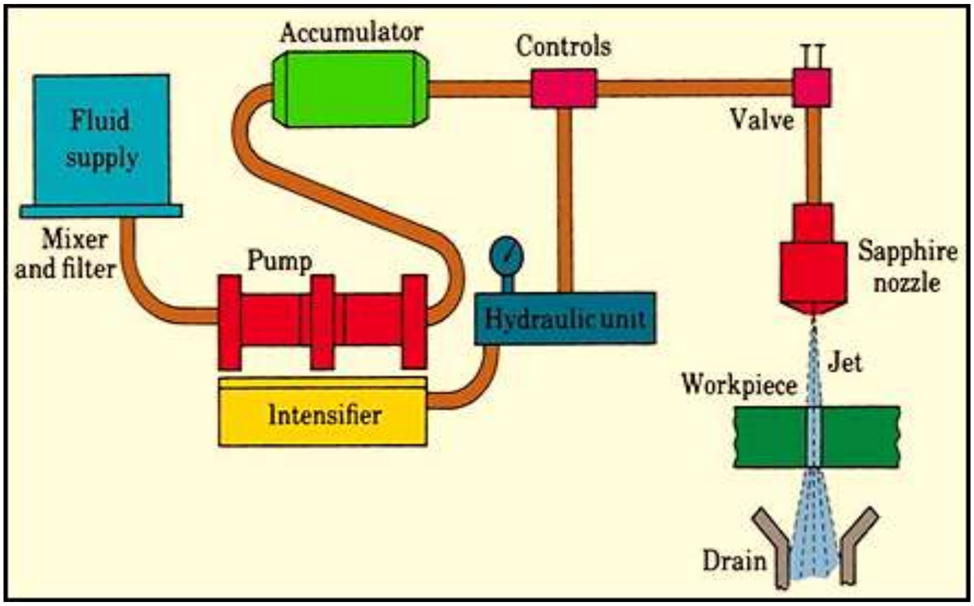
Machine structure:

Any standard **Abrasive Water Jet Machining** (AWJM) system using the **entrained** AWJM methodology, according to figure below, consists of following modules:



- LP booster pump
- Hydraulic unit
- Additive Mixer
- Intensifier
- Accumulator
- Flexible high pressure transmission line
- On-off valve
- Orifice
- Mixing Chamber
- Focussing tube or inserts
- Catcher
- CNC table
- Abrasive metering device
- Catcher

The **Intensifier**, shown below, is driven by a hydraulic power pack. The heart of the hydraulic power pack is a positive displacement hydraulic pump. The power packs in modern commercial systems are often controlled by microcomputers to achieve programmed rise of pressure, etc.



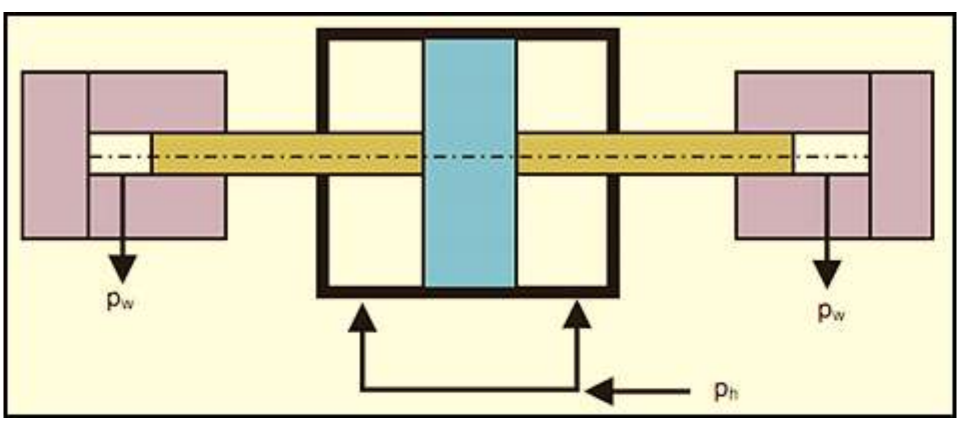
The hydraulic power pack delivers the hydraulic oil to the intensifier at a pressure pw. The ratio of cross-section of the two cylinders in the intensifier is named, ***A ratio (A large = A small)***. Thus, pressure amplification would take place at the small cylinder as follows.

$$p_h \times A_{large} = p_w \times A_{small}$$

$$p_w = p_h \times \frac{A_{large}}{A_{small}}$$

$$p_w = p_h \times A_{ratio}$$

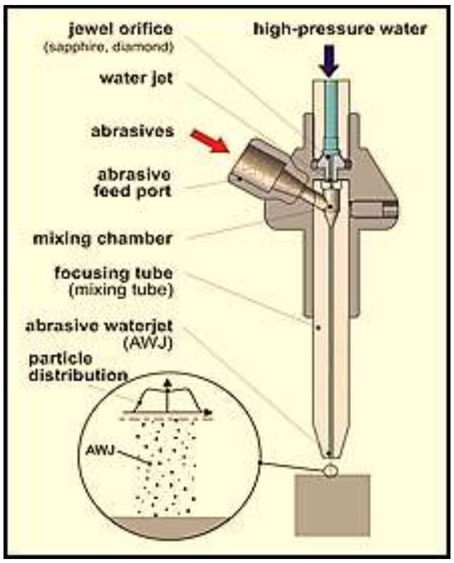
Thus, if the hydraulic pressure is set as **100 bar** and area **ratio is 40**, thus, **pw = 100 x 40 = 4000 bar**. By using direction control valve, the intensifier is driven by the hydraulic unit. The water may be directly supplied to the small cylinder of the intensifier or it may be supplied through a booster pump, which typically raises the water pressure to 11 bar before supplying it to the intensifier. Sometimes water is stabilized or “softened”, as long chain polymers are added in the “additive unit”.

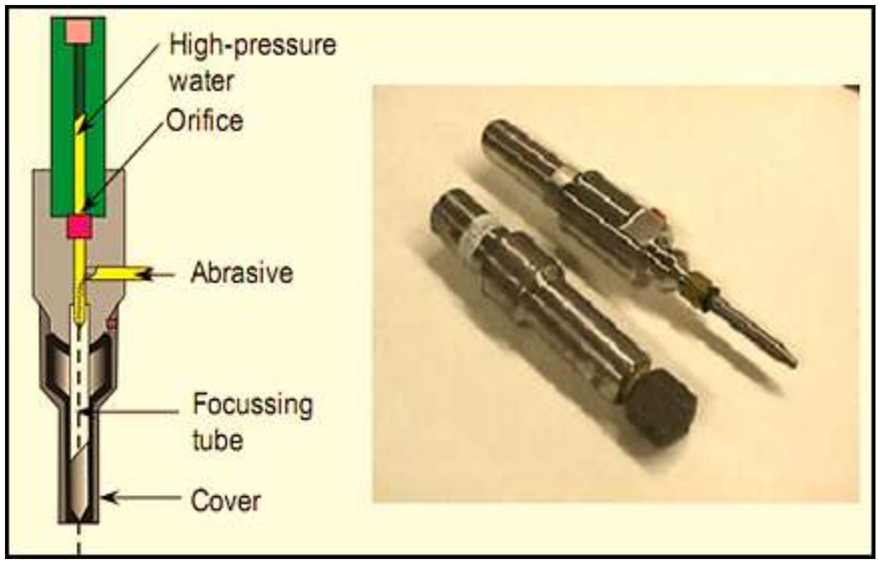


Thus, as the intensifier works, it delivers high pressure water (figure above). As the larger piston changes direction within the intensifier, there would be a drop in the delivery pressure. To counter such drops, a thick cylinder is added to the delivery unit to accommodate water at high pressure. This is called an “accumulator” which acts like a “fly wheel” of an engine and minimises fluctuation of water pressure.

High-pressure water is then fed through the flexible stainless steel pipes to the cutting head. Such pipes may carry water at 4000 bar (400 MPa) with flexibility incorporated by joints, without any leakage. Cutting heads consists of orifice, mixing chamber and focussing tube or insert where water jet is formed and mixed with abrasive particles to form abrasive water jet.

Below, is shown cutting heads or jet formers, 6 mm typical diameters, with flexible stainless steel pipes. The high pressure water is carried through the pipes through the jet formers or cutting heads. The potential or pressure head of the water is converted into velocity head by allowing the high-pressure water issuing through an orifice of small diameter (0.2 – 0.4 mm). The velocity of the water jet thus can be estimated assuming no losses, using Bernoulli’s equation. The orifices are typically made of sapphire.



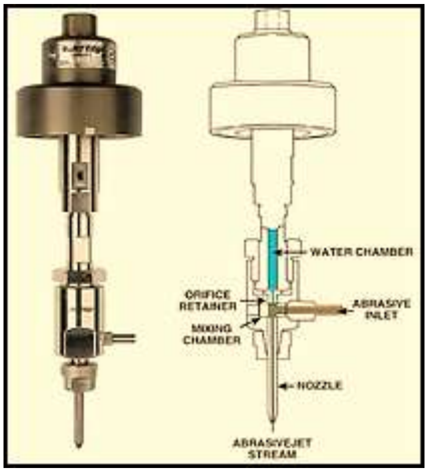


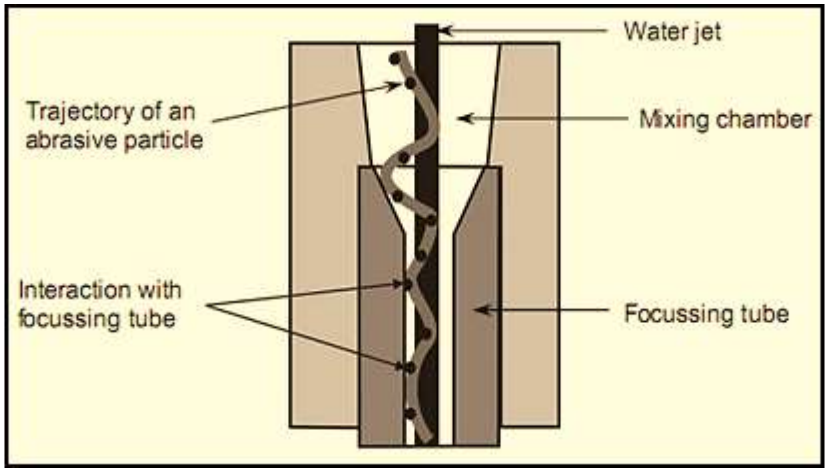
In commercial machines, the life of the sapphire orifice is typically around 100 – 150 hours. In WJM, this high velocity water jet is used for the required application where is directed into the mixing chamber which has a typical dimension of inner diameter **6 mm and a length of 10 mm**. As the high velocity water is issued from the orifice into the mixing chamber, a low pressure (vacuum) is created within the mixing chamber, and abrasive particles are introduced into the mixing chamber through a port, using different techniques, such as vibratory feeders or toothed belt feeders.

Abrasive mixing:

Abrasive mixing means gradual entrainment of abrasive particles within the water jet and finally the abrasive water jet comes out of the focusing tube or the nozzle. During the mixing process, the abrasive particles are gradually accelerated from the water phase to abrasive phase, and when the jet finally leaves the focusing tube, water and abrasive, are assumed to be at same velocity.

The focusing tube, is generally made of tungsten carbide (powder metallurgy material) having an inner diameter of **0.8 to 1.6 mm** and a length of **50 to 80 mm**. Tungsten carbide is used for its abrasive resistance. Abrasive particles, during mixing try to enter the jet, but are reflected away due to interplay of buoyancy and dragging forces, as can seen below:





There is an interacting with the jet and the inner walls of the mixing tube, as are accelerated using the momentum of the water jet. Mixing process may be mathematically modelled as follows. Taking into account the energy loss during water jet formation at the orifice, the **water jet velocity** may be given as:

$$v_{wj} = \Psi \sqrt{\frac{2\, p_w}{\rho_w}}$$

Where:

Ψ = Velocity coefficient of the orifice (0.8~1.0);
Pw = Water pressure
ρ_{w} = Water density (1000 kg/m³)

The volume flow rate of water may be expressed as:

$$q_w = \phi \times v_{wj} \times A_{orifice}$$
$$\dot{q}_w = \phi \times v_{wj} \times \frac{\Pi}{4} d_o^{\,2}$$
$$\dot{q}_w = \phi \times \frac{\Pi}{4} d_o^{\,2} \times \Psi \sqrt{\frac{2\, p_w}{\rho_w}}$$
$$\dot{q}_w = c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2\, p_w}{\rho_w}}$$

And,

$$q_w = \phi \times v_{wj} \times A_{orifice}$$
$$\dot{q}_w = \phi \times v_{wj} \times \frac{\Pi}{4} d_o^{\,2}$$
$$\dot{q}_w = \phi \times \frac{\Pi}{4} d_o^{\,2} \times \Psi \sqrt{\frac{2\, p_w}{\rho_w}}$$
$$\dot{q}_w = c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2\, p_w}{\rho_w}}$$

where,

ϕ = Coefficient of "vena-contracta"
c_d = Discharge coefficient of the orifice

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

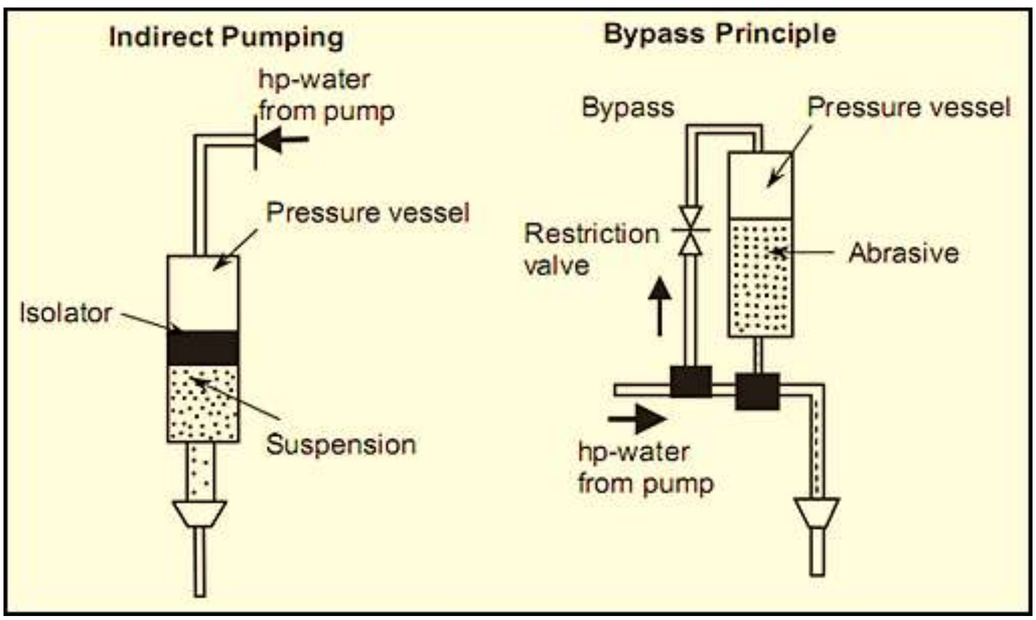
$$P_{wj} = p_w \times q_w$$

$$P_{wj} = p_w \times c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2\,p_w}{\rho_w}}$$

$$P_{wj} = c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2\,p_w^{\,3}}{\rho_w}}$$

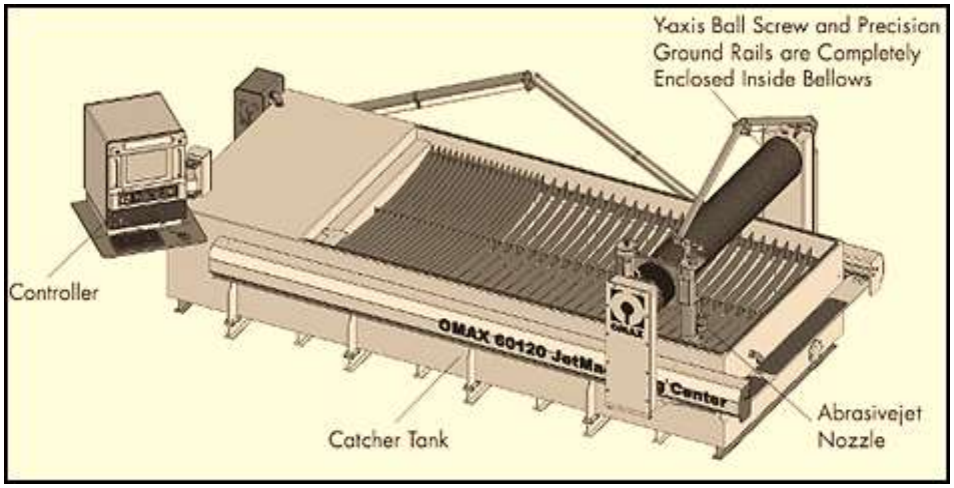
Suspension jet:

In entrained AWJM, the abrasive water jet, which comes from the focussing tube or nozzle, can be used to machine different materials. In suspension AWJM, the abrasive water jet is formed differently. In suspension AWJM, the preformed mixture of water and abrasive particles is pumped to a high pressure pressure vessel and stored. Then, the pre-mixed high-pressure water and abrasive is allowed to discharge from a nozzle, forming the abrasive water jet. There are three different types of suspension AWJ formed by **direct, indirect and bypass pumping** methods.

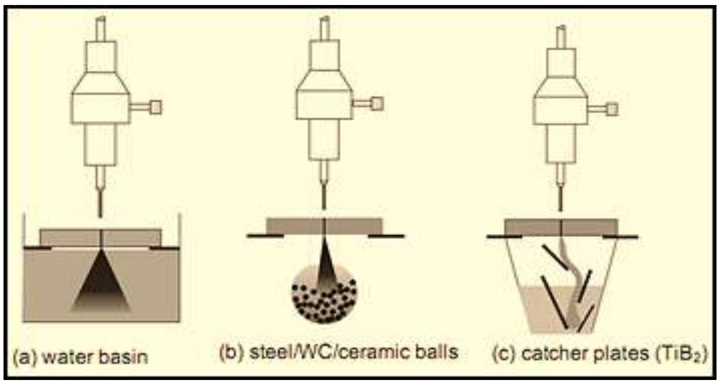


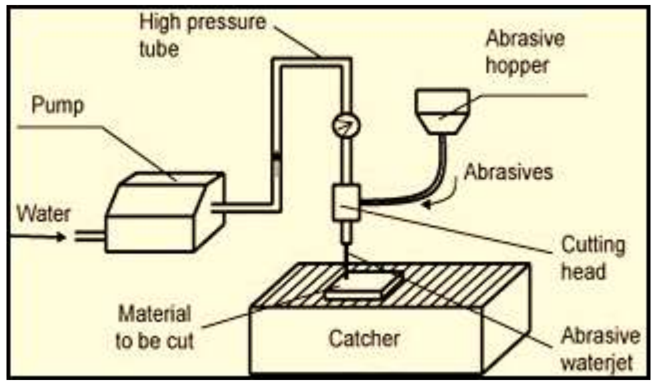
Catcher:

"Catcher" is used to absorb the residual energy of the AWJ and dissipate the high level of energy, depending on the type of application. Such high-energy abrasive water jet needs to be contained before they can damage any part of the machine or operators. The catchers can be of pocket type or line type. In pocket type, the catcher basin travels along the jet. In line type, the catcher basin travels along one axis of the CNC table, and its length covers the width of the other axis of the CNC table.

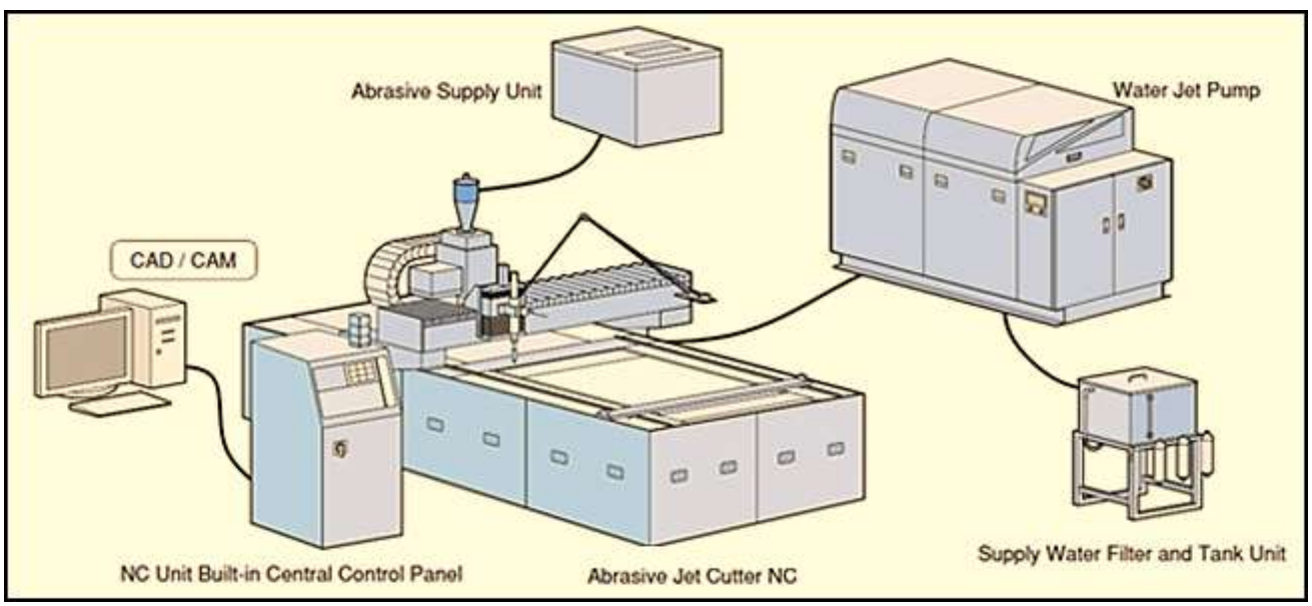


Below, is shown three different types of catchers and a schematically catcher process. Water basin type, submerged steel balls, and a TiB2 plate type.





Under the higher angle of impact, the material removal involves plastic failure. In case of AWJM of brittle materials, other than the above two models, the material would be removed due to crack initiation and propagation because of brittle failure of the material. Below is shown a complete AWJM system:



Mechanism of material removal:

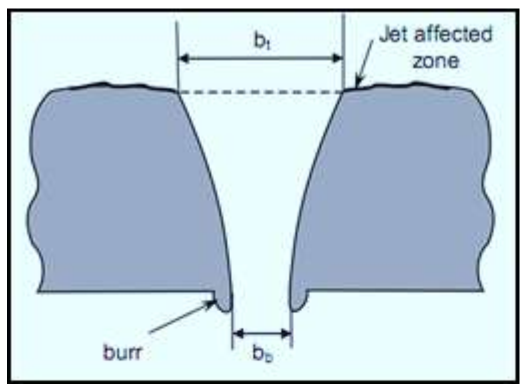
The parameters of the entrained type AWJ machining system, is given below:

- Orifice – Sapphires – 0.1 to 0.3 mm;
- Focussing Tube – WC – 0.8 to 2.4 mm;
- Pressure – 2500 to 4000 bar;
- Abrasive – garnet and olivine - #125 to #60 mesh;
- Abrasive flow - 0.1 to 1.0 kg/min;
- Stand off distance – 1 to 2 mm;
- Machine Impact Angle – 60°- to 90°;
- Traverse Speed – 100 mm/min to 5 m/min;
- Depth of Cut – 1 mm to 250 mm;

Mechanism of material removal in machining with Water Jet and Abrasive Water Jet is rather complex. In AWJM, ductile materials are mainly removed by low angle impact and abrasive particles leading to ploughing and micro cutting. In Water Jet Machining, the material removal rate may be assumed to be proportional to the power of the water jet.

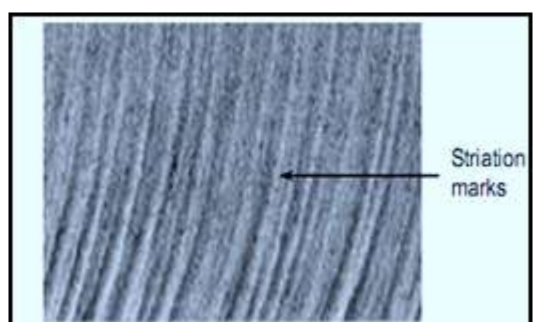
$$MRR \propto P_{wj} \propto c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2p_w^{\,3}}{\rho_w}}$$

$$MRR = u \times c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2p_w^{\,3}}{\rho_w}}$$



The proportionality constant '*u'* is the specific energy requirement and would be a property of the work material. Below is shown the cut generated by an AWJM in different sections, which is called *a kerf*.

Photographic view of kerf (cross section)



Photographic view of kerf (longitudinal section)

The water, often mixed with an abrasive, is forced through a nozzle on one of the machine's cutting heads and penetrates through the material positioned on the machine's large cutting table. The shape of the piece, the speed at which it is processed, and the number of parts produced, are all computer controlled giving the operator precise control over the cutting process.

Abrasive jets are much faster than EDM, and machine a wider variety of materials (virtually any material). Abrasive Jet Machining is useful for creating start holes or for wire insertion later on. New technology allows abrasive jets to obtain tolerances of up to +/-.003" (0.075mm) or better.

The process starts with the customer's design specifications. A technician programs the specifications into the water jet cutting machine's software. The software not only allows the technician to control variables such as pressure and speed, it also determines where parts will be cut from the material to minimize waste. This process, called nesting, positions parts as closely as possible to maximize the number of parts that can be cut from a single piece of material.

Environmental issues:

Nowadays, every manufacturing process is being re-evaluated in terms of its impact on the environment. For example, use of conventional coolants in machining and grinding is being looked upon critically from the point of view of its impact on environment. The environmental issues relevant to AWJM are:

- Water recycling;
- Spent water disposal;
- Chip recovery;
- Abrasive recovery and reuse.

Environmental issues and concerns have lead the researchers to use such mediums and abrasives that do not require disposal, recycling or lead to pollution. Work is going on in the area of high-pressure cryogenic jet machining, where liquid nitrogen replaces the water.

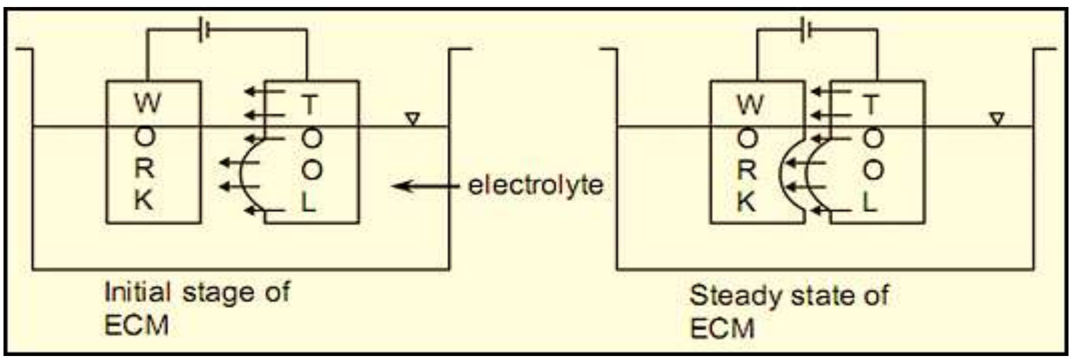
Dry ice crystals (solid CO2 crystals) replace the abrasive phase leading to no need of disposal or waste generation. The removed work material in the form of microchips can be collected much easily reducing the chances of environmental degradation.

IV. ELETROCHEMICAL MACHINING (ECM):

Electrochemical Machining (ECM) is a method of removing metal by an electro-chemical process. Thus, ECM is a controlled anodic dissolution at atomic level, electrically conductive by a shaped tool, due to flow of a high current at relatively low potential difference, through an **electrolyte** which is quite often water based neutral salt solution. The ECM cutting tool is guided along the desired path close to the work but **without touching the piece**, and can cut small or odd-shaped angles, intricate contours or cavities in hard and exotic metals, such as titanium, inconel, high nickel, cobalt, and rhenium alloys.

ECM is often characterized as "reverse electroplating," that is, it removes material instead of adding it. It is similar in concept to Electrical Discharge Machining (EDM) where a high current is passed between an electrode, through an electrolytic material removal process, having a negatively charged electrode (cathode), a conductive fluid (electrolyte), and a conductive workpiece (anode). Unlike EDM, however, no sparks are created.

Both external and internal geometries can be machined. It is normally used for mass production, commonly used for working extremely hard materials difficult to machine using conventional methods, but, limited to electrically conductive materials. High metal removal rates are possible, with no thermal or mechanical stresses being transferred to the part and mirror surface finishes can be achieved. The figure below, schematically shows the basic principle of ECM.



Electrochemical machining process:

In the ECM process, a cathode (tool) is advanced into an anode (workpiece). The pressurized electrolyte is injected at a set temperature to the area being cut. The feed rate is the same as the rate of "liquefaction" of the material. The gap between the tool and the workpiece varies within **80-800 micrometers** (0.003 in. and 0.030 in.). As electrons cross the gap, the material of the **workpiece is dissolved**, as the tool forms the desired shape according to design. The electrolytic fluid **carries away** the metal hydroxide formed in the process.

There will be reactions occurring at the electrodes, the anode (or workpiece), and the cathode (or the tool) along within the electrolyte. For electrochemical machining of carbon steel, generally a neutral salt solution of sodium chloride (NaCl) is taken as the electrolyte. The electrolyte and water undergoes an ionic dissociation, as potential difference is applied, as shown below:

$$NaCl \leftrightarrow Na^{+} + Cl^{-}$$
$$H_2O \leftrightarrow H^{+} + (OH)^{-}$$

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:

$2H^+ + 2e^- = H_2\uparrow$ at cathode

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

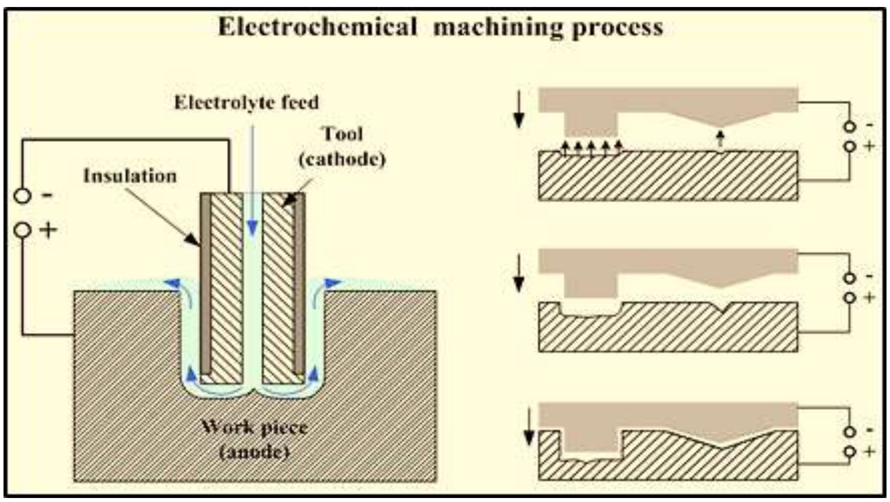
$Fe = Fe^{++} + 2e^-$

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:

$Na^+ + OH^- = NaOH$

The workpiece is mounted in a fixture electrically isolated from the tank and other machine parts. The workpiece is connected to the positive terminal (anode) of the Power Supply. The tool is connected to the negative terminal (cathode). The electrolyte is continuously flowing through a hole in the tool to the gap between the work piece and the tool surfaces.

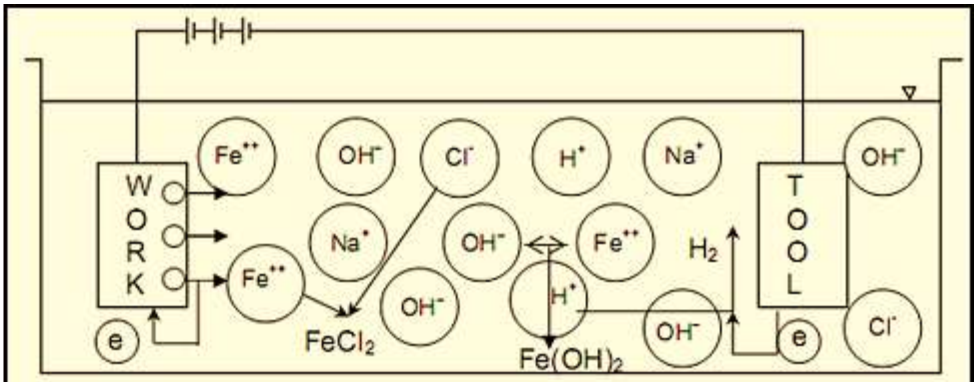
The tool is moving towards the workpiece at a constant speed of about **0.05"/min** (1.25 mm/min). The gap between the tool and the work piece is kept constant. Stable behavior of the process is a result of a control of the power supply voltage. The final shape of the work piece formed as a result of the electrochemical machining process conforms the shape of the tool. The principle scheme of electrochemical process is presented in the figure below.



In practice the FeCl2 and 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. The figure below, 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.

The voltage is required to be applied for the electrochemical reaction to proceed at a steady state. That voltage or potential difference is around **2 to 30 V**. The applied potential difference, however, also overcomes the following resistances or potential drops, as described below:

- The electrode potential;
- The activation over potential;
- Ohmic potential drop;
- Concentration over potential;
- Ohmic resistance of electrolyte.



Schematic representation of electro-chemical reactions

ECM equipment:

The electrochemical machining system has the following modules:

- DC Power supply;
- Electrolyte filtration and circulation system;
- Electrolyte circulation system;
- Mechanical parameters:
- Control system
- Electrolytes:

DC power supply: The machining rate in ECM is proportional to the electric current density. In order to achieve high values of the machining rate, the electrochemical machining is commonly performed at a high direct current exceeding 1000 A. The voltage of the process is around **5-25 V**.

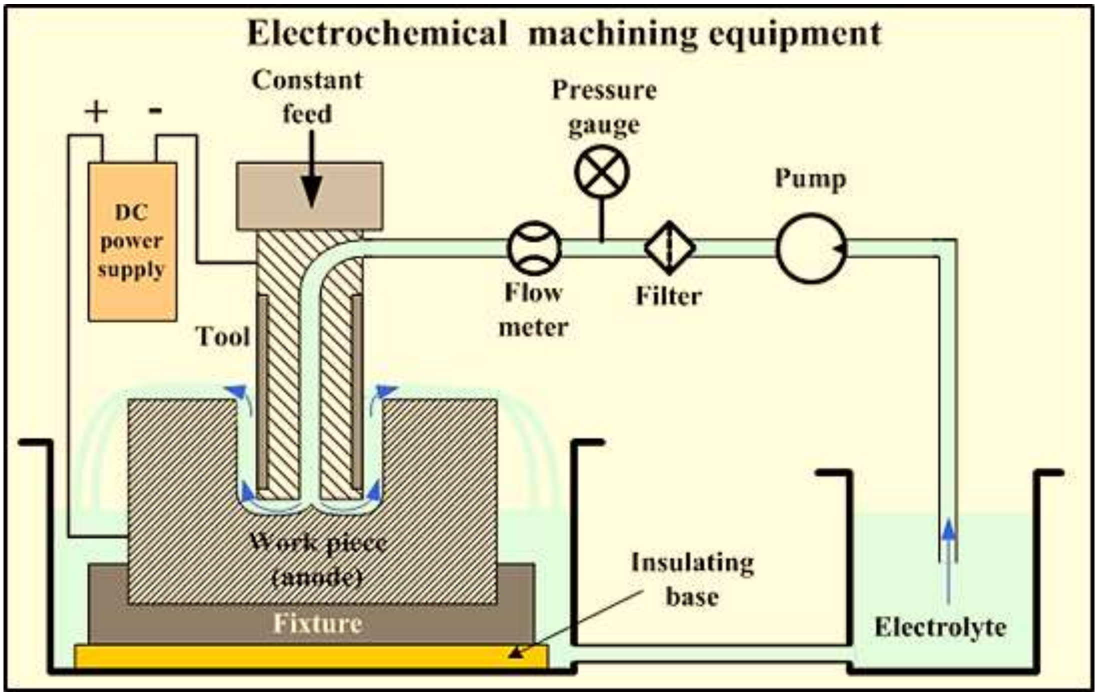
Electrolyte circulation system: The products of the electrochemical reaction should be removed from the gap between the work piece and the tool. Accumulation of the reaction products causes decrease of the process efficiency and reduction of the rate of machining. Therefore the electrolyte flow speed should be high, commonly in the range **1,000-10,000 ft/min (300-3,000 m/min)**. The electrolyte is continuously filtered in order to trap the precipitated reaction products (sludge).

Mechanical parameters: One of the most important parameters of electrochemical machining is maintaining a constant voltage level. This is achieved by the control system providing a movement of the tool at a constant speed equal to the linear rate of machining, (typically gap **0.004-0.016”/0.1-0.4 mm)**. Conventional machining equipment including CNC, may be modified, for electrochemical machining purposes.

Control system: Electrical parameters of the process, tool feed speed and parameters of electrolyte circulation system are controlled by the control system, which provide stable and efficient operation of the unit.

Electrolytes: The electrolytes used in electrochemical machining are:

- Sodium chloride (NaCl) at the concentration of 20% - for ferrous alloys(e.g. Steels and cast irons and cobalt alloys.
- Sodium nitrate (NaNO3) - for ferrous alloys.
- Hydrochloric acid (HCl) - for Nickel alloys.
- A mixture of sodium chloride (NaCl) and sulfuric acid (H2SO4) - for nickel alloys.
- A mixture of 10% hydrofluoric acid (HF), 10% hydrochloric acid (HCl), 10% nitric acid (HNO3) - for Titanium alloys.
- Sodium hydroxide (NaOH) - for tungsten carbide (WC).



Modelling of material removal rate:

In ECM, **the 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 x 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.

$$m \; \alpha \; ECE \; \alpha \; \frac{A}{\nu} = m \; \alpha \; \frac{QA}{\nu}$$

Where:

F = Faraday's Constant = 96500 coulombs

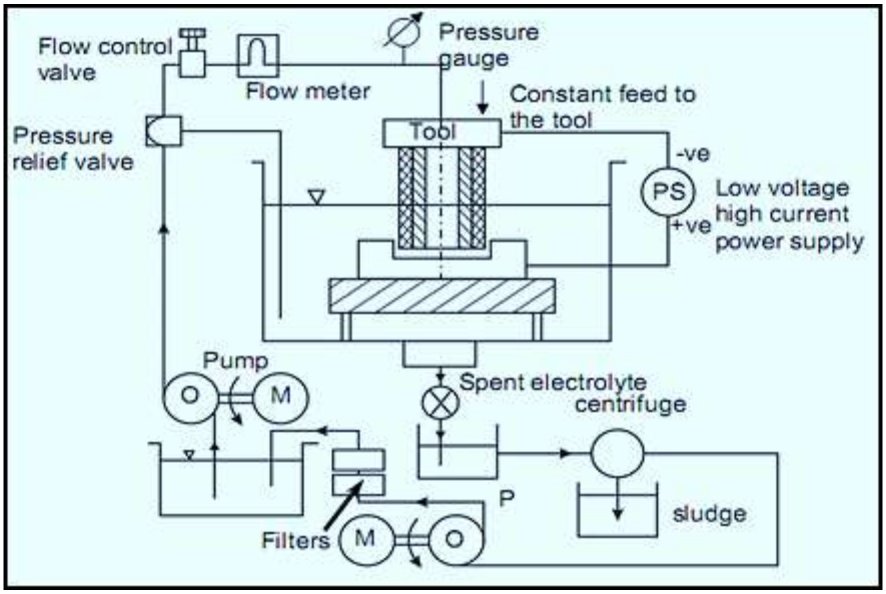
$$m = \frac{ItA}{F\nu}$$

$$MRR = \frac{m}{t\rho} = \frac{IA}{F\rho\nu}$$

Where:

I = current
ρ= density of the material

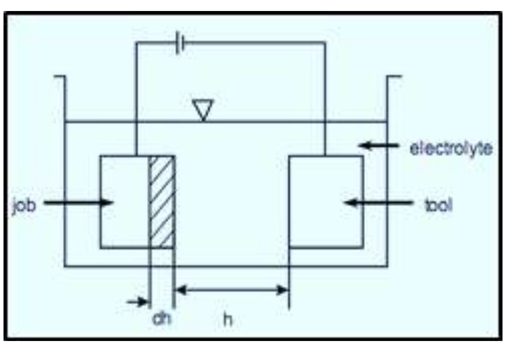
The figure below, schematically shows an electrochemical drilling unit and an ECM picture:



Dynamics of electrochemical machining:

ECM can add accuracy and substitute processes, such as drilling, polishing, or milling, along with machining and designing, what is not possible to be done by conventional machining, such as micro-machining and shaping hard-to-reach locations in practically any electro-conductive material.

The 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. The figure below, schematically shows the machining (ECM) with no feed to the tool and an instantaneous gap between the tool and workpiece of 'h', and some examples of workpieces.



In resume, the electrochemical machining is a process of a selective dissolution of the anodically connected workpiece material submerged in an electrolyte together with an anodically connected tool, similar to electro-polishing where the work piece surface roughness decreases due to the conversion of the atoms into ions and their removal from the surface as a result of a passage of an electric current.

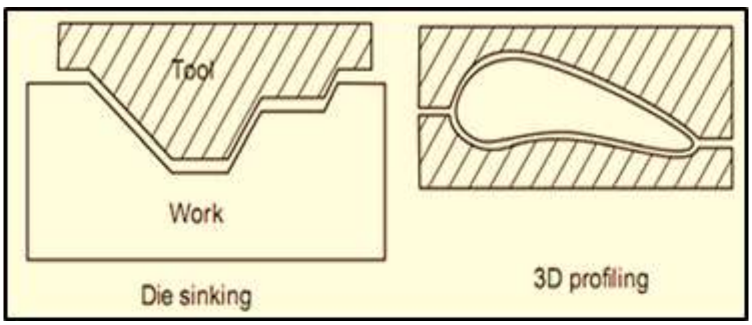
Electrochemical machining is generally opposite to electroplating where the metallic ions traveling through the electrolyte solution deposit on the surface of the cathodically connected work piece. As described above, the ECM technique **removes material by atomic level dissolution** of the same by electro-chemical action.

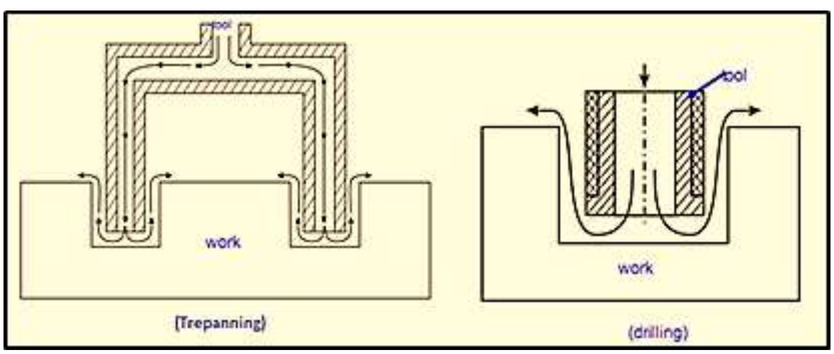
ECM applications:

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;
- ✓ Profiling and contouring;
- ✓ Trepanning;
- ✓ Grinding;
- ✓ Drilling;
- ✓ Micro-machining.





Process parameters:

Power Supply:
Type: Direct current;
Voltage: 2 to 35 V;
Current: 50 to 40,000 A;
Current density: 0.1 A/mm² to 5 A/mm².

Electrolyte:

Material: NaCl and NaNO3;

Temperature: 20ºC – 50°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: Ra 0.2 to 1.5 µm.

Electrochemical Grinding (ECG):

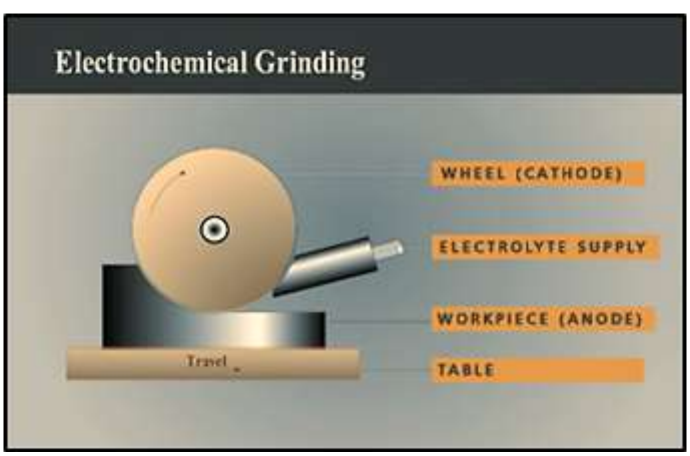
Electrochemical Grinding, or ECG, is a variation of ECM that combines electrolytic activity with the physical removal of material by means of charged **grinding wheels**. Electrochemical Grinding (ECG) can produce **burr free** and stress free parts **without heat** or other metallurgical damage, caused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

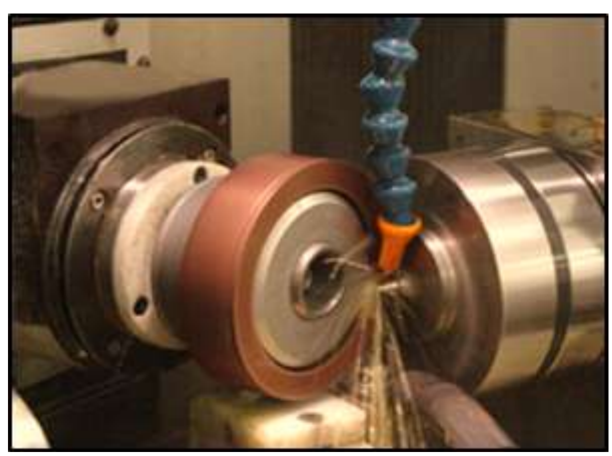
Electrochemical Grinding (ECG) can process conductive material that is electrochemically reactive. Difficult materials to machine by conventional methods, that harden easily or subject to heat damages are also good candidates for the stress free and no heat characteristics of Electrochemical Grinding. The stress free cutting capability of the process also make it ideal for thin wall and delicate parts.

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

Conventional surface grinding typically uses shallow reciprocating cuts that sweep across the work surface to create a flat plane or groove and typically uses slower feeds to remove the material in deep cuts. Due the abrasive nature of these processes, the equipment used must be rigid and this is true of creep feed grinding.

The tolerances that can be achieved using ECG depend greatly on the material being cut, the size and depth of cut and ECG parameters being used. On small cuts, tolerances of **0.0002" (0.005 mm)** can be achieved with careful control of the grinding parameters. The process does not leave the typical shiny finish of abrasive grinding. This is because there is no smearing of the metal as in conventional grinding. A **16 micro inch finish** or better can be achieved but it will have a matte (dull) rather than a polished look.





V. ELECTRO DISCHARGE MACHINING (EDM):

Sometimes, colloquially, also referred to as spark machining, spark eroding, burning, die sinking or wire e-rosion, is a manufacturing process where a desired shape is obtained using electrical discharges (sparks). The **material is removed** from the workpiece by a series of rapidly recurring current discharges between two electrodes, separated by a dielectric liquid and subject to an electric voltage. One of the electrodes is called the **tool-electrode**, or simply the 'tool' or 'electrode', while the other is called the **workpiece-electrode**, or 'workpiece'.

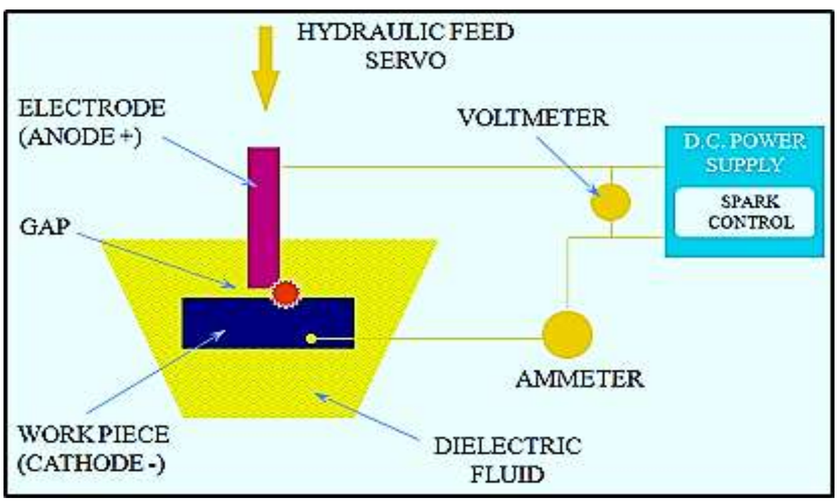
Basically, Electric Discharge Machining (EDM) is a process for eroding and removing material by transient action of electric sparks on electrically conductive materials. This process is achieved by applying consecutive spark discharges, between the charged workpiece and the electrode immersed in a dielectric liquid and separated by a small gap.

When the distance between the two electrodes is reduced, the intensity of the electric field in the volume between the electrodes becomes greater than the strength of the dielectric (at least in some point(s), which breaks, allowing current to flow between the two electrodes. This phenomenon is the same as the breakdown of a capacitor (condenser). As a result, material is removed from both the electrodes.

Usually, localized breakdown of the dielectric liquid occurs where the local electrical field is highest. Each **spark melts and even evaporates** a small amount of material from both electrode and workpiece. Part of this material is removed by the dielectric fluid and the remaining part resolidifies rapidly on the surfaces of the electrodes.

The net result is that each discharge leaves a small crater on both workpiece and electrode. Application of consecutive pulses with high frequencies together with the forward movement of the tool electrode towards the workpiece, results with a form of a complementary shape of the electrode on the workpiece.

The EDM is also 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. The work material to be machined, by EDM, has to be electrically conductive. Every EDM machine has the following basic elements as shown below:

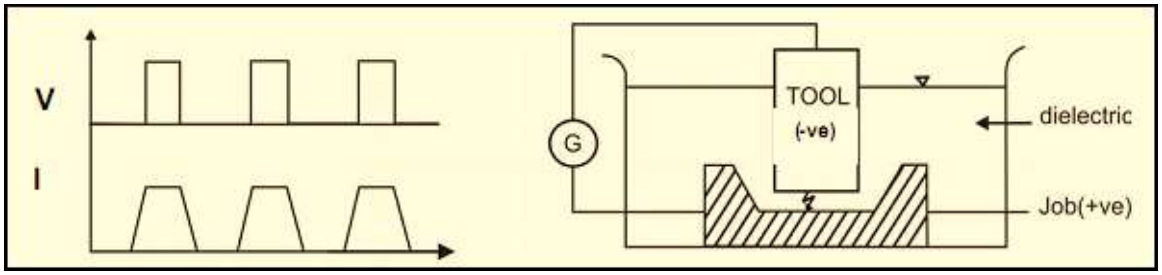


The material removal rate, electrode wear, surface finish, dimensional accuracy, surface hardness and texture and cracking depend on the size and morphology of the craters formed. The applied current, voltage and pulse duration, thermal conductivity, electrical resistivity, specific heat, melting temperature of the electrode and workpiece, size and composition of the debris in dielectric liquid can be considered as the main physical parameters effecting to the process.

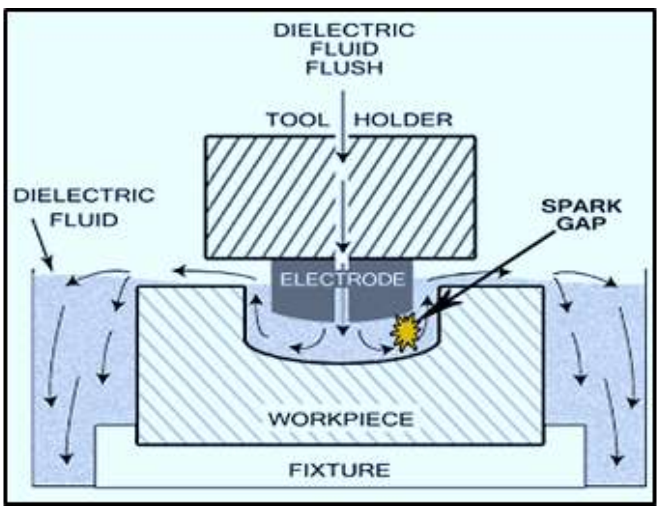
In EDM, a potential difference is applied between the tool and workpiece. Both the tool and the work material are to be conductors of electricity. The tool and the work material are immersed in a dielectric medium. Generally **kerosene or deionised water** is used as the **dielectric** medium. A gap 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.

EDM Process:

The figure below, shows schematically, the basic working principle of EDM process:



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 below, 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.

EDM conditions:

(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 μm** 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.

Dielectric fluid:

The dielectric fluid should provide an oxygen free machining environment, as thermal processing is required in absence of oxygen, so that the process can be controlled and oxidation avoided. Oxidation often leads to poor surface conductivity (electrical) of the workpiece hindering further machining. Enough strong dielectric resistance does not cause breakdown and at the same time ionise when electrons collide with its molecule. Moreover, during sparking it should be thermally resistant, as well.

Generally, **kerosene** and **deionised water** is used as **dielectric fluid** in EDM. Tap water cannot be used as it ionises too early, and thus breakdown due to presence of salts, as impurities occur. The dielectric medium is generally flushed around the spark zone. It is also applied through the tool to achieve efficient removal of molten material.

Electrode characteristics:

The electrode material should be such, that it would not undergo much tool wear, when it is impinged by positive ions. Thus the localised temperature rise has to be less by tailoring or properly choosing its properties or even when temperature increases, there would be less melting. Further, the tool should be easily workable as intricate shaped geometric features are machined in EDM. Thus the basic characteristics of electrode materials are:

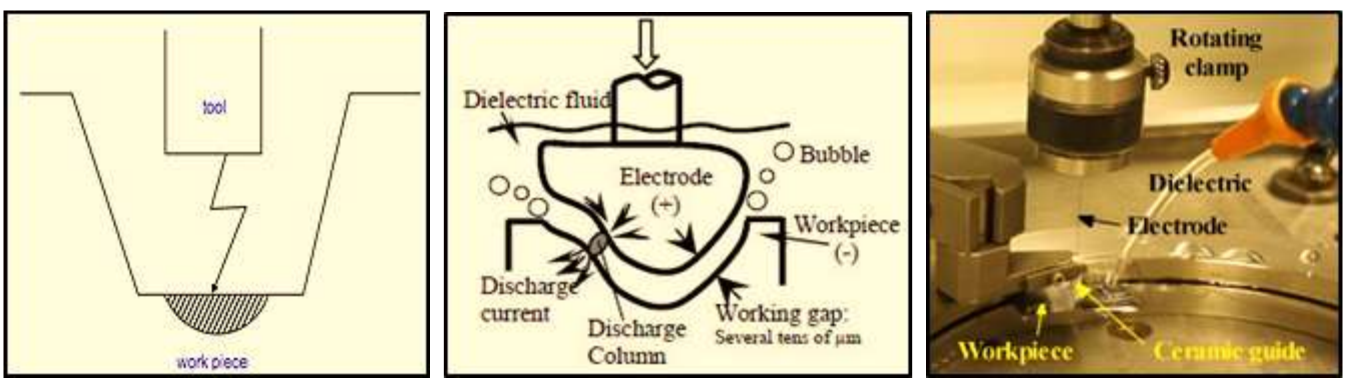
- ✓ High electrical conductivity – electrons are cold emitted more easily and there is less bulk electrical heating;
- ✓ High thermal conductivity – for the same heat load, the local temperature rise would be less due to faster heat conducted to the bulk of the tool and thus less tool wear;
- ✓ Higher density – for the same heat load and same tool wear by weight there would be less volume removal or tool wear and thus less dimensional loss or inaccuracy;
- ✓ High melting point – high melting point leads to less tool wear due to less tool material melting for the same heat load;
- ✓ Easy manufacturability;
- ✓ Cost – cheap.

The different electrode materials used commonly in the industry are:

- ✓ Graphite;
- ✓ Electrolytic oxygen free copper;
- ✓ Tellurium copper – 99% Cu + 0.5% tellurium;
- ✓ Brass.

Modelling of Material Removal:

Material removal in EDM mainly occurs due to intense localised heating almost by point heat source for a rather small time frame, as shown below:



The severity of the wear is strictly dependent on the technological parameters used in the operation (for instance: polarity, maximum current, open circuit voltage). For example, in micro-EDM, also known as µ-EDM, these parameters are usually set with values which generate severe wear. Product quality is a very important characteristic of a manufacturing process along with MRR such as, surface finish, overcut and tapercut.

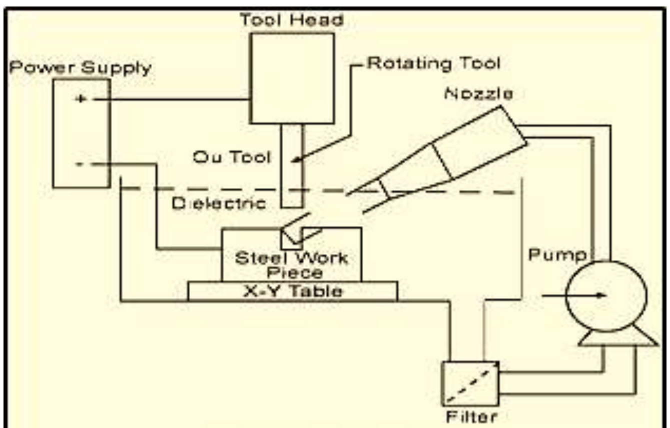
Such heating leads to melting and crater formation on the tool results in the gradual erosion of the electrode also referred to as wear. Strategies are needed to counteract the detrimental effect of the wear on the geometry of the work piece. One possibility is of continuously replacing the tool-electrode during a machining operation.

Conventional, RAM EDM or Sinker EDM

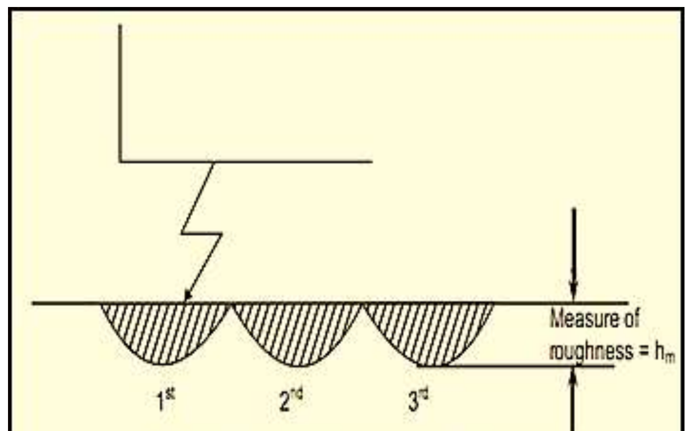
Conventional EDM is commonly known as Spark EDM. This process is often used when the desired cut or design feature does not penetrate through the entire workpiece. The electrodes for Spark EDM are mostly manufactured from graphite or copper tungsten. RAM EDM electrodes utilize a negative-formed shape which contains all the detail of the final workpiece.

Through CNC programming, the electrode is moved along the workpiece, never contacting the piece but creating an area between the electrode and workpiece referred to as Spark Gap. As the electrode moves along the x, y, c, and z axes, complex indentations, shapes, vents and cavities are created. The intricacy that can be achieved with conventional EDM is unmatched by any other method of machining.

Typically RAM EDM applications are performed with the workpiece fully submerged in solution bath. This fluid serves various purposes including flushing away of the eroded material, cooling the heat affected zone and preventing damage to the workpiece, and acting as a conductor between the electrode and the workpiece. As the electrode approaches the workpiece, the dielectric breakdown occurs in the fluid, forming a plasma channel, and a small spark jumps.



Electric Discharge Machining Operation



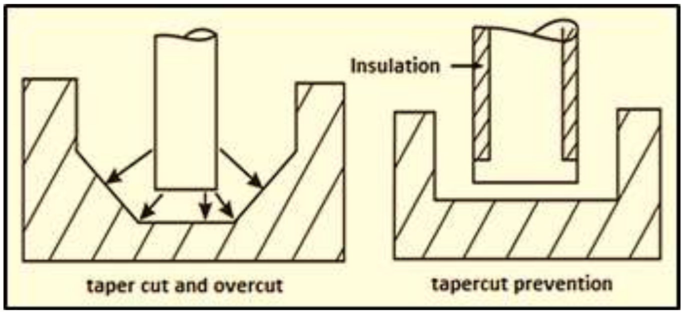
Schematic representation of the sparks in EDM process.

These sparks usually strike one at a time because it is very unlikely that different locations in the inter-electrode space have the identical local electrical characteristics which would enable a spark to occur simultaneously in all such locations. These sparks happen in huge numbers at seemingly random locations between the electrode and the workpiece.

As the base metal is eroded, and the spark gap subsequently increased, the electrode is lowered automatically by the machine so that the process can continue uninterrupted. Several hundred thousand sparks occur per second, with the actual duty cycle carefully controlled by the setup parameters. These controlling cycles are sometimes known as "on time" and "off time", which are more formally defined in the literature.

The on time setting determines the length or duration of the spark. Hence, a longer on time produces a deeper cavity for that spark and all subsequent sparks for that cycle, creating a rougher finish on the workpiece. These settings can be maintained in microseconds. The typical part geometry is a complex 3D shape, often with small or odd shaped angles. Vertical, orbital, vectorial, directional, helical, conical, rotational, spin and indexing machining cycles are also used.

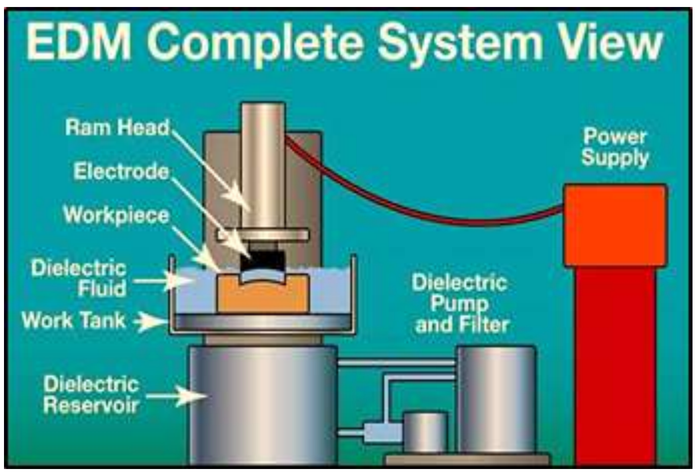
The spark occurs between the two nearest point on the tool and workpiece, thus, machining may occur on the side surface, as well, leading to **overcut** and **tapercut**, as depicted in figure below. Tapercut can be prevented by suitable insulation of the tool. Overcut cannot be prevented as it is inherent to the EDM process. But the tool design can be done in such a way so that same gets compensated.



The Basic EDM System

In a basic, ram-type EDM system, the ram head is driven up and down with extreme accuracy by a servo-driven system. The servo system is controlled by a microprocessor connected to the power supply. The power supply is solid-state and is also microprocessor controlled. One lead from the power supply is connected to the workpiece, which is immersed in a tank of dielectric oil.

The dielectric tank is connected to a dielectric pump, an oil reservoir, and a filter system. The pump provides pressure for flushing the work area and moving the oil while the filter system removes and traps debris in the oil. The oil reservoir stores surplus oil and provides a container for draining the oil between operations. The other lead from the power supply is connected to the electrode.

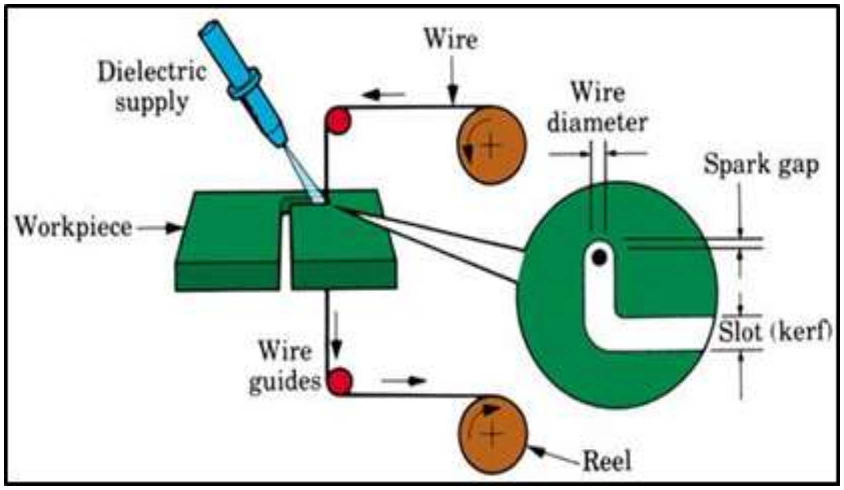


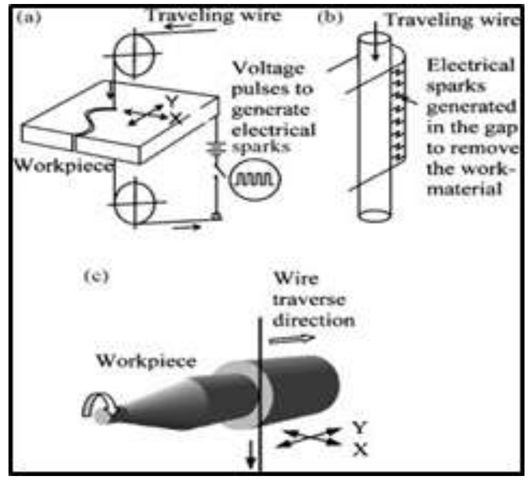
The power supply provides a pulsed DC output to the electrode/workpiece system. On-times and off-times are set manually, along with voltage and current values. When the EDM machine is turned on, the servo microprocessor, sensing that the gap is too wide for cutting to take place, signals the servo mechanism to lower the ram head. The EDM machine has the following major modules as shown above:

- ✓ Dielectric reservoir, pump and circulation system;
- ✓ Power generator and control unit;
- ✓ Working tank with work holding device;
- ✓ X-y table accommodating the working table;
- ✓ The tool holder;
- ✓ The servo system to feed the tool.

Wire EDM:

The Wire Electrical Discharge Machining (WEDM), also known as **Wire-cut EDM** or Wire Cutting, uses a thin single-strand metal wire, usually brass, which is fed through the workpiece, submerged in a tank of dielectric fluid, typically deionized water. The Wire-cut EDM is commonly used to cut plates, **as thick as 300 mm (12 inches)**, and to make punches, tools, and dies from hard metals that are difficult to machine with other methods. The wire, which is constantly fed from a spool, is held between upper and lower diamond guides.





A spark is sent from the shortest distance between a single strand of wire, usually brass, and the work-piece where it jumps the gap (known as the spark gap) at which point material is burned away from the workpiece. In order to control the sparking process from shorting out, dielectric, a non-conductive fluid solution is used to either flush or submerge the entire Wire EDM process.

The eroded waste material is removed by the continuous flow of the dielectric fluid which is cooled and filter throughout the entire process. Since Wire EDM is mainly used for cutting shapes through assemblies and inserts, it is usually necessary to predrill a hole for the wire to be fed through, in order machining be completed. The Wire EDM is utilized only when the required cut goes through the entire work-piece.

This allows the Wire-cut EDM to be programmed to cut very intricate and delicate shapes. The upper and lower diamond guides are usually accurate to **0.004 mm**, and can have a cutting path or kerf, as small as, **0.021 mm** using **Ø0.02 mm wire**, though the average cutting kerf that achieves the best economic cost and machining time is **0.335 mm** using **Ø0.25 brass wire**.

Small tooling inserts made by wire EDM

Block used to make thin, L-shaped blades

EDM general considerations:

- **The sparks made by EDM:**

The EDM machines generate thousands of **sparks per second**. The frequency or number of sparks can be controlled by the machine operator or by software built into the machine control by the machine manufacturer.

- **The dielectric fluid:**

The dielectric fluid acts as an an insulator. The dielectric fluid flushes away eroded particles from the "Gap". Older 'plunge' machines uses Kerosene. Mineral based or synthetic oils are now used. Deonized water is used as a dielectric medium on Wire EDM machines.

Note: Cheap oils may contain chlorine and sulfur levels that can be hazardous to the operator and to the cutting process.

- **The electrodes materials:**

Graphite (Melting point is 3,500 ºC); cuts faster than copper; less electrode wear; stable during cutting.
Copper (Melting point is 1,083 ºC); produces better surface finishes. Copper can move.

Wire EDM materials:

A brass wire is used on wire EDM machines. Wire sizes of between **0.004" to 0.012"** diameter are used. Most often, a **0.010" diameter wire** is used. The brass wire is guided by ceramic or diamond guides.

- **The materials machined with EDM:**

EDM is very suitable for machining hard steel; The hardness of the steel is not important. Metals that have a high thermal conductivity, and melting point, are difficult to machine with the EDM. process. Tungsten carbide can be machined reasonably well, normally with a graphite electrode.

- **Wear of the electrode:**

Electrode wear can be minimal on newer machines, depends on the skill of the operator and desired results, that can be severe on older machines and tap disintegrators. Ideally, use a roughing instead of a finishing electrode on 'plunge' machines. Fresh wire is fed continually to cutting on Wire EDM machines, and the worn wire is disposed off.

- **HAZ (Heat Affected Zone):**

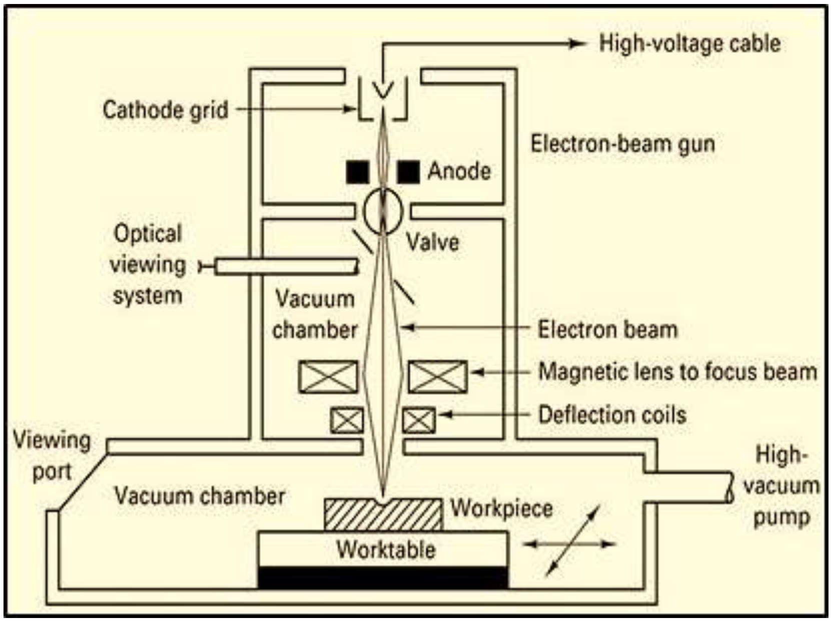
Sink and Wire EDM machines produce a slightly different HAZ due to the different dielectric mediums used. Temperature is around **11,000 ºC,** when spark initially touches work surface, literally vaporizing the outer layer of the part. The HAZ in a sink operation, may be chemically altered by the carbon from the hydro carbons in the dielectric oil combining with the steel surface.

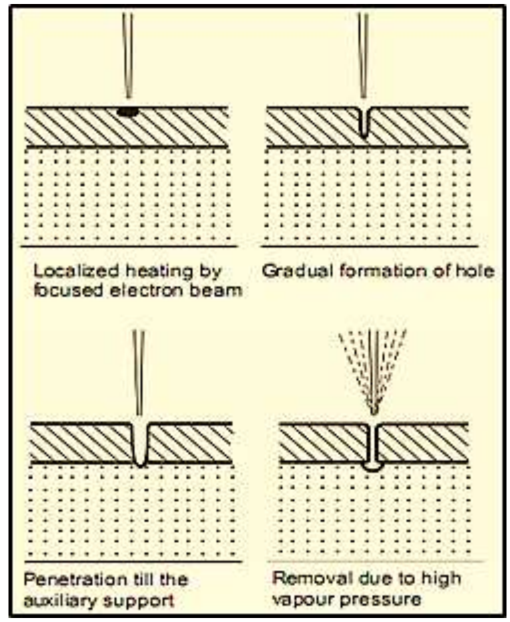
The HAZ layer may be reduced by shortening the on-time and lengthening the off-time. Also by lowering the current (Amps). This creates smaller and shallower craters. Stresses in the recast layer and HAZ can cause micro cracking. This layer may have to be removed for critical parts, i.e., turbine blades in jet engines. The HAZ may be less than **0.001" thick**.

VI. ELECTRON BEAM MACHINING (EBM):

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

Electron Beam Machining (EBM) is a process where high-velocity electrons, is concentrated in a narrow beam, are directed toward the work piece **creating heat and vaporizing the material**. EBM machines usually utilize voltages in the range of **150 to 200 kV** to accelerate electrons to about **200,000 km/s**. **Magnetic lenses** are used to focus the **electron beam** to the surface of the work-piece. By means of a electroma-gnetic deflection system, the beam is positioned as needed, usually through a computer.





EBM process:

The electron beam is generated in an electron beam gun. The construction and working principle of the e-lectron beam gun would be discussed in the next section. Electron beam gun provides high velocity elec-trons over a very small spot size. Electron Beam Machining is required to be carried out in vacuum.

The kinetic energy of the electrons, upon striking the workpiece, **changes to heat**, which vaporizes little a-mounts of the material. The vacuum prevents the electrons from scattering, due to collisions with gas mo-lecules. The EBM is used for cutting holes as small as **0.001 inch** (0.025 millimetre) in diameter or slots as narrow as **0.001 inch** in materials up to **0.250 inch** (6.25 millimetres) in thickness.

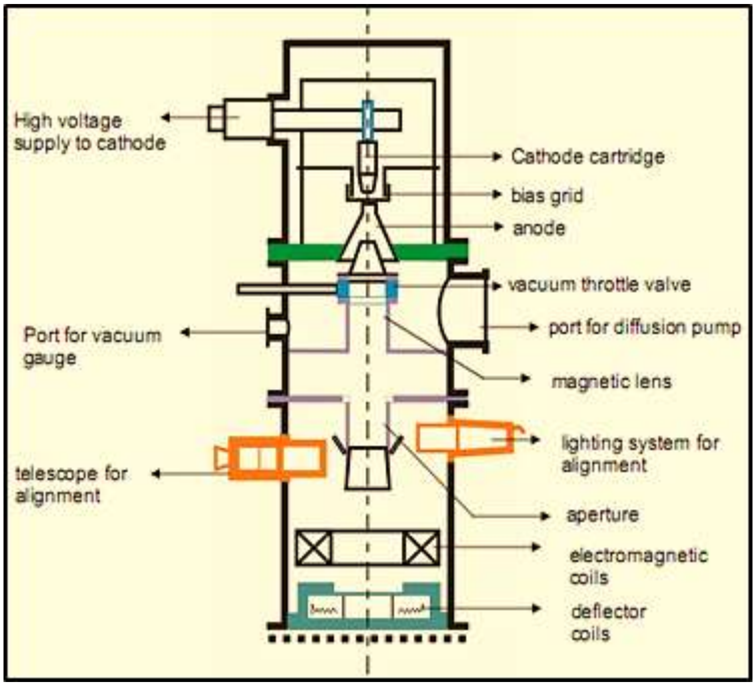
Otherwise the electrons would interact with the air molecules, thus they would loose their energy and cut-ting ability. Thus the workpiece to be machined is located under the electron beam and is kept under va-cuum. The high-energy focused electron beam is made to impinge on the workpiece, with a spot size of **10 to 100 μm**. The kinetic energy of the high velocity electrons is converted to heat energy as the electrons strike the work material.

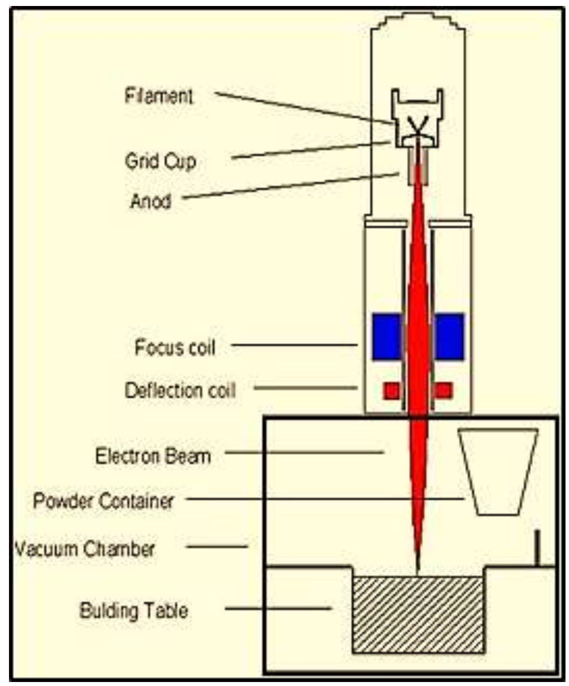
Due to high power density, instant melting and vaporisation starts and gradually progresses. Finally the molten material, if any at the top of the front, is expelled from the cutting zone by the high vapour pressure at the lower part. In Electron Beam Welding, the gun in EBM is used in pulsed mode. Holes can be drilled in thin sheets using a single pulse. For thicker plates, multiple pulses would be required. The electron beam can also be manoeuvred, using the electromagnetic deflection coils, for drilling holes of any shape.

EBM equipment :

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

The cathode is generally made of tungsten or tantalum. Such cathode filaments are heated, often inductively, to a temperature of around **25000°C**. Such heating leads to thermoionic emission of electrons, further enhanced by maintaining very low vacuum within the chamber of the electron beam gun. This cathode cartridge is highly negatively biased, so that, the thermoionic electrons are strongly repelled away from the cathode. This cathode is often in form of a cartridge, the way it can be changed very quickly to reduce down time in case of failure.





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

The nature of biasing just after the cathode, controls the flow of electrons and the biased grid is used as a switch to operate the electron beam gun in pulsed mode. After the anode, the electron beam passes through a series of magnetic lenses and apertures. The magnetic lenses, shape the beam and try to reduce the divergence.

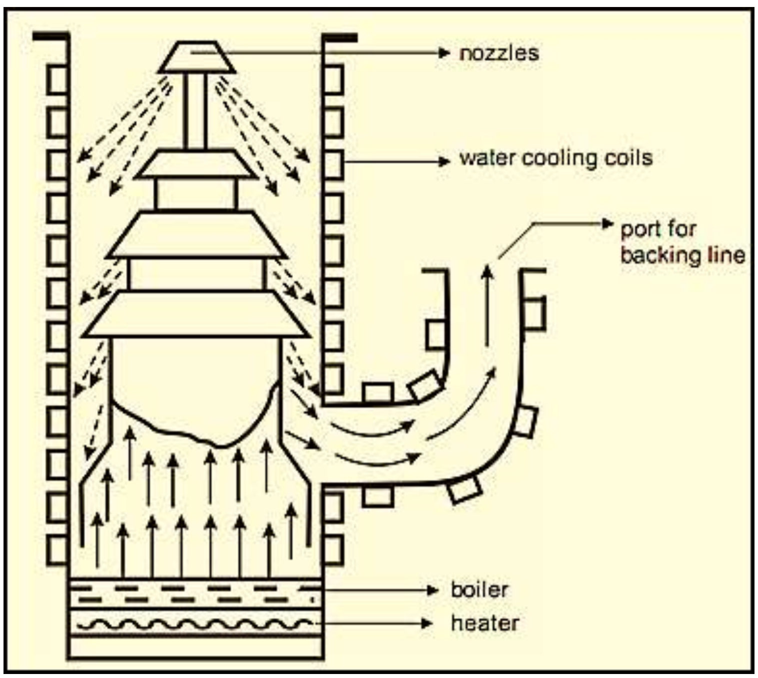
Apertures on the other hand, allow only the convergent electrons to pass and capture the divergent low energy electrons from the fringes. This way, the aperture and the magnetic lenses improve the quality of the electron beam. Then, the electron beam passes through the final section of the electromagnetic lens and a deflection coil. The electromagnetic lens focuses the electron beam to a desired spot.

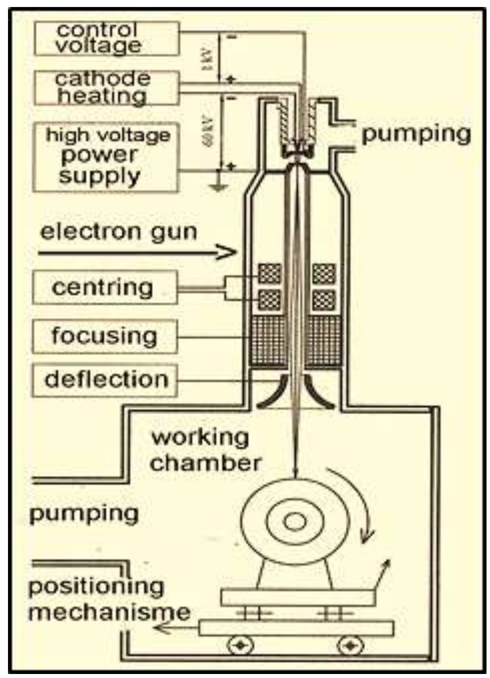
The deflection coil can manoeuvre the electron beam, though by small amount, to improve shape of the machined holes. Generally, in between the electron beam gun and the workpiece, which is also under vacuum, there would be a series of slotted rotating discs. Such discs allow the electron beam to pass and machine materials but helpfully prevent metal fumes and vapour generated during machining to reach the gun. Thus it is essential to synchronize the motion of the rotating disc and pulsing of the gun.

The electron beam guns are also provided with illumination facility and a telescope for alignment of the beam with the work-piece. The workpiece is mounted on a CNC table so that holes of any shape can be machined using the CNC control and beam deflection in-built in the gun.

One of the major requirements of EBM operation of electron beam gun is maintenance of desired vacuum. Level of vacuum within the gun is in the order of **10~4 to 10~6 Torr.** *{1 Torr = 1mm of Hg}*. The maintenance of **suitable vacuum** is essential so that electrons do not loose their energy and a significant life of the cathode cartridge is obtained. Such vacuum is achieved and maintained using a combination of rotary pump and diffusion pump.

The diffusion pump, as shown below, is attached to the diffusion pump port of the electron beam gun. The diffusion pump **is essentially an oil heater**. As the oil is heated, the oil vapour rushes upward gradually. The nozzles change the direction of motion of the oil vapour and the oil vapour starts moving downward at a high velocity as a jet. Such high velocity jets the oil vapour, entrain any air molecules present within the gun. This oil is evacuated by a rotary pump, via the backing line. The oil vapour condenses due to presence of cooling water jacket around the diffusion pump, as shown below:





EBM Parameters:

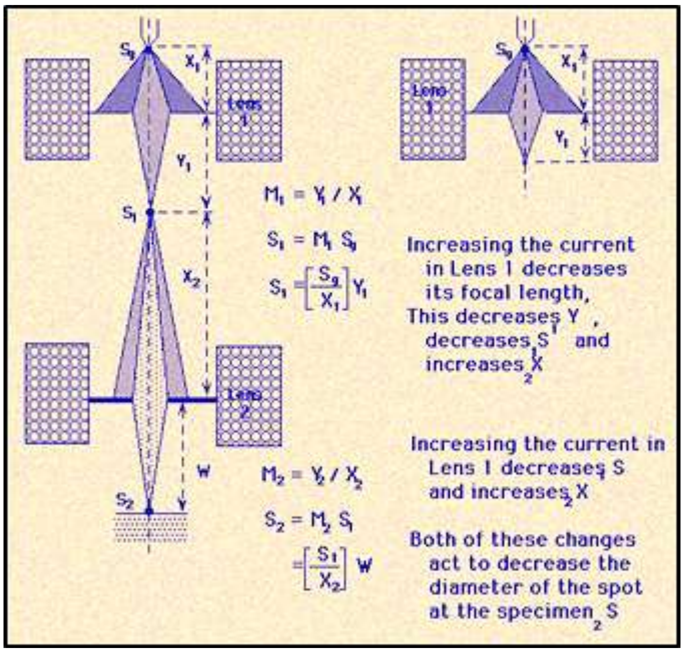
The process parameters, which directly affect the machining characteristics in EBM, are:

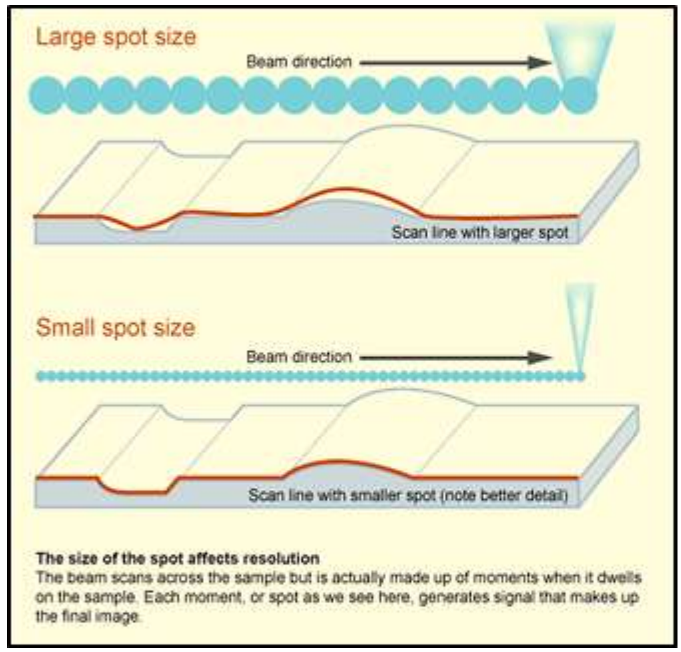
- The accelerating voltage;
- The beam current;
- Pulse duration;
- Energy per pulse;
- Power per pulse;
- Lens current;
- Spot size;
- Power density.

As described above the EBM gun is operated in pulse mode. This is achieved by appropriately biasing the biased grid located just after the cathode. Switching pulses are given to the bias grid, to achieve the pulse duration as low as **50 μs** to as long as **15 ms**. Beam current is directly related to the number of electrons emitted by the cathode, available in the beam, again as low as **200 μamp** to **1 amp**.

Increasing the beam current, directly increases the energy per pulse. Similarly, increase in pulse duration also enhances energy per pulse. High-energy pulses (in excess of **100 J/pulse**) can machine larger holes on thicker plates. The energy and power density is governed by energy per pulse duration and spot size.

Spot size, on the other hand is controlled by the degree of focusing, achieved by the **electromagnetic lenses.** A higher energy density, i.e., for a lower spot size, the material removal would be faster, though the size of the hole would be smaller. The plane of focusing would be on the surface of the workpiece or just below the surface of the workpiece. This controls the **kerf shape** or the shape of the hole as schematically shown below.





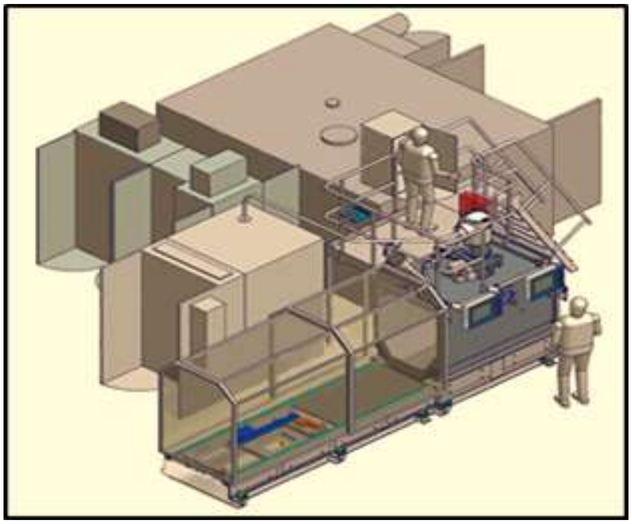
EBM capability:

EBM can **provide holes** of diameter in the range of **100 μm to 2 mm** with a depth **up to 15 mm**. The hole can be tapered along the depth or barrel shaped. By focusing the beam below the surface a reverse taper can also be obtained. Generally, burr formation does not occur in EBM. A wide range of materials as, steel, stainless steel, Ti and Ni superalloys, aluminium, as well as, plastics, ceramics, leathers can be machined successfully using electron beam.

EBM DRILLING EXAMPLES

material	workpiece thickness (mm)	Hole diameter (micro m)	Drilling time (sec)	Accelerating Voltage (KV)	Beam Current (micro A)
tungsten	0.25	25	<1	140	50
stainless steel	2.5	125	10	140	100
stainless steel	1.0	125	<1	140	100
aluminum	2.5	125	10	140	100
alumina (Al_2O_3)	0.75	300	30	125	60
Quartz	3.0	25	<1	140	10

As the mechanism of material removal is thermal in nature, there would be also thermal damages. However, the heat-affected zone is rather narrow due to shorter pulse duration. Typically, the heat-affected zone is around **20 to 30 µm**. Some of the materials, like Al and Ti alloys, are more readily machined compared to steel. The number of holes drilled per second depends on the hole diameter, power density and depth of the hole, as well as, material type.




Electron Beam Drilling machine and a drilled work piece

Electron Beam Welding (EBW):

EBW equipment is used for welding circular seams (60 mm maximum outer diameter) and linear seams (200 mm maximum length) of refractory as well as high strength materials such as Niobium, Zircalloy and maraging steel, and can produce deep penetration welds with very low mechanical distortion.

EBW is useful in welding thick sections in a single pass. This process is preferred in applications where the purity of the weld is of utmost importance since the weld process is carried out under vacuum. EBW is mainly used for welding of nuclear and aerospace components. Hence this welding process is presently receiving wider application in automotive and microelectronics industries.

Fine process control electron beam machines are capable of performing processing with small distortion. They reduce sputtering during welding by optimizing output waveform, which enables high-quality processing. They have high thermal conductivity, and are suitable for processing of copper for which low heat input welding is difficult or processing of small parts that are susceptible to damage from heat.

EB Welding machine


Conventional welding and EB Welding

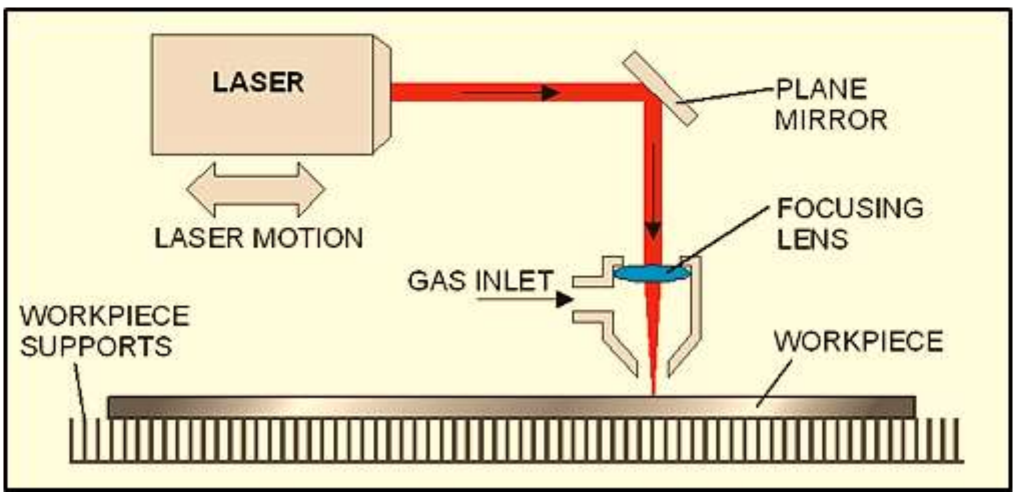
VII. LASER BEAM MACHINING (LBM):

Laser beam machining (LBM) is an unconventional machining process, in which **a beam** of highly coherent light, called a **laser** is directed towards the work piece for machining. Since the rays of a **laser beam** are monochromatic and parallel, it can be focused to a very small diameter and can produce energy as high as 100 MW of energy for a square millimeter of area.

Nowadays, laser is also possible finding application in regenerative machining or rapid prototyping as in processes like stereo-lithography, selective laser sintering, etc. Laser stands for ***Light Amplification by Stimulated Emission of Radiation***. The underline working principle of laser was first put forward by Albert Einstein in 1917, though the first industrial laser for experimentation was developed around 1960s.

Laser Beam Machining, or more broadly laser material processing, deals with machining and material processing like heat treatment, alloying, cladding, sheet metal bending, etc. It is especially suited to making accurately placed holes. It can be used to perform precision **micro-machining** on all microelectronic substrates such as ceramic, silicon, diamond, and graphite.

A coherent beam of monochromatic light is focused on the workpiece causing material removal by vaporization. Machines are generally CAD/CAM compatible, with 3-axis and 5-axis available. Profile creation of sheet metal parts is the most common applications, but it is also possible to drill holes and create blind features in many different types of material. Gas-assisted laser beam machining is common. The **gas** type can be oxygen, inert gas, or air, depending on material type and quality requirements.



LBM schematic

Such processing is carried out utilizing the energy of coherent **photons or laser beams**, which is mostly converted into **thermal energy** upon interaction with most of the materials. Laser beam can very easily be focused using optical lenses as their wavelength ranges from **half micron to around 70 microns**.

The focussed laser beam can have power density, in excess, of 1MW /mm². As laser interacts with the material, the **energy of the photon is absorbed** by the work material, leading to rapid substantial rise in local temperature. This results in **melting and vaporisation** of the work material and finally, the material removal.

LBM process:

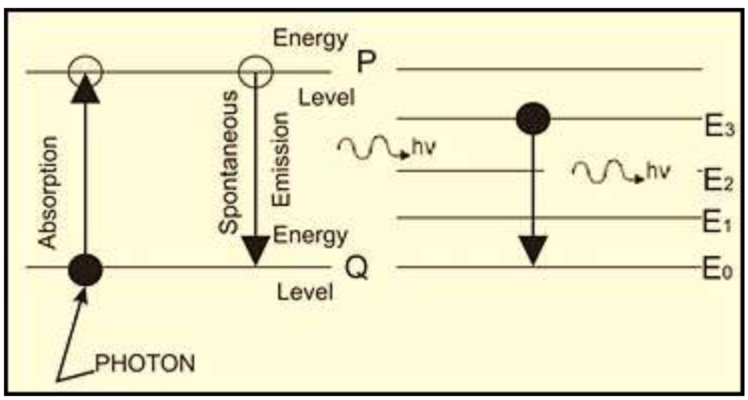
Lasing process describes the basic operation of laser, i.e. generation of coherent (both temporal and spatial) beam of light by “light amplification” using “stimulated emission”. In the model of atom, **negative** charged **electrons** rotate around the **positive** charged **nucleus,** in some specified orbital paths. The geometry and radii of such orbital paths depend on a variety of parameters like number of electrons, presence of neighbouring atoms and their electron structure, presence of electromagnetic field, etc.

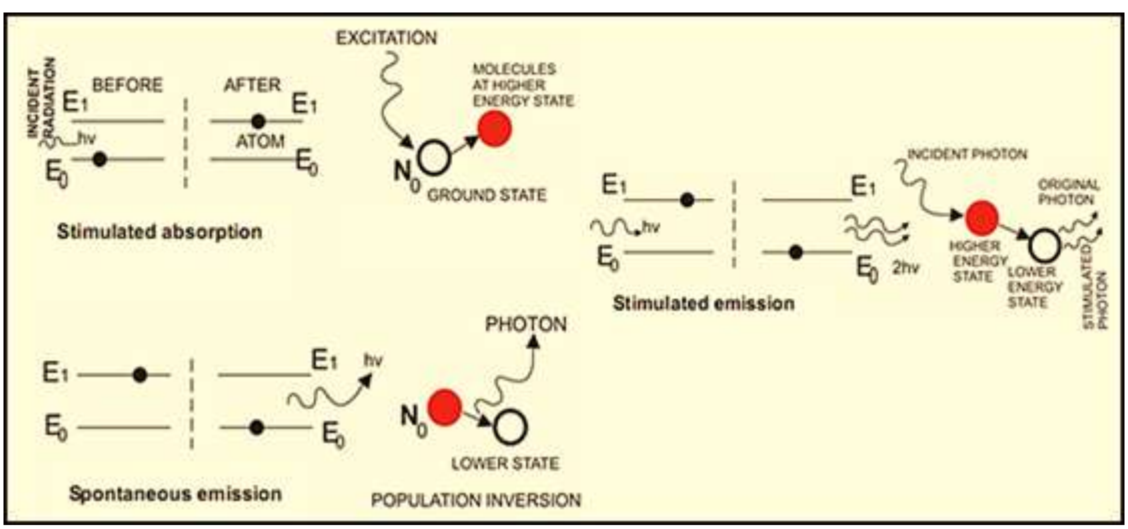
Each of the **orbital electrons** is associated with unique energy levels. At absolute zero temperature an atom is considered to be at ground level, when all the electrons occupy their respective lowest potential energy. The electrons, at ground state, can be excited to higher state of energy by absorbing energy form external sources, like increase in electronic vibration, at elevated temperature, through chemical reaction as well as, via absorbing energy of the photon, as shown below:

On reaching the **higher energy level**, the electron reaches an unstable energy band, and it comes back to its ground state within a very small time by releasing a photon. The spontaneously emitted photon would have the same frequency as that of the "exciting" photon. Sometimes, such change of energy state, puts the electrons in a meta-stable energy band. Instead of coming back to its ground state immediately (within tens of ns) it stays at the elevated energy state for micro to milliseconds.

In a material, if more number of electrons can be somehow pumped to the higher meta-stable energy state as compared to number of atoms at ground state, then it is called "population inversion". Such electrons, at higher energy meta-stable state, can return to the ground state in the form of an avalanche provided stimulated by a photon of suitable frequency or energy. This is called **stimulated emission**.

If it is stimulated by a photon of suitable energy, then the electron will come down to the lower energy state and in turn, one original photon, and another emitted photon by stimulation, having some temporal and spatial phase would be available. In this way coherent laser beam can be produced.





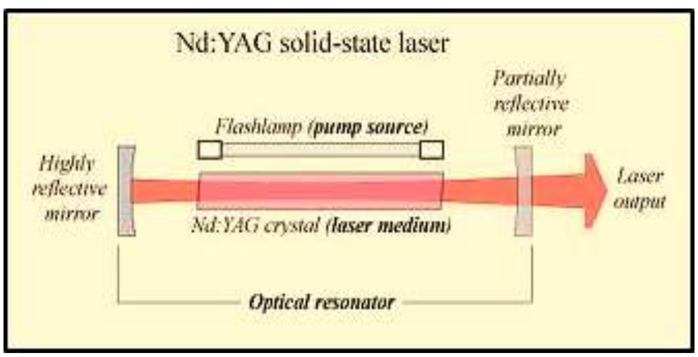
There is a **gas** in a cylindrical glass vessel, called the **lasing medium**. One end of the glass, is blocked with 100% of a reflective mirror and the other end is having a partially reflective mirror. The population inversion can be carried out by exciting the gas atoms or molecules by **pumping** it with flash lamps. Then the stimulated emission of photons would initiate the lasing action, and could be in all di-rections. The photons in the longitudinal direction would form a coherent, highly directional, **intense laser beam**.

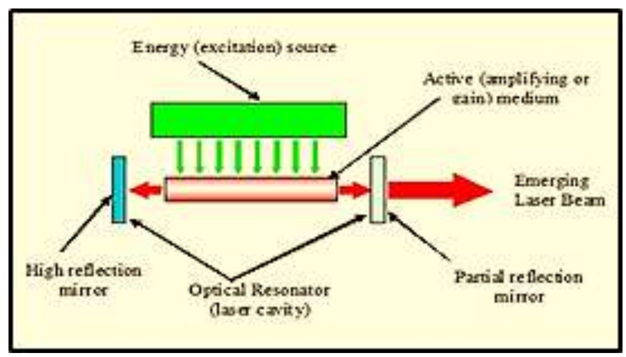
The **active laser medium** (also called **gain medium** or **lasing medium**) is the source of optical gain within a laser. The gain results from the stimulated emission of electronic or molecular transitions to a lower energy state, form a higher energy state previously populated by a pump source.

In order to lase, the active gain medium must be in a non-thermal energy distribution known as a population inversion. The preparation of this state requires an external energy source and is known as laser pumping, which may be achieved with electrical currents (e.g. semiconductors, or gases via high-voltage discharges) or with light, generated by discharge lamps or by other lasers (semiconductor lasers). The more exotic media can be pumped by chemical reactions, nuclear fission, or with high-energy electron beams.

Examples of active laser media include:

- Certain crystals, typically doped with rare-earth ions (neodymium, ytterbium, or erbium) or transition metal ions (titanium or chromium); most often yttrium aluminium garnet (YAG), yttrium orthovana date (YVO_4), or sapphire (Al_2O_3);
- Glasses, (silicate or phosphate glasses), doped with laser-active ions;
- Gases, (mixtures of helium and neon (HeNe), nitrogen, argon, carbon monoxide, carbon dioxide), or metal vapors;
- Semi-conductors, gallium arsenide (GaAs), indium gallium arsenide (InGaAs), or gallium nitride (GaN).





Lasing medium:

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

The **solid-state lasers** are more commonly used in machining process, generally of the following type:

- Ruby which is a chromium – alumina alloy having a wavelength of 0.7 µm;
- Nd-glass lasers having a wavelength of 1.64 µm;
- Nd-YAG laser having a wavelength of 1.06 µm.

The commonly used **gas lasers** or mixtures of gases, as decribed above, are:

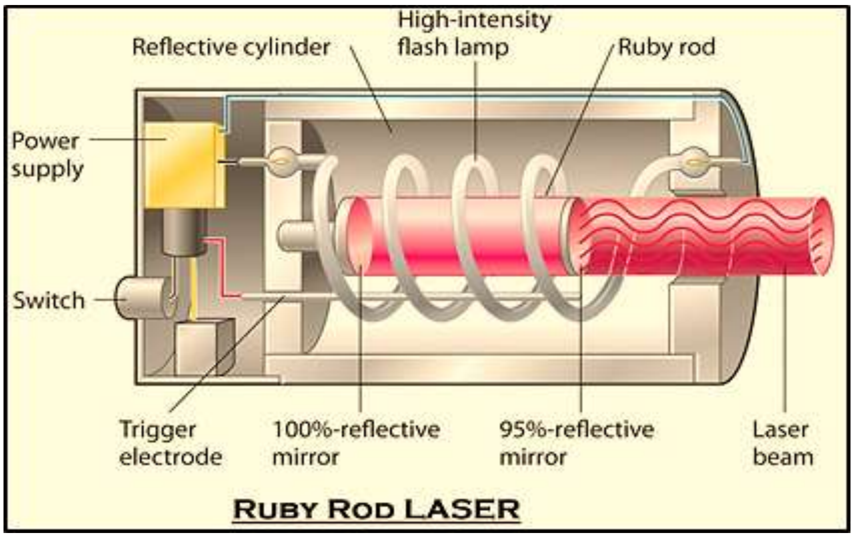
- Helium and neon;
- Argon, nitrogen;
- CO, CO2, etc.

Lasers can be operated in **continuous mode** or **pulsed mode**. Typically **CO2 gas laser** is operated in **continuous mode**, and **Nd – YAG** laser is operated in **pulsed mode**.

The first ruby laser:

The ruby laser was the first laser invented in 1960. Ruby is an aluminum oxide crystal in which some of the aluminum atoms have been replaced with chromium atoms. Chromium gives ruby its characteristic red color and is responsible for the lasing behavior of the crystal. Chromium atoms absorb green and blue light and emit or reflect only red light.

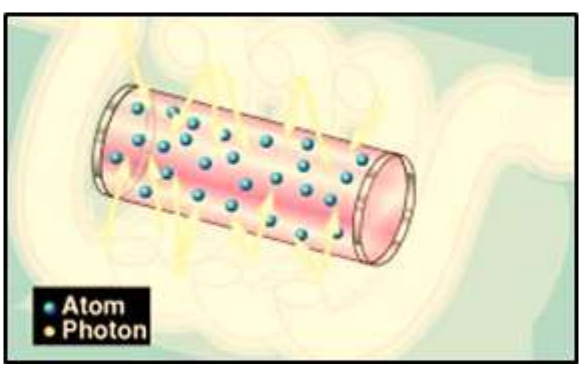
The figure below, shows a typical **Nd-YAG laser**, solid-state, with its optical pumping unit that is pumped using a **flash tube**. Flash tubes can be helical or flat. Typically, the lasing material is at the focal plane of the flash tube, though helical flash tubes provide better pumping, they are difficult to maintain.



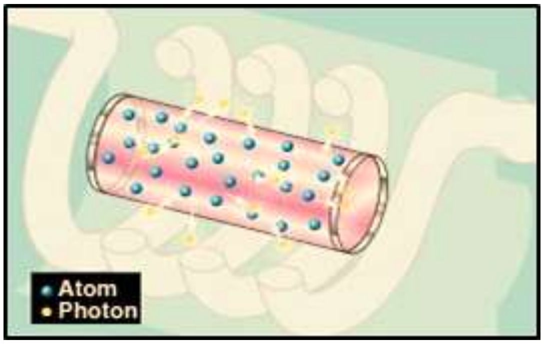
For a ruby laser, a crystal of ruby is formed into a cylinder. A fully reflecting mirror is placed on one end and a partially reflecting mirror on the other. A high-intensity lamp is spiraled around the ruby cylinder to provide a flash of white light that triggers the laser action. The green and blue wavelengths in the flash excite electrons in the chromium atoms to a higher energy level.

Upon returning to their normal state, the electrons emit their characteristic ruby-red light. Mirrors reflect some of the light back and forth inside the ruby crystal, stimulating other excited chromium atoms to produce more red lights, until the light pulse builds up to high power and drain the energy stored in the crystal.

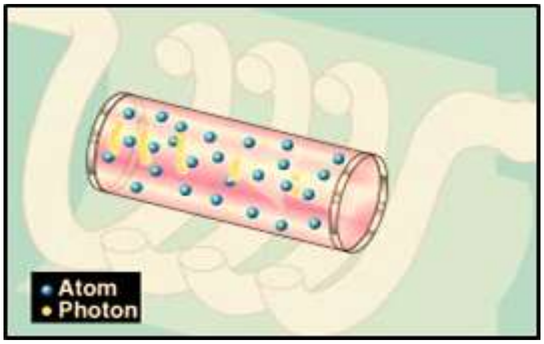
1. High-voltage electricity causes the quartz flash tube to emit an intense burst of light, exciting some of the atoms in the ruby crystal to higher energy levels:



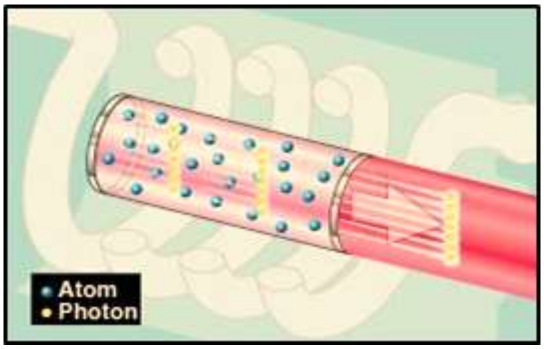
2. At a specific energy level, some atoms emit particles of light called photons. At first the photons are emitted in all directions. Photons from one atom stimulate emission of photons from other atoms and the light intensity is rapidly amplified:



3. Mirrors at each end reflect the photons back and forth, continuing this process of stimulated emission and amplification.



4. The photons leave through the partially silvered mirror at one end. This is laser light.

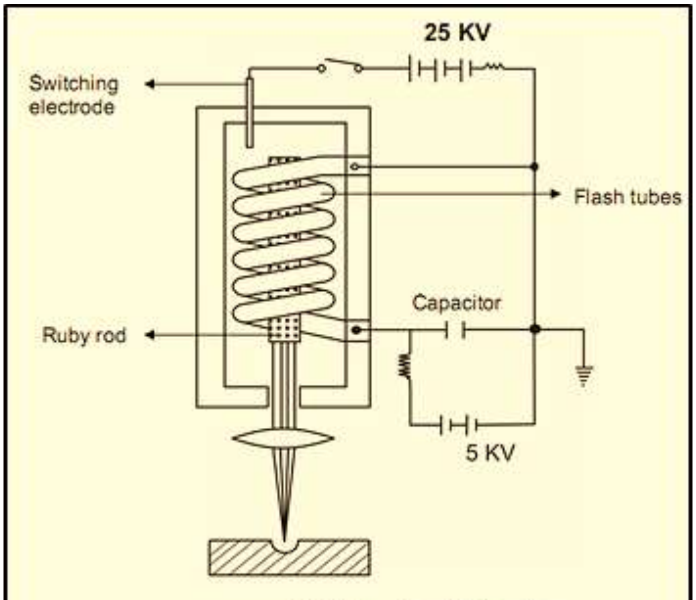


The laser flash that escapes through the partially reflecting mirror lasts for only about 300 millionths of a second, but is very intense. Early lasers could produce peak powers of some 10,000 watts. Modern lasers can produce pulses that are billions of times more powerful.

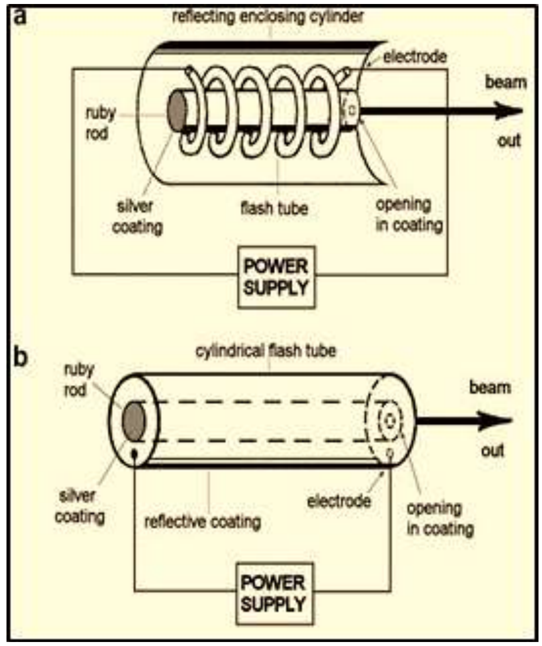
The 1,000-watt light used in modern lighthouses can be seen from 20 miles away. But beyond that distance, the light beam has spread out so much that it is difficult to see. A laser beam, however, will run straight and true for very long distances. A laser beam has been bounced off the moon to accurately measure the distance of more than 250,000 miles.

The beam stays roughly the same size as it travels this vast distance. Coherence means that laser light can be focused with great precision. Many different materials can be used as lasers. Some, like the ruby laser, emit short pulses of laser light. Others, like helium–neon gas lasers or liquid dye lasers, emit a continuous beam of light. The NIF lasers, like the ruby laser, are solid-state, pulsed lasers.

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

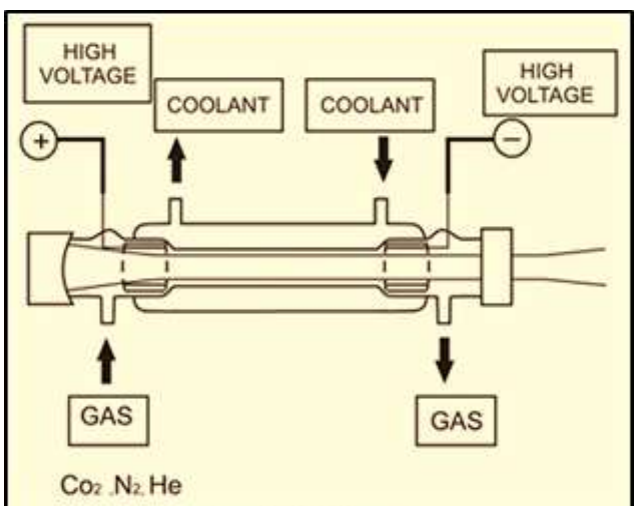


Working of a solid-state laser



Gas lasers can be axial flow, as shown below, transverse flow and folded axial flow. The power of a CO2 laser is typically around 100 Watt per metre of tube length. Thus to make a high power laser, a rather long tube is required which is quite inconvenient. For optimal use of floor space, high-powered CO2 lasers are made of folded design.

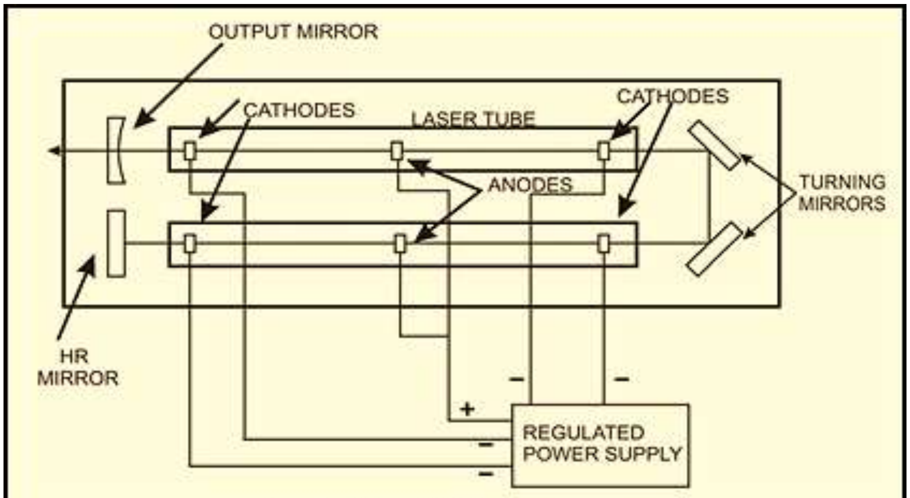
In a CO2 laser, a mixture of CO2, N2 and He continuously circulate through the gas tube. Such continuous recirculation of gas is done to minimize consumption of gases. CO2 acts as the main lasing medium whereas Nitrogen helps in sustaining the gas plasma. Helium on the other hand helps in cooling the gases.



Construction of a CO_2 laser

A high voltage is applied at the two ends leading to discharge and formation of gas plasma. Energy of this discharge leads to population inversion and lasing action. At the two ends of the laser there is a 100% reflector and one partial reflector, which redirects the photons inside the gas tube and partial reflector allows a part of the laser beam to be issued so that the same can be used for material processing.

Typically the laser tube is cooled externally. The CO2 lasers are folded to achieve high power. In folded gas laser there would be a few 100% reflective turning mirrors for manoeuvring the laser beam from gas supply as well as high voltage supply.



Construction of folded gas laser

LBM application:

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

Typical uses:

- ✓ Profiling of sheet parts;
- ✓ Holes (0.005 mm diameter to 1.3 mm), profiling, scribing, engraving and trimming;
- ✓ Prototype parts;
- ✓ Non-standard shaped holes, slots and profiling;
- ✓ Features in silicon wafers (electronics industry);
- ✓ Small diameter lubrication holes;
- ✓ Suitable for thin or delicate parts as there is no mechanical contact.

Laser Beam Machining – advantages:

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

Laser Beam Machining – limitations:

- ✓ High initial capital cost;
- ✓ High maintenance cost;
- ✓ Not very efficient process;
- ✓ Presence of Heat Affected Zone – specially in gas assist CO2 laser cutting;
- ✓ Thermal process – not suitable for heat sensitive materials like aluminium glass fibre laminates.

The table below shows the capability and characteristics of common lasers:

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

Process characteristics of different lasers:

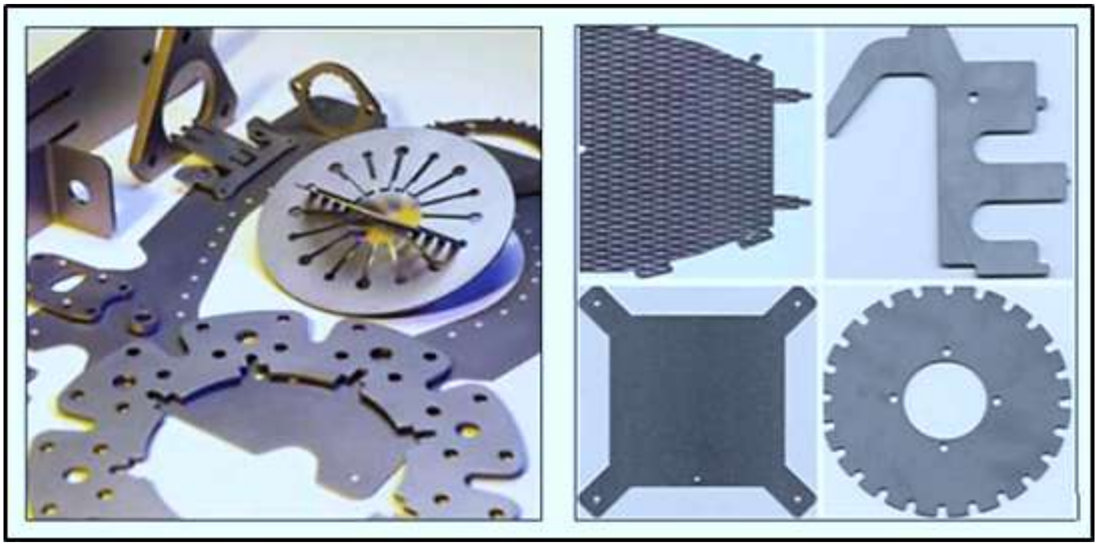
Lasing materials	Ruby	**Nd-YAG**	Nd-glass	**CO_2**
Type	Solid state	**Solid state**	Solid state	**Gas**
Composition	0.03 – 0.7% Nd in Al_3O_2	**1% Nd doped Yttrium – Aluminium-Garnet**	2-6% Nd in glass	**CO_2+He+N_2 (3:8:4)**
Wavelength (radiation)	0.69 μm	**1.064 μm**	1.064 μm	**10.6 μm**
Efficiency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

LBM examples of uses:

Lasers work best on materials such as carbon steel or stainless steels. Metals such as aluminum and copper alloys are more difficult to cut due to their ability to reflect the light as well as absorb and conduct heat. This requires lasers that are more powerful. LBM **is not a bulk material removal process**. It is most suited to contour cutting, slitting and drilling small diameter deep holes (length to diameter ratios of up to 50:1 is possible). The process follows:

- Blind or stepped features, but less accurate;
- Sharp corners are possible, but radii should be provided for in the design;

- Some distortion may be caused in very thin parts.
- Maximum workpiece thickness:
- Mild steel = 25mm, Stainless steel = 13mm, Aluminum 10mm;



Miscellaneous components made by LBM.

Process variations:

- LBT (Laser Beam Torch): uses a simultaneous gas stream;
- Laser Texturing and Laser Etching: performed at lower energy levels;
- Laser Beam Welding (LBW): laser marking or laser printing can be used to create graphics, text or barcodes on most materials.

Trade names or alternative names:

- Laser cutting;
- YAG laser cutting;
- Laser Tex (Laser Texturing).

Note: The heat may potentially cause the generation of toxic fumes.

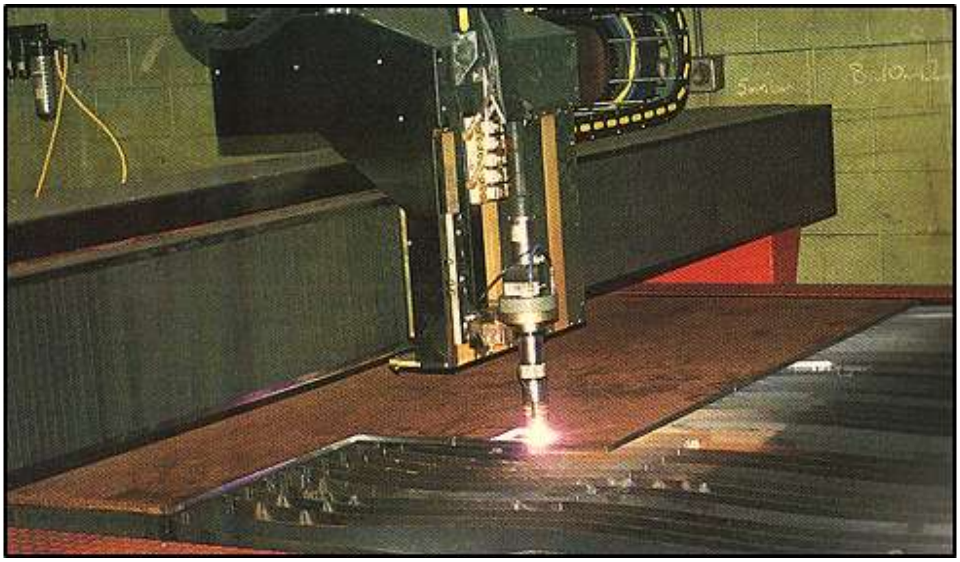
VIII. PLASMA ARC MACHINING (PAM):

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

Temperatures in the plasma zone range from **20,000 to 50,000 °F** (11,000 to 28,000 °C). It is used as an alternative to oxyfuel-gas cutting, employing an electric arc at very high temperatures to melt and vaporize the metal. The materials cut by PAM are generally those that are difficult to cut by any other means, such as stainless steels and aluminum alloys. It has an accuracy of about **0.008 inches**.

Plasma Arc Cutting (PAC):

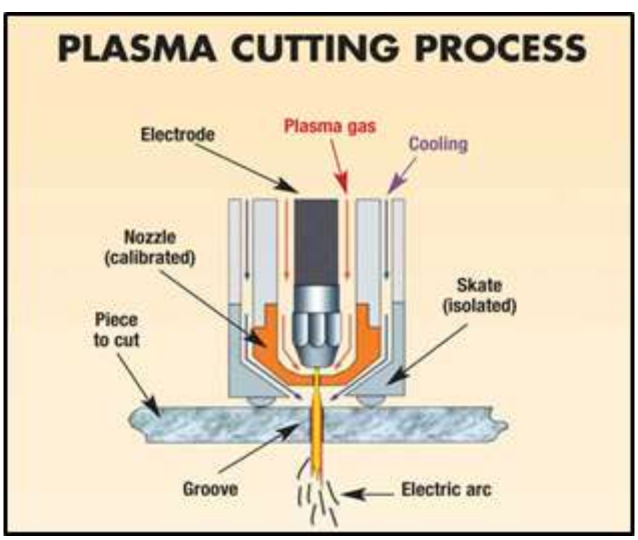
Plasma cutting is a process that is used to cut steel and other metals of different thicknesses (or sometimes other materials), using a plasma torch. In this process, an inert gas (in some units, compressed air) is blown at high speed out of a nozzle; at the same time an electrical arc is formed through that gas from the nozzle to the surface being cut, turning some of that gas to plasma. The plasma is sufficiently hot to melt the metal being cut and moves sufficiently fast to blow molten metal away from the cut.

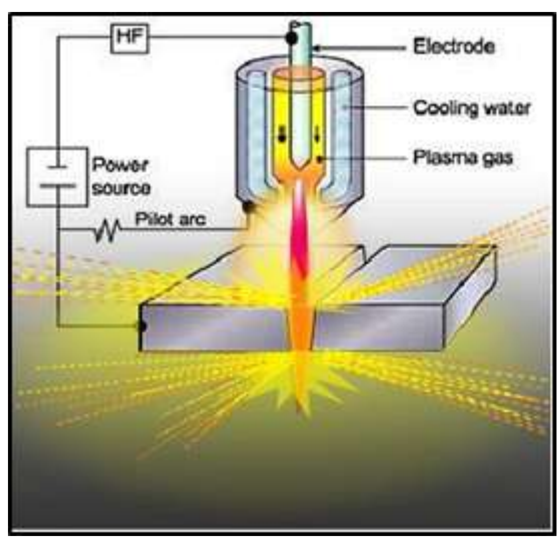


The HF type plasma cutting machine uses a **high-frequency**, high-voltage spark to ionize the air through the torch head and initiate an arc, and do not require the torch to be in contact with the job material when starting, suitable for applications involving computer numerical controlled (CNC) cutting. The Pilot Arc type uses a two cycle approach to producing plasma, avoiding the need for initial contact.

First, a high-voltage, low current circuit is used to initialize a very small high-intensity spark within the torch body, thereby generating a small pocket of plasma gas. This is referred to as the pilot arc. The pilot arc has a return electrical path built into the torch head. The pilot arc will maintain itself until it is brought into proximity of the workpiece where it ignites the main plasma cutting arc.

Plasma arcs are extremely hot generally in the range of 25 000 °C. Plasma is an effective means of cutting **thin** and **thick** materials. Hand-held torches can usually cut steel plates, up to 50 mm thick, and stronger computer-controlled torches can cut steel plates, up to 150 mm thick. Since plasma cutters produce a very hot and much localized "cone" to cut with, are also extremely useful for cutting sheet metal in curved or angled shapes.





CNC tables allow a computer to control the torch head producing clean sharp cuts. Modern CNC plasma equipment is capable of multi-axis cutting of thick material, allowing opportunities for complex welding seams that are not possible otherwise. For thinner material, **plasma cutting** is being progressively **replaced by laser cutting**, due mainly to the laser cutter's superior hole-cutting abilities.

Plasma gouging is a related process, typically performed on the same equipment as plasma cutting. Instead of cutting the material, plasma gouging uses a different torch configuration (torch nozzles and gas diffusers are usually different), and a longer torch-to-workpiece distance, to blow away metal.

Plasma gouging can be used in a variety of applications, including removing a weld for rework. The additional sparks generated by the process requires the operator to wear a leather shield protecting their hand and forearm. Torch leads also can be protected by a leather sheath or heavy insulation.

IX. CHEMICAL MACHINING (CHM):

Chemical machining is one of the non-conventional machining processes, where material is removed in contact of a strong **chemical enchant**. Thus, it is the controlled chemical dissolution of the machined work piece material, by contact with a **strong acidic or alkaline chemical reagent**. Special coatings, called mask ants, protect areas from which the metal is not to be removed. This process is used to produce pockets and contours as well as removes materials from parts that have a high strength-to-weight ratio.

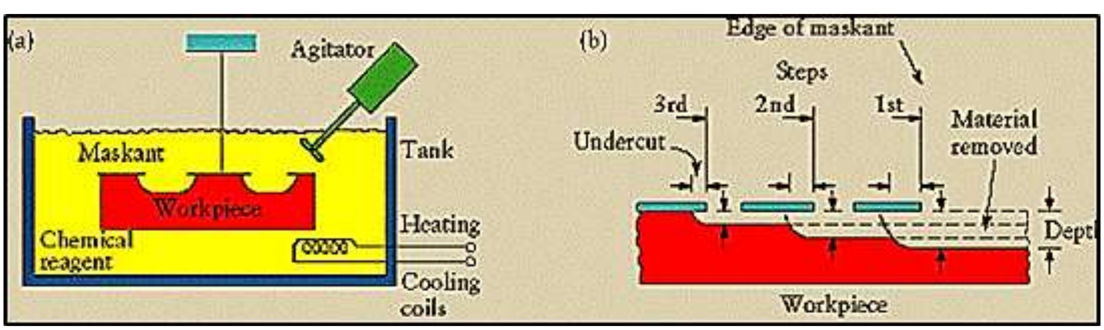
Furthermore, the chemical machining method is commonly used to **produce micro-components** for several industrial applications such as micro electromechanical systems and semiconductor industries. There are different chemical machining methods base on this like chemical milling, chemical blanking, photo-chemical machining, etc.

Chemical machining has been used since ancient Egypt, to shape copper with citric acid. Until the 19th century, however, this process was widely used for decorative etching. The process and advancement in photography made way for a new dimension to chemical machining. In the mid-19th century, J.N. Niece was the first to use a photo resist made from bitumen of Judea asphalt for etching pewter though, the main industrial implementation of chemical machining did not develop until after the Second World War.

CHM process:

The main working principle of chemical machining is chemical etching. The part of the workpiece 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 method of making contact of metal with the enchant is masking. The portion of workpiece where no material is to be removed, is mashed before chemical etching.

Etching is the material removal from the unprotected sections of the workpiece by means of a microscopic electrochemical cell action, as in corrosion or chemical dissolution of metal, without the involvement of any external circuit. Chemical machining is the targeted use of chemical etchants (acids and alkaline solutions) in the removal of material from metal parts' surfaces.



Not only is chemical machining used to produce **complex machine parts**, but decorative parts, as well. However, there are many environmental issues in the operations of chemical machining. Most chemicals like the, **etchants and strippers** used during chemical machining are **hazardous** liquids, therefore the disposal of them is very costly.

In order to prevent the removal of material from unwanted regions, a **maskant** / resist on the surface of the workpiece, resistant to the etchant is used. The industrial trend is to use and select environmentally safe chemicals for the machining process, according to environmental laws.

This controlled chemical dissolution will simultaneously etch all exposed surfaces even though the penetration rates of the material removal may be only **0.0025–0.1 mm/min**. The basic process takes many forms: chemical milling of pockets, contours, overall metal removal and chemical blanking.

The basic chemical machining processes are:

- ✓ Chemical milling: used for pockets, contours and overall metal removal;
- ✓ Chemical blanking: etching through thin sheets;
- ✓ Photochemical machining: photosensitive resists are used for masks;
- ✓ Gel milling: uses reagent in gel form;
- ✓ Chemical or electrochemical polishing: weak chemical reagents are used for polishing.

Chemical milling:

In chemical milling, shallow cavities are produced on plates, sheets, forgings and extrusions. As described above, the two key materials used in chemical milling process are etchant and masking. Etchants are acid or alkaline solutions maintained within controlled ranges of chemical composition and temperature. Masking is specially designed for elastomeric products and chemically resistant to the harsh etchants.

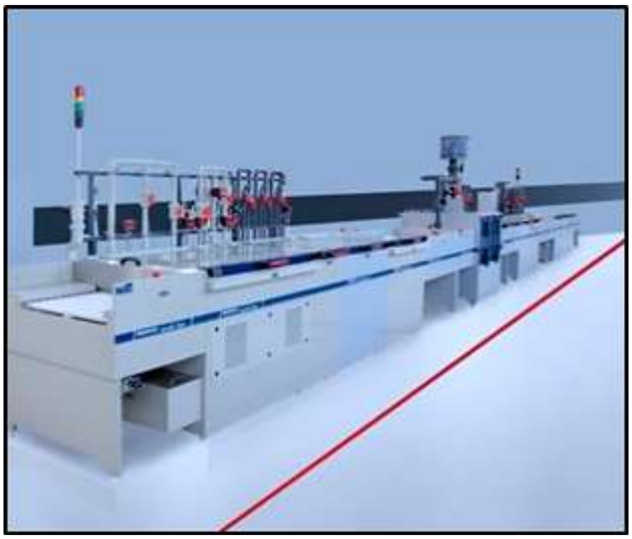
Steps in chemical milling:

- ✓ Residual stress relieving: If the part to be machined has residual stresses from the previous processing, these stresses first should be relieved in order to prevent warping after chemical milling;
- ✓ Preparing: The surfaces are degreased and cleaned thoroughly to ensure both good adhesion of the masking material and the uniform material removal;
- ✓ Maskant: Maskant material is applied (coating or protecting areas not to be etched);
- ✓ Etching: The exposed surfaces are machined chemically with etchants;
- ✓ Demasking: After machining, the parts should be washed to prevent further reactions to etchant residues. Then the rest of the masking material is removed and the part is cleaned and inspected.

X. PHOTOCHEMICAL MACHINING (PCM):

Photochemical machining (PCM), also known as photochemical milling or **photo etching**, is a chemical milling process used to fabricate sheet metal components using a **photoresist and etchants** to corrosively machining away selected areas. This process emerged in the 1960s, as an off-shoot of the printed circuit board industry. The photo etching can produce highly complex parts with very fine detail accurately and e-conomically.

This process can offer economical alternatives to stamping, punching, lasing, water jet cutting or wire electrical discharge machining (EDM) for thin gauge precision parts. The tooling is inexpensive and quickly produced. This makes the process useful for prototyping and easy changes in mass production. It maintains dimensional tolerances and does not create burrs or sharp edges. It can make a part in hours, after receiving the drawing.



PCM can be used on virtually any commercially available metal or alloy, of any hardness. It is limited to materials with a thickness of **0.0005 to 0.080 in (0.013 to 2.0 mm)**. Metals include aluminum, brass, copper, inconel, manganese, nickel, silver, steel, stainless steel, zinc and titanium. Thin metal parts are manufactured using chemical blanking, micro chemical milling or the photo etching process, all generally classified under the banner of photochemical machining or “PCM”.

PCM fabrication and manufacturing processes can offer economical alternatives to CNC machining, CNC milling, laser or water jet cutting, stamping, punching, or wire electrical discharge machining “EDM” for thin gauge precision metal parts manufacturing. Production variables such as time and cost are significantly reduced; and with prototypes being able to be produced quickly. Machined parts allow you to develop the design quickly before going to mass production with stampings.

PCM Process:

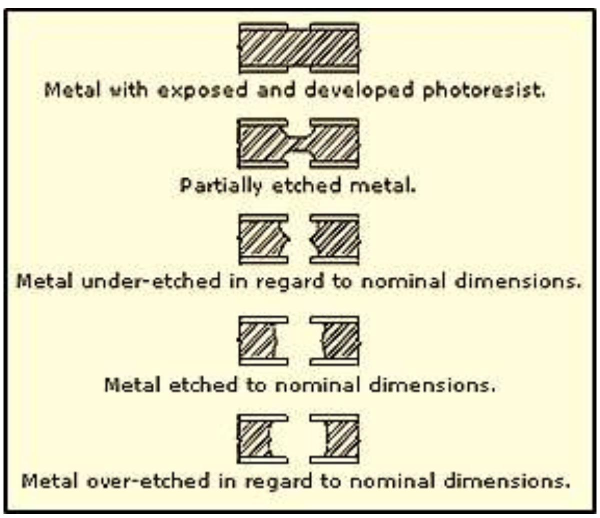
The process starts by printing the shape of the part onto optically clear and dimensionally stable photographic film. The "photo tool" consists of two sheets of this film showing negative images of the parts (meaning that the area that will become the parts is clear and all of the areas to be etched are black). The two sheets are optically and mechanically registered to form the top and bottom halves of the tool.

The metal sheets are cut to size, cleaned and then laminated on both sides with a UV-sensitive photoresist. The coated metal is placed between the two sheets of the photo tool and a vacuum is drawn to ensure intimate contact between the photo tool and the metal plate. The plate is then exposed in UV light that allows the areas of resist that are in the clear sections of the film to be hardened. After exposure, the plate is "developed", washing away the unexposed resist and leaving the areas to be etched unprotected.

The etching line is a multi-chambered machine that has driven-wheel conveyors to move the plates and arrays of spray nozzles above and below the plates. The etchant is typically an aqueous solution of acid, frequently ferric chloride, which is heated and directed under pressure to both sides of the plate. The etchant reacts with the unprotected metal essentially corroding it away fairly quickly. After neutralizing and rinsing, the remaining resist is removed and the sheet of parts is cleaned and dried.

PCM application:

Thin gauge, under **0.050 in** (**1.3 mm**) and a broad range of alloys are candidates for **photo etching**. Industrial applications include fine screens and meshes, apertures and masks, battery grids, fuel cell components, sensors, springs, pressure membranes, heat sinks, flexible heating elements, RF and microwave circuits and components, semiconductor lead frames, motor and transformer laminations, metal gaskets and seals, shields and retainers, electrical contacts, encoders and light choppers, EMI/RFI shields, jewelry and washers.

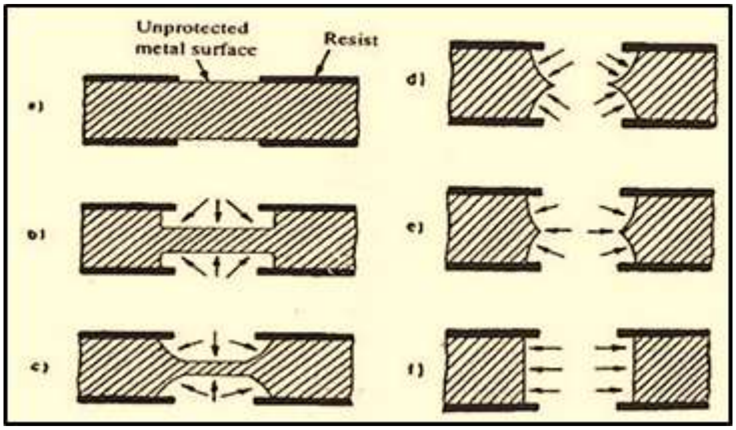


Most alloys etch at rates between **0.0005 – 0.001 in (0.013 – 0.025 mm)** of depth per minute per side. In general, steel, copper or aluminium work pieces with a thickness up to **0.020 in (0.51 mm**) have low costs. As the geometry of the part becomes more complex, photochemical machining gains greater economic **advantage** over sequential processes such as **CNC punching, laser or water-jet cutting**, and electrical discharge machining.

Chemical blanking:

Chemical blanking is similar to the **blanking of sheet metals** and it is applied to produce features, which penetrate through the thickness of the material, with the exception that the material is removed by chemical dissolution rather than by shearing. Typical applications for chemical blanking are the burr-free etching of printed-circuit boards, decorative panels, and thin sheet metal stampings, as well as the production of complex or small shapes.

It is otherwise called as Chem-blanking, Photo forming, Photo fabrication, or Photo etching. In this process, the metal is totally removed from certain areas by chemical action. The process is used chiefly on the sheets and foils. This process can work almost any metal, however, it is not recommended for material thinner than 2 mm. A schematic sketch of the chemical blanking process is shown below:



The work piece is cleaned, degreased and pickled by acid or alkalis. The cleaned metal is dried and photo resist material is applied to the work piece by dipping, whirl coating or spraying. It is then dried and cured. The technique of photography has been suitably employed to produce etchant resistant images in photo resist materials. This type of maskant is sensitive to light of a particular frequency, usually ultraviolet light, and not to room light.



This surface is now exposed to the light through the negative, actually a photographic plate of the required design, just as in developing pictures. After exposure, the image is developed. The unexposed portions are dissolved out during the developing process exposing the bare metal. The treated metal is next put into a machine, which sprays it with a chemical etchant, or it may be dipped into the solution.

The etching solution may be hydrofluoric acid (for titanium), or one of the several other chemicals. After **1** to **15 minutes**, the unwanted metal has been eaten away, and the finished part is ready for immediate rising to remove the etchant. Chemical blanking by using photo resist maskants can suitably make printed circuit boards and blanking of intricate designs.

The advantages of this process are summarized below:

- Very thin material **(0.005 mm**) can be suitably etched;
- High accuracy of the order of plus or minus **0.015 mm** can be maintained;
- High production rate can be met by using automatic photographic technique.

XI. ELECTRO JET DRILLING (EJD):

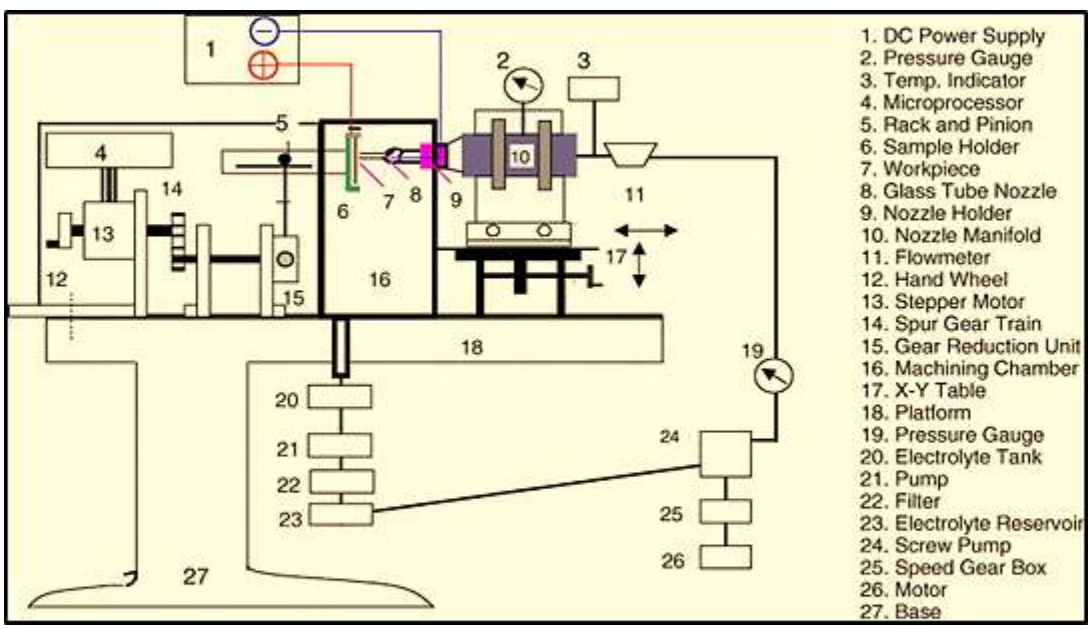
Electro jet drilling (EJD) is one such promising technique, which is finding ever-increasing applications in several industries including aerospace, medical, automobile and micro-fabrication (electronic and computers). There are experimental findings on the effects of important process parameters such as applied voltage, capillary outside diameter, feed rate, electrolyte concentration and inlet electrolyte pressure on the productivity and the quality of small holes (<800μm diameter) produced by using the EJD process.

Roundness error and surface roughness have been used as the response parameters for evaluating the quality of hole whereas material removal rate has been used as the response parameter for evaluating the process productivity. An analysis of variance performed to test the significance of the variables at the 5% level indicates that applied voltage and electrolyte concentration significantly affect the response parameters.

In EJD, a negatively charged stream of acid electrolyte is impinged on the workpiece to form a hole. The acid electrolyte (10-25% concentration) is passed under pressure (0.3- 1.0 MPa) through a finely drawn glass tube nozzle. The electrolyte jet gets charged when a platinum wire, inserted into the glass tube is connected to the negative terminal of DC power supply.

The rule base was created on the basis of the results obtained from the previous experiments and certain assumption that exists in an ideal electrochemical jet machining process. The workpiece acts as anode. With the power supply switched on, the material removal takes place through electrolytic dissolution as the charged electrolyte stream strikes the workpiece. The metal ions thus removed from the work surface are carried away with the flow of the electrolyte.

Controlling the gap between the electrodes (cathode and anode) has long been a major research area in electrochemical machining. The metal ions thus removed from the workpiece surface are carried away with the flow of the electrolyte. It has several applications, like aviation, space, automobile, electronics and computer, medical, optics and micro-machining.



The present system represents the model for 350V input voltage, 17% concentration of acid electrolyte (sulphuric acid) in tap water, 0.5 mm as initial setting of the gap between workpiece surface and the glass capillary tip, and 32°C as inlet electrolyte temperature. The purpose of the controller is to adjust the feed rate in such a way so as to maintain a gap of 0.5 mm between capillary tip and workpiece surface and in any case this should not be allowed to be less than 0.35 mm.

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