Chapter 2

Specialized machining processes

Traditional, also termed conventional, machining requires the presence of a tool that is harder than the workpiece to be machined. This tool should be penetrated in the workpiece to a certain depth. Moreover, a relative motion between the tool and workpiece is responsible for forming or generating the required shape. The absence of any of these elements in any machining process such as the absence of tool-workpiece contact or relative motion, makes the process a non-traditional one, also known as specialized machining process. Non-traditional manufacturing processes is therefore defined as a group of processes that remove excess material by various techniques involving mechanical, thermal, electrical or chemical energy or combinations of these energies but do not use a sharp cutting tools as it needs to be used for traditional manufacturing processes. Figure 2.0.1 shows the classification of material removal processes.

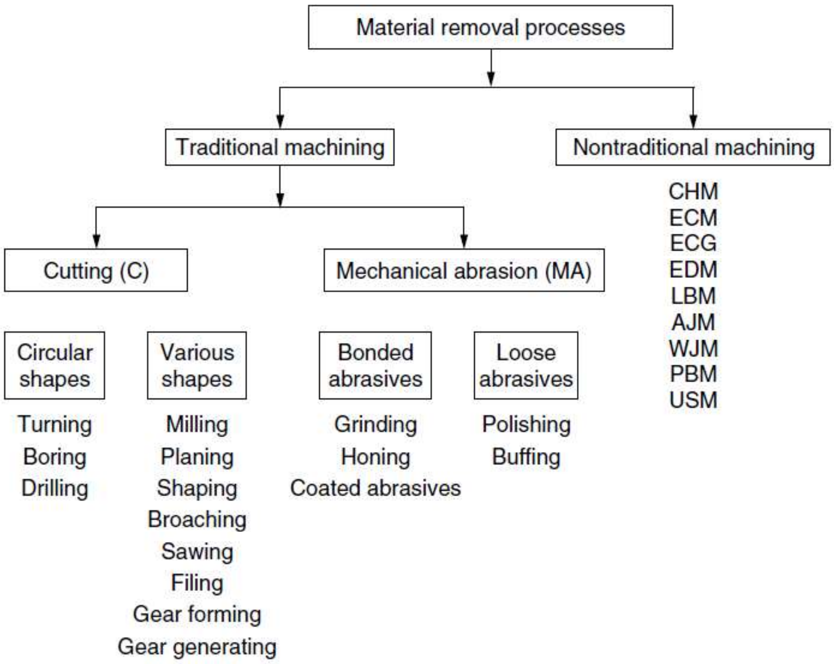

Figure 2.0.1: Material removal processes

The non-traditional machining methods are classified according to the machining actions causing the removal of material from the workpiece. This is illustrated in Figure 2.0.2.

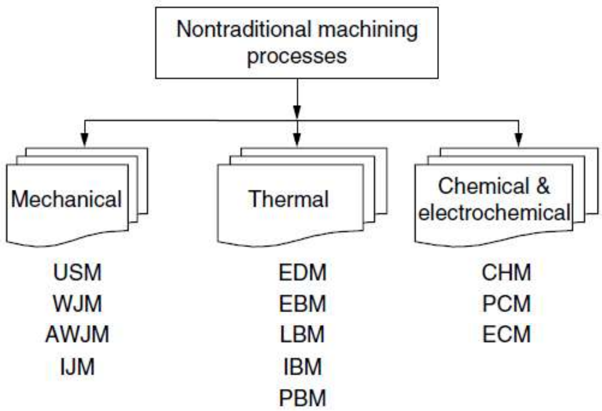

Figure 2.0.2: Non-traditional machining processes.

2.1 Ultrasonic Machining

Ultrasonic machining (USM) is the removal of hard and brittle materials using an axially oscillating tool at ultrasonic frequencies [18 - 20 kilohertz (kHz)]. During that oscillation, the abrasive slurry of B_4C or SiC is continuously fed into the machining zone between a soft tool (brass or steel) and the workpiece. The abrasive particles are, therefore, hammered into the workpiece surface and cause chipping of fine particles from it. The oscillating tool, at amplitudes ranging from 10 to 40 μm, imposes a static pressure on the abrasive grains and feeds down as the material is removed to form the required tool shape.

2.1.1 The machining system

The machining system, shown in Figure 2.1.1 is composed mainly of the magnetostrictor, concentrator, tool, and slurry feeding arrangement. The magnetostrictor is energized at the ultrasonic frequency and produces small-amplitude vibrations. Such a small vibration is amplified using the concentrator (mechanical amplifier) that holds the tool. The abrasive slurry is pumped between the oscillating tool and the brittle workpiece. A static pressure is applied in the tool-workpiece interface that maintains the abrasive slurry.

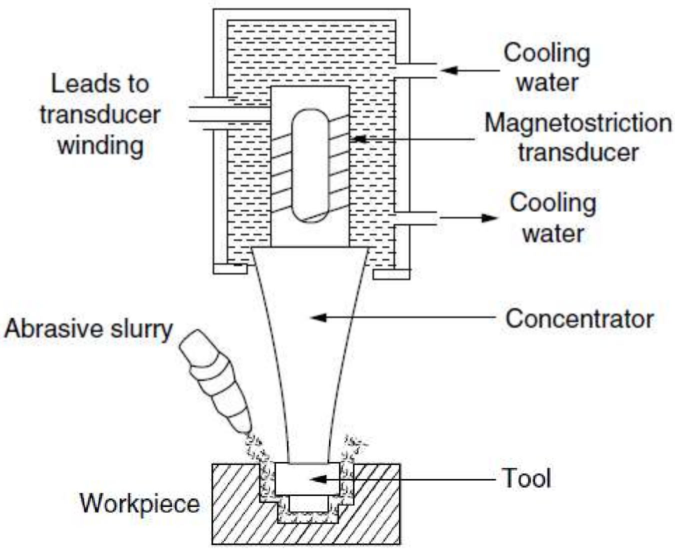

Figure 2.1.1: Main elements of an ultrasonic machining system.

Abrasive slurry is usually composed of 50 percent (by volume) fine abrasive grains (100-800 grit number) of boron carbide (B_4C), aluminum oxide (Al_2O_3), or silicon carbide (SiC) in 50 percent water. The abrasive slurry is circulated between the oscillating tool and workpiece.

2.1.2 Factors affecting material removal rate

i. **Tool oscillation**: The amplitude of the tool oscillation has the greatest effect of all the process variables. The material removal rate increases with a rise in the amplitude of the tool vibration. The vibration amplitude determines the velocity of the abrasive particles at the interface between the tool and workpiece. Under such circumstances the kinetic energy rises, at larger amplitudes, which enhances the mechanical chipping action and consequently increases the removal rate.

ii. **Abrasive grains**: Both the grain size and the vibration amplitude have a similar effect on the removal rate. The removal rate rises at greater grain sizes until the size reaches the vibration amplitude, at which stage, the material removal rate decreases. When the grain size is large compared to the vibration amplitude, there is a difficulty of abrasive renewal in the machining gap. Water is commonly used as the abrasive carrying liquid for the abrasive slurry while benzene, glycerol, and oils are alternatives. The increase of slurry viscosity reduces the removal rate. The improved flow of slurry results in an enhanced machining rate.

iii. **Workpiece impact-hardness**: The machining rate is affected by the ratio of the tool hardness to the workpiece hardness. In this regard, the higher the ratio, the lower will be the material removal rate. For this reason soft and tough materials are recommended for USM tools.

iv. **Tool shape**: The machining rate is affected by the tool shape and area. An increase in the tool area decreases the machining rate due to the problem of adequately distributing the abrasive slurry over the entire machining zone.

2.1.3 Applications of Ultrasonic machining

i. **Drilling and coring**

Figure 2.1.2 shows the rotary ultrasonic machining (RUM) where a tool bit is rotated against the workpiece in a similar fashion to conventional drilling. RUM ensures high removal rates, lower tool pressures for delicate parts, improved deep hole drilling, less breakout or through holes, and no core seizing during core drilling.

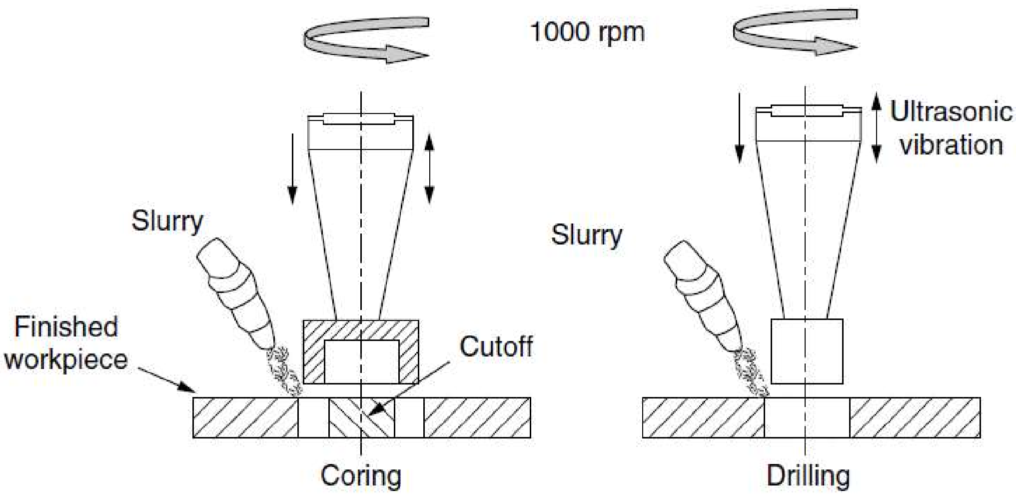

Figure 2.1.2: Rotary USM.

ii. **Ultrasonic sinking and contour machining**

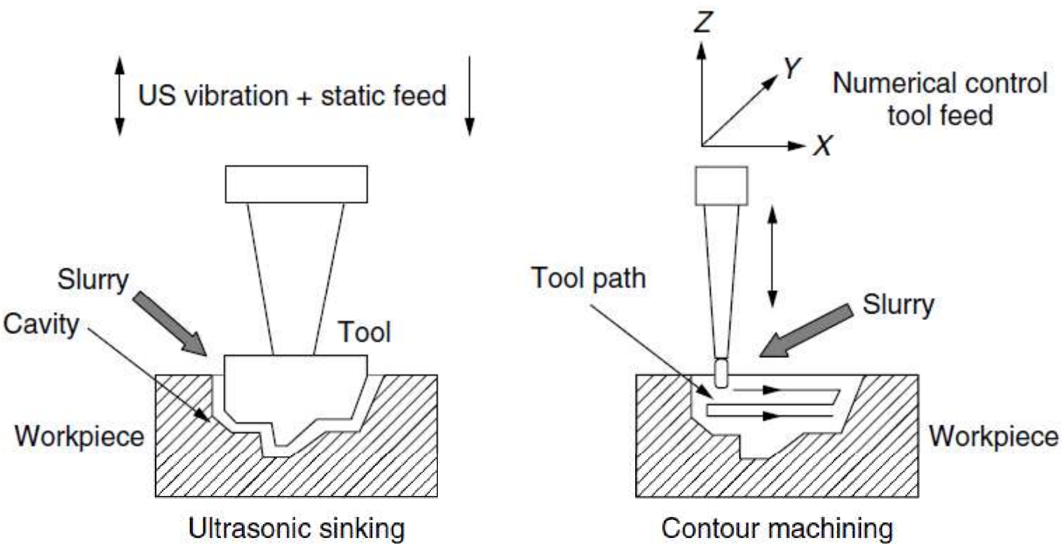

Figure 2.1.3: Ultrasonic sinking and contour machining

Figure 2.1.3 shows ultrasonic sinking and contour machining. During USM sinking, the material removal is difficult when the machined depth exceeds 5 to 7 mm, therefore the depth should not exceed 5 mm. Contouring USM employs simple tools that are moved in accordance to the contour required.

iii. **Production of EDM electrodes**

USM is used to produce graphite EDM electrodes as shown in Figure 2.1.4. Typical ultrasonic machining speeds, in graphite, range from 0.4 to 1.4 centimeters per minute (cm/min). Small machining forces permit the manufacture of fragile

Figure 2.1.4: Graphite EDM electrodes machined by USM graphite EDM electrodes.

iv. **Ultrasonic polishing**

Ultrasonic polishing occurs by vibrating a brittle tool material such as graphite or glass into the workpiece at an ultrasonic frequency and a relatively low vibration amplitude.

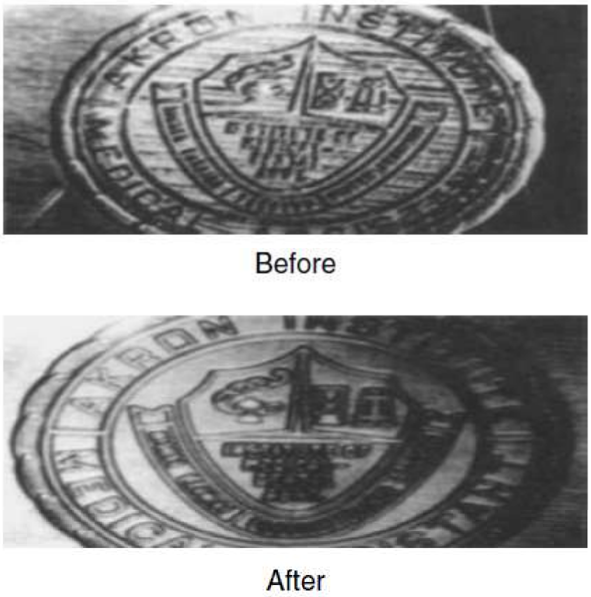

Figure 2.1.5: Ultrasonic polishing of CNC machined parts

v. **Micro-ultrasonic machining.** Micro-ultrasonic machining (MUSM) is a method that utilizes workpiece vibration. Using MUSM, microholes of 5 μm diameter on quartz, glass, and silicon have been produced using tungsten carbide (WC) alloy microtools.

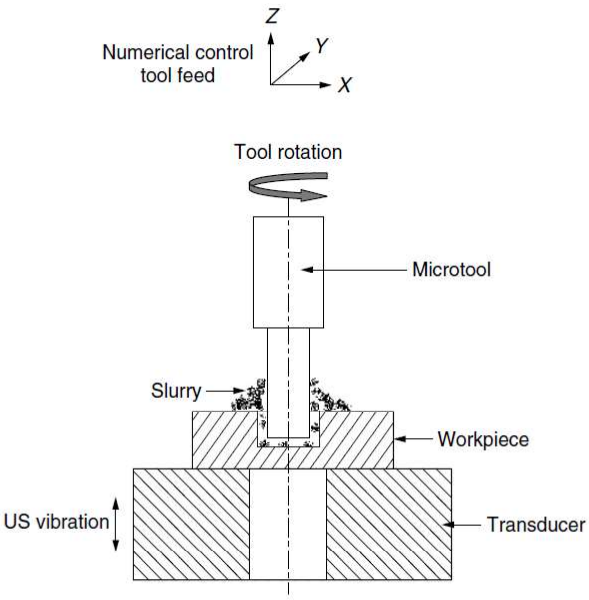

Figure 2.1.6: Micro-ultrasonic machining

2.2 Abrasive Jet Machining

In abrasive jet machining (AJM) a focused stream of abrasive grains of Al_2O_3 or SiC carried by high-pressure gas or air at a high velocity is made to impinge on the work surface through a nozzle of 0.3 - 0.5 mm diameter. The workpiece material is removed by the mechanical abrasion (MA) action of the high-velocity abrasive particles. AJM machining is best suited for machining holes in superhard materials. It is typically used to cut, clean, peen, deburr, deflash, and etch glass, ceramics, or hard metals.

2.2.1 Machining system

In the machining system shown in Figure 2.2.1, a gas (nitrogen, CO_2, or air) is supplied under a pressure of 2 to 8 kg/cm^2. Oxygen should never be used because it causes a violent chemical reaction with workpiece chips or abrasives. After filtration and regulation, the gas is passed through a mixing chamber that contains abrasive particles and vibrates at 50 Hz. From the mixing chamber, the gas, along with the entrained abrasive particles (10 - 40 μm), passes through a 0.45 mm diameter tungsten carbide nozzle at a speed of 150 to 300 m/s. The abrasive powder feed rate is controlled by the amplitude of vibrations in the mixing chamber. The nozzle standoff distance is 0.81 mm. The relative motion between the workpiece and the nozzle is manually or automatically controlled using cam drives, pantographs, tracer mechanisms, or using

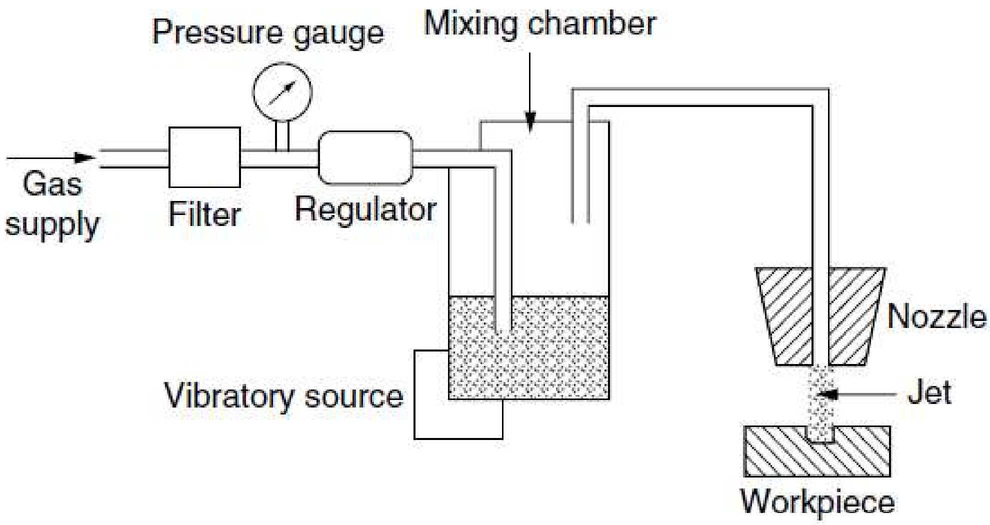

Figure 2.2.1: AJM system

computer control according to the cut geometry required.

The material removal rate, cut accuracy, surface roughness, and nozzle wear are influenced by the size and distance of the nozzle; composition, strength, size, and shape of abrasives; flow rate; and composition, pressure, and velocity of the carrier gas.

2.2.2 Applications of abrasive jet machining

1. Drilling holes, cutting slots, cleaning hard surfaces, deburring, polishing, and radiusing.
2. Machining intricate shapes or holes in sensitive, brittle, thin, or difficult-to-machine materials.
3. Insulation stripping and wire cleaning without affecting the conductor.
4. Micro-deburring of hypodermic needles.
5. Frosting glass and trimming of circuit boards, hybrid circuit resistors, capacitors, silicon, and gallium.
6. Removal of films and delicate cleaning of irregular surfaces because the abrasive stream is able to follow contours

2.3 Chemical Milling

Chemical milling (CHM) is the controlled chemical dissolution (CD) of the workpiece material by contact with a strong reagent. Special coatings called maskants protect areas from which the metal is not to be removed. The process is used to produce pockets and contours and to remove materials from parts having a high strength-to-weight ratio. CHM consists of the following steps:

1. Preparing and precleaning the workpiece surface to provides good adhesion of the masking material and assure the absence of contaminants.

2. Masking using readily strippable mask, which is chemically impregnable and adherent enough to stand chemical abrasion during etching.

3. Scribing of the mask, which is guided by templates to expose the areas that receive CHM.

4. The workpiece is then etched and rinsed, and the mask is removed before the part is finished.

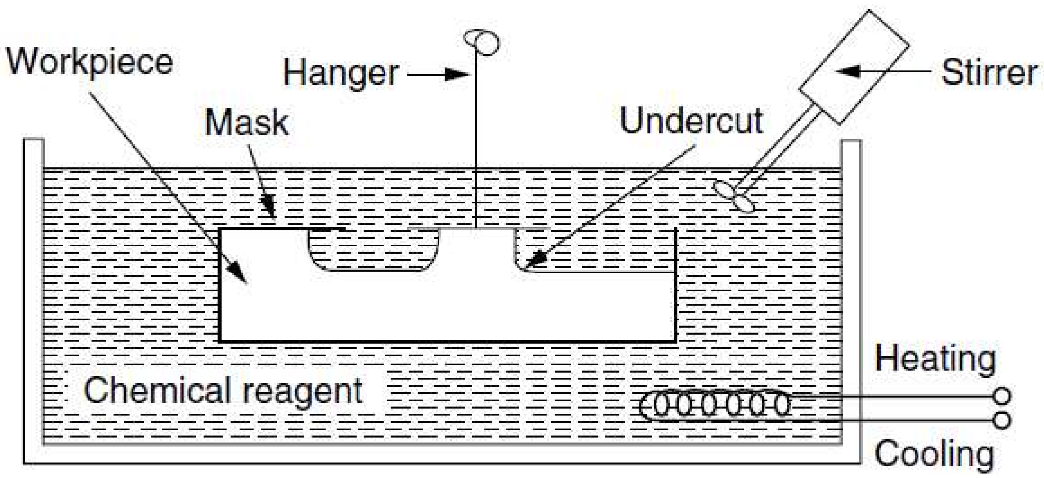

Figure 2.3.1: CHM setup

Figure 2.3.1 shows a set-up of the chemical milling process. The depth of the etch is controlled by the time of immersion. In order to avoid uneven machining, the chemicals that impinge on the surface being machined should be fresh. The chemicals used are very corrosive and, therefore, must be handled with adequate safety precautions.

2.3.1 Tooling for CHM

Tooling for CHM is relatively inexpensive and simple to modify. Four different types of tools are required: maskants, etchants, scribing templates, and accessories.

Maskants: Maskants are generally used to protect parts of the workpiece where CD action is not needed. Synthetic or rubber base materials are frequently used. Maskants should, however, possess the following properties:

1. Be tough enough to withstand handling
2. Adhere well to the workpiece surface
3. Scribe easily
4. Be inert to the chemical reagent used
5. Be able to withstand the heat generated by etching
6. Be removed easily and inexpensively after etching

Etchants: Etchants are acid or alkaline solutions maintained within a controlled range of chemical composition and temperature. Their main technical goals are to achieve the following:

1. Good surface finish
2. Uniformity of metal removal
3. Control of selective and inter-granular attack
4. Control of hydrogen absorption in the case of titanium alloys
5. Maintenance of personal safety
6. Best price and reliability for the materials to be used in the construction of the process tank.
7. Maintenance of air quality and avoidance of possible environmental problems.
8. Low cost per unit weight dissolved.
9. Ability to regenerate the etchant solution and/or readily neutralize and dispose of its waste products.

Scribing templates: Scribing templates are used to define the areas for exposure to the chemical machining action. The most common workpiece scribing method is to cut the mask with a sharp knife followed by careful peeling of the mask from the selected areas. Layout lines or simple templates of metal or fiberglass guide the scribing process.

Accessories: Accessories include tanks, hooks, brackets, racks, and fixtures. These are used for single - or multiple -piece handling into and out of the etchants and rinses.

2.3.2 Process parameters

CHM process parameters include the reagent solution type, concentration, properties, mixing, operating temperature, and circulation. The process is also affected by the maskant and its application. These parameters will have direct impacts on the workpiece regarding the following: etch factor (d/T), etching and machining rate, production tolerance and surface finish.

2.3.3 Applications

All the common metals including aluminium, copper, zinc, steel, lead, and nickel can be chemically machined. Many exotic metals such as titanium, molybdenum, and zirconium, as well as non-metallic materials including glass, ceramics, and some plastics, can also be used with the process. CHM applications range from large aluminium airplane wing parts to minute integrated circuit chips.

2.4 Electrochemical Machining

Electrochemical machining (ECM) is a modern machining process that relies on the removal of workpiece atoms by electrochemical dissolution (ECD) in accordance with the principles of Faraday. In this process, particles travel from the anodic material (workpiece) toward the cathodic material (machining tool). A current of electrolyte fluid carries away the deplated material before it has a chance to reach the machining tool. The cavity produced is the female mating image of the tool shape. The workpiece hardness is not a factor, making ECM suitable for machining difficult-to-machine materials. A schematic representation of ECM process is shown in Figure 2.4.1. The

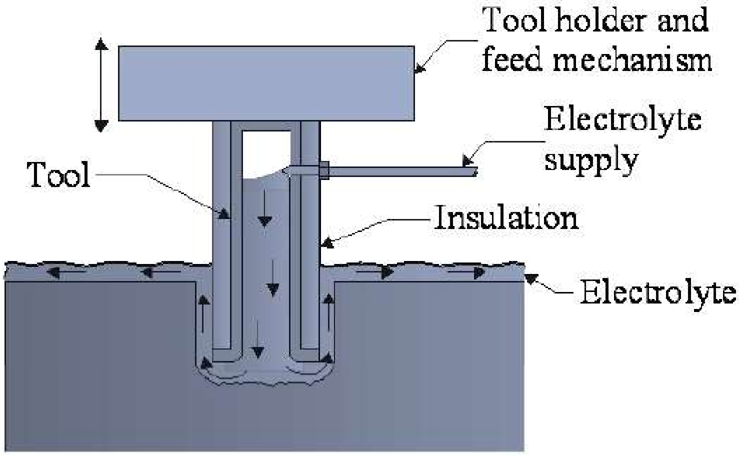

Figure 2.4.1: ECM process

ECM tool is positioned very close to the workpiece and a low voltage, high amperage DC current is passed between the workpiece and electrode. Some of the shapes made by ECM process are shown in Figure 2.4.2.

Figure 2.4.2: Parts made by ECM

2.4.1 Advantages of ECM

- The components are not subject to either thermal or mechanical stress.
- No tool wear during ECM process.
- Fragile parts can be machined easily as there is no stress involved.
- ECM deburring can debur difficult to access areas of parts.
- High surface finish (up to 25 μ m) can be achieved by ECM process.
- Complex geometrical shapes in high-strength materials particularly in the aerospace

industry for the mass production of turbine blades, jet-engine parts and nozzles can be machined repeatedly and accurately.

- Deep holes can be made by this process.

2.4.2 Limitations of ECM

- ECM is not suitable to produce sharp square corners or flat bottoms because of the tendency for the electrolyte to erode away sharp profiles.
- ECM can be applied to most metals but, due to the high equipment costs, is usually used primarily for highly specialised applications.

Material removal rate, MRR, in electrochemical machining:

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

I: current (amp);

h: current efficiency (90 - 100%).

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

2.4.3 Applications:

ECM has been used in a wide variety of industrial applications ranging from cavity sinking to deburring. The ability to machine high-strength alloys and hardened steel has led to many cost-saving applications where other processes are impractical. Typical applicators for the ECM process are shown in Figure 2.4.2.

2.5 Electrodischarge Machining (EDM)

In EDM, the removal of material is based upon the electrodischarge erosion (EDE) effect of electric sparks occurring between two electrodes that are separated by a dielectric liquid. Metal removal takes place as a result of the generation of extremely high temperatures generated by the high-intensity discharges that melt and evaporate the two electrodes.

2.5.1 The machining system

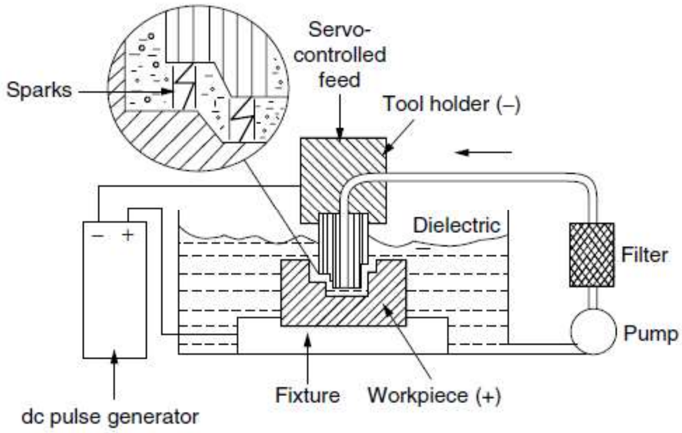

Figure 2.5.1: EDM schematic

Figure 2.5.1 shows the main components of the EDM system. These components include the tool feed servo-controlled unit, which maintains a constant machining gap that ensures the occurrence of active discharges between the two electrodes. The power supply is responsible for supplying pulses at a certain voltage, current, on time and off time. The dielectric circulation unit flushes the dielectric fluid to the inter-electrode gap after being filtered from the machining debris.

EDM Electrodes: Metals with a high melting point and good electrical conductivity are usually chosen as tool materials for EDM. Common materials used are: Graphite, copper, copper tungsten, silver tungsten, steel, brass etc.

Dielectric fluids: The main functions of the dielectric fluid are to:

1. Flush the eroded particles from the machining gap.

2. Provide insulation between the electrode and the workpiece.

3. Cool the section that was heated by the discharging effect.

Process Parameters: The performance of EDM is determined by three main properties, i.e., material removal rate, surface quality and accuracy. These are determined by the process parameters such as: pulse characteristics, workpiece thermal properties (melting and boiling point, conductivity), dielectric properties, tool electrode (material, movement, wear).

2.5.2 Application

EDM has become an indispensable process in the modern manufacturing industry. It produces complex shapes to a high degree of accuracy in difficult-to-machine materials such as heat-resistant alloys, superalloys, and carbides. The incorporation of EDM within a computer integrated manufacturing (CIM) system reduces the length of time that the unit operates without stops for maintenance. Typical applications include:

- Micro-EDM: Micromachining of holes, slots, and dies.
- EDM drilling such as the creation of cooling channels in turbine blades made of hard alloys.
- ED sawing where billets and bars are created.
- Machining of spheres, dies and molds
- Wire EDM a special form of EDM which uses a continuously moving conductive wire electrode. It is used in the machining of superhard materials such as polycrystalline diamond (PCD) and cubic boron nitride (CBN) blanks, and other matrix composites.
- EDM of insulating ceramics.
- Texturing: Texturing is applied to the steel sheets during the final stages of cold rolling

2.6 Laser Beam Machining

Laser is the abbreviation of light amplification by stimulated emission of radiation. A highly collimated, monochromatic, and coherent light beam is generated and focused to a small spot. High power densities (10^6 W/mm^2) are then obtained. Laser beam machining (LBM) uses the light energy from a laser to remove material by vaporization and ablation.

The types of lasers used in LBM are basically the carbon dioxide (CO_2) gas lasers.

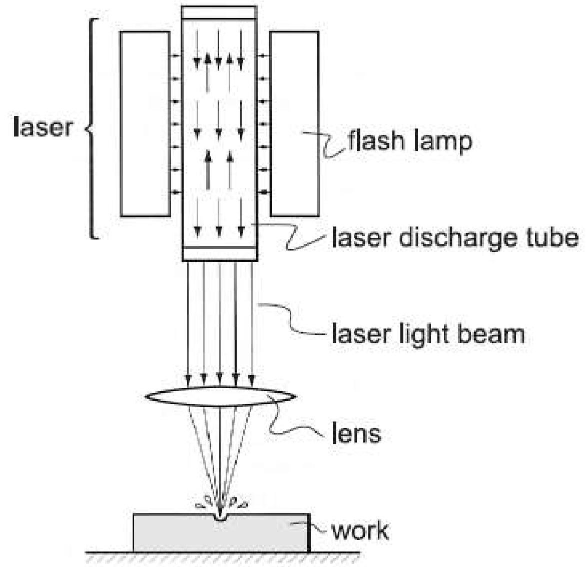

Figure 2.6.1: The set-up of laser beam machining process.

Lasers produce collimated monochromatic light with constant wavelength. In the laser beam, all of the light rays are parallel, which allows the light not to diffuse quickly like normal light. The light produced by the laser has significantly less power than a normal white light, but it can be highly focused, thus delivering a significantly higher light intensity and respectively temperature in a very localized area.

Materials: The range of work materials that can be machined by LBM is virtually unlimited including metals with high hardness and strength, soft metals, ceramics, glass, plastics, rubber, cloth, and wood.

2.6.1 Applications

Lasers are being used for a variety of industrial applications, including heat treatment, welding, and measurement, as well as a number of cutting operations such as drilling, slitting, slotting, and marking operations. Drilling small-diameter holes is possible, down to 0.025 mm. For larger holes, the laser beam is controlled to cut the outline of the hole.

LBM can be used for 2D or 3D workspace. The LBM machines typically have a laser mounted, and the beam is directed to the end of the arm using mirrors. Mirrors are often cooled (water is common) because of high laser powers.

2.7 Electron beam machining (EBM)

Electron beam machining uses a high-velocity stream of electrons focused on the workpiece surface to remove material by melting and vaporization.

2.7.1 Basic equipment and removal mechanism

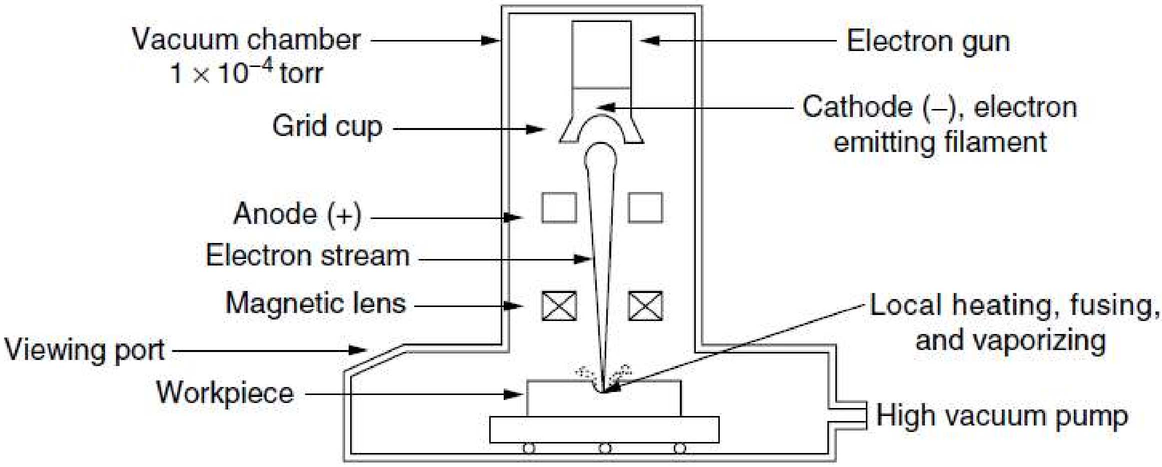

Figure 2.7.1: Components of an EBM system.

An electron beam gun generates a continuous stream of electrons that are focused through an electromagnetic lens on the work surface. The electrons are accelerated with voltages of approx. 150,000 V to create velocities over 200,000 km/s. The lens is capable of reducing the area of the beam to a diameter as small as 0.025 mm. On impinging the surface, the kinetic energy of the electrons is converted into thermal energy of extremely high density, which vaporizes the material in a very localized area. EBM must be carried out in a vacuum chamber to eliminate collision of the electrons with gas molecules.

Electron beam machining is used for a variety of high-precision cutting applications on any known material. Applications include drilling of extremely small diameter holes, down to 0.05 mm diameter, drilling of holes with very high depth-to-diameter ratios, more than 100:1, and cutting of slots that are only about 0.025 mm wide. Besides machining, other applications of the technology include heat treating, integrated circuit fabrication and welding.

The process is generally limited to thin parts in the range from 0.2 to 6 mm thick.

Other limitations of EBM are the need to perform the process in a vacuum, the high energy required, and the expensive equipment.

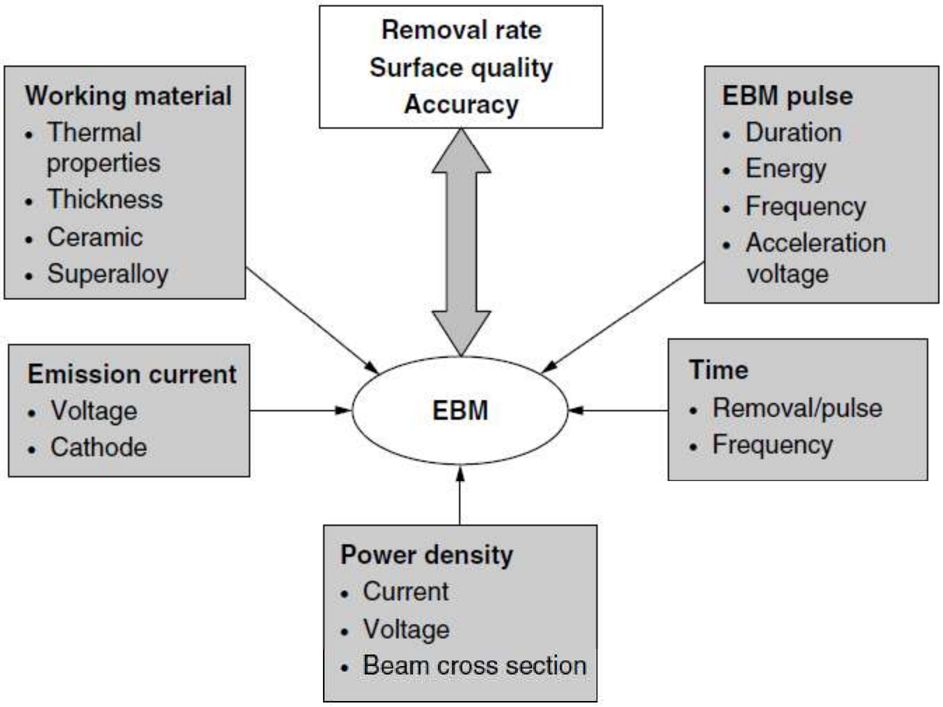

Figure 2.7.2: Parameters affecting EBM performance.

2.8 Plasma Beam Machining

When the temperature of a gas is raised to about 2000 °C, the gas molecules become dissociated into separate atoms. At higher temperatures, 30,000 °C, these atoms become ionized. The gas in this stage is termed plasma.

In plasma machining a continuous arc is generated between a hot tungsten cathode and the water-cooled copper anode. A gas is introduced around the cathode and flows through the anode. The temperature, in the narrow orifice around the cathode, reaches 28,000 °C, which is enough to produce a high-temperature plasma arc. Under these conditions, the metal being machined is very rapidly melted and vaporized. The stream of ionized gases flushes away the machining debris as a fine spray creating flow lines on the machined surface.

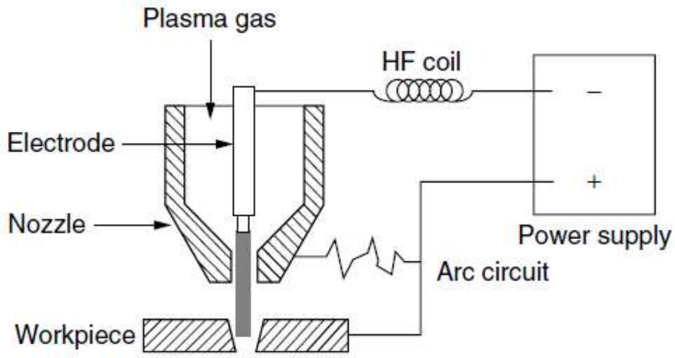

Figure 2.8.1: Transferred plasma arc system

2.8.1 Applications

1. PBM is an attractive turning method for difficult-to-machine materials by conventional methods.
2. Computer numerical controlled PBM is used for profile cutting of metals that are difficult to tackle by oxyacetylene gas technique such as stainless steel and aluminium.
3. PBM can cut 1.5-mm-deep, 12.5-mm-wide grooves in stainless steel at 80 mm3/min, using 50 kW as the cutting power. Such a high machining rate is 10 times the rate of grinding and chipping methods.
4. The process is recommended for parts that have subsequent welding operations.
5. A plasma arc can cut tubes of wall thickness of up to 50 mm. In this case no deburring is required before tube welding.
6. Underwater NC plasma cutting can achieve machining accuracy of ± 0.2 mm in 9 m at low cutting speeds.