

# NONTRADITIONAL MANUFACTURING PROCESSES

## INTRODUCTION

Many material removal processes have been developed since World War II to address problems that can't be handled with conventional, that is, "traditional chip-forming" machining processes. The processes described in this chapter are often called nontraditional machining (NTM) processes, and have the following advantages:

- Complex geometries beyond simple planar or cylindrical features can be machined.
- Parts with extreme surface-finish and tight tolerance requirements can be obtained.
- Delicate components that cannot withstand large cutting forces can be machined.
- Parts can be machined without producing burrs or inducing residual stresses.
- Brittle materials or materials with very high hardness can be easily machined.
- Microelectronic or integrated circuits can be mass-produced.

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

1. *Chemical*. Chemical reaction between a liquid reagent and the work piece results in etching.
2. *Electrochemical*. An electrolytic reaction at the work piece surface is responsible for material removal.
3. *Thermal*. High temperatures in very localized regions evaporate materials.
4. *Mechanical*. High-velocity abrasives or liquids like abrasive jet machining, ultra sonic machining and water-jet machining are used to remove material.

Machining processes that involve *chip* formation have a number of inherent **limitations**. Large amounts of energy are expended to produce unwanted chips that must be removed and discarded. Much of the machining energy ends up as undesirable heat that often produces problems of distortion and surface cracking. Cutting forces require that the work piece be held, which can also lead to distortion. Unwanted distortion, residual stresses, and burrs caused by the machining process often require further processing. Finally, some geometries are too delicate to machine, while others are too complex.

In comparison to conventional machining [for example milling], NTM processes typically have lower feed rates and require more power consumption when compared to machining. However, some processes permit batch processing, which increases the overall output of these processes and enables them to compete with machining. A major advantage of some NTM processes is that feed rate is independent of the material being processed. As a result, these processes are often used for difficult-to-machine materials. NTM processes typically have better accuracy and surface finish, with the ability of some processes to machine larger feature sizes at lower capital costs. In most applications, NTM requires part-specific tooling, while general-purpose cutting and work holding tools make machining very flexible.

## ELECTROCHEMICAL MACHINING PROCESSES

Electrochemical machining, commonly designated **ECM**, removes material by anodic dissolution with a rapidly flowing electrolyte. The process is shown schematically in Figure. It is basically a de-plating process in which the **tool is the cathode** and the **work piece is the anode**; both must be electrically conductive.

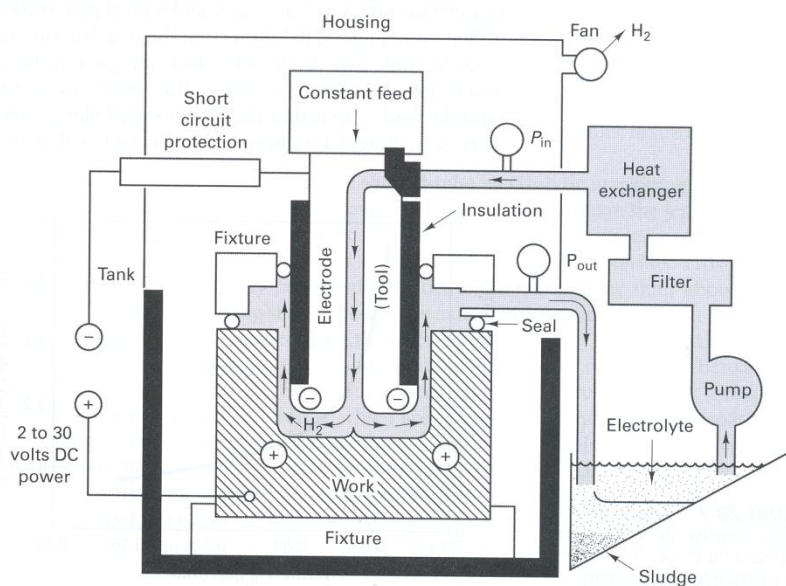


FIGURE: Schematic of electrochemical machining process (ECM).

The electrolyte, which can be pumped rapidly through or around the tool, sweeps away any heat and waste product (sludge) given off during the reaction. The sludge is captured and removed from the electrolyte through filtration. The shape of the cavity is defined by the tool, which is advanced by means of a servomechanism that controls the gap between the electrodes (i.e., the inter electrode gap) to a range from 0.254 mm. The tool advances into the work at a constant feed rate, or penetration rate, that matches the de-plating rate of the work piece. The electrolyte is a highly conductive solution of inorganic salt - usually Na Cl, KCl, and NaNO<sub>3</sub> - and is operated at about 24 to 65°C with flow rates ranging from 16 to 60 m/sec. The temperature of the electrolyte is maintained through appropriate temperature controls. Tools are usually made of copper or brass and sometimes stainless steel.

The behavior of the ECM process is governed by the laws of electrolysis (the use of electrical current to bring about chemical change). Faraday's first law of electrolysis states that the amount of chemical change (material removed) during electrolysis is proportional to the charge (number of electrons) passed.

### **Advantages and Disadvantages of Electrochemical Machining**

ECM is well suited for the machining of complex two-dimensional shapes into delicate or difficult to-machine geometries made from poorly machinable but conductive materials. The principal tooling cost is for the preparation of the tool electrode, which can be time consuming and costly, requiring several cut-and-try efforts for complex shapes, because it is difficult to predict the precise final geometry due to variable current densities produced by certain electrode geometries (e.g., corners) or electrolyte flow variations. There is no tool wear during actual cutting, which suggests that the process becomes more economical with increasing volume. The process produces a stress-free surface, which can be advantageous, especially for small, thin parts. The ability to cut a large area simultaneously makes the production of small parts very productive. However, as in chemical machining, ECM requires the disposal of environmentally harmful by-products .

## ELECTRICAL DISCHARGE MACHINING

EDM processes remove metal by discharging electric current from a pulsating DC power supply across a thin inter electrode gap between the tool and the work piece as shown schematically in Figure. The gap is filled by a dielectric fluid, which becomes locally ionized at the point where the inter electrode gap is the narrowest-generally, where a high point on the work piece comes close to a high point on the tool. The ionization of the dielectric fluid creates a conduction path in which a spark is produced. The spark produces a tiny crater in the work piece by melting and vaporization, and consequently tiny, spherical "chips" are produced by re-solidification of the melted quantity of work piece material.

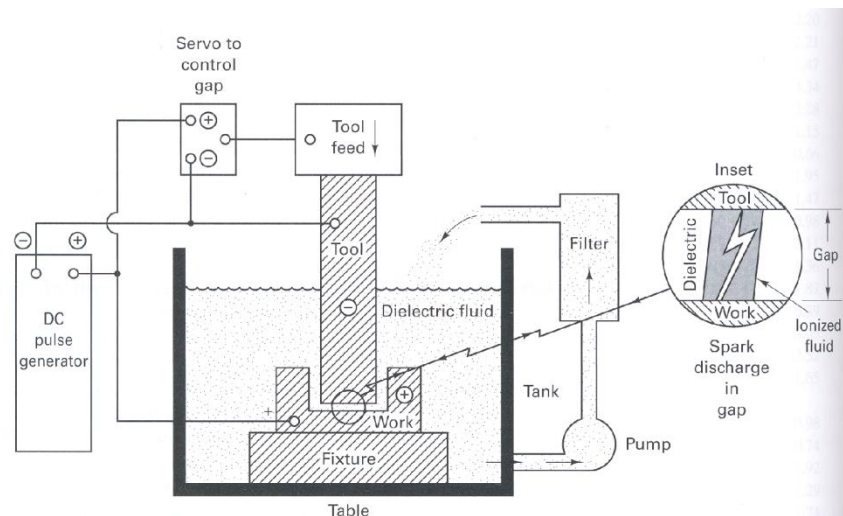


FIGURE: EDM or spark erosion machining of metal, using high-frequency spark discharge across a thin dielectric, between the shaped tool (cathode) and the work (anode). The table can make X-Y movements.

Bubbles from discharge gases are also produced. In addition to machining the work piece, the high temperatures created by the spark also melt or vaporize the tool, creating tool wear. The dielectric fluid is pumped through the inter electrode gap and flushes out the chips and bubbles while confining the sparks. Once the highest point of the work piece is removed, a subsequent spark is created between the tool and next highest point, and so the process proceeds into the

work piece. Literally hundreds of thousands of sparks may be generated per second. This material removal mechanism, is described as **spark erosion**.

Two different types of EDM exist based on the shape of the tool electrode used. In **ram EDM**, also known as **die-sinking EDM** or simply EDM, the electrode is a die in the shape of the negative of the cavity to be produced in a bulk material. By feeding the die into the work piece, the shape of the die is machined into the work piece.

In wire EDM, also known as **electrical discharge wire cutting**, the electrode is a wire used for cutting through-cut features, driving the work piece with a computer numerical controlled (CNC) table as in Figure.

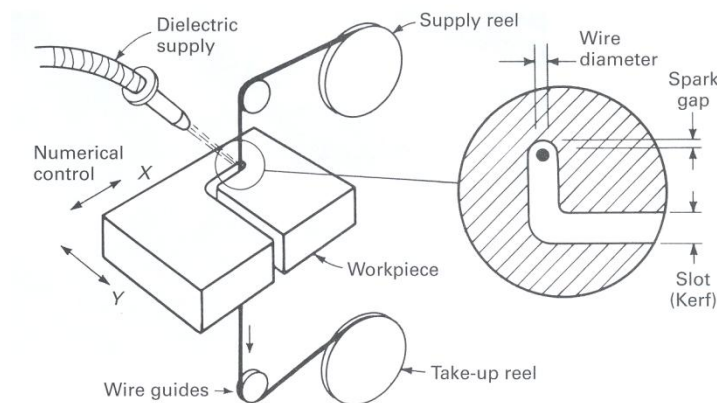


FIGURE: Schematic of equipment for wire EDM using a moving wire electrode.

Wire EDM uses a continuously moving conductive wire as the tool electrode. The tensioned wire of copper, brass, tungsten, or molybdenum is used only once, travelling from a take-off spool to a take-up spool while being "guided" to produce a straight, narrow kerf in plates up to 75mm thick. The wire diameter ranges from 0.05 to 0.25 mm, with positioning accuracy up to  $\pm 0.0005$  mm in machines with numerical control (NC). The dielectric is usually deionized water because of its low viscosity.

This process is widely used for the manufacture of punches, dies, and stripper plates, with modern machines capable of routinely cutting die relief, intricate openings, tight radius contours, and corners as in Figure for some examples.

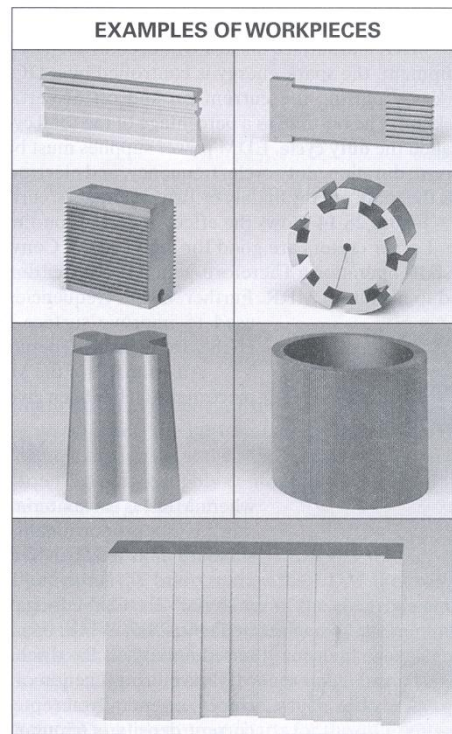


FIGURE: Examples of wire EDM work pieces made on an NC machine.

EDM processes are slow compared to more conventional methods of and they produce a matte surface finish composed of many small craters. While feed rates in EDM are slow, EDM processes can still compete with conventional in producing complex geometries, particularly in hardened tool materials. As a result, one of the biggest applications of EDM processes is tool and die making. Another drawback of EDM is the formation of a recast or remelt layer on the surface and a **heat affected zone (HAZ)** below the surface of the work piece.

Figure [below] shows a scanning electron micrograph of a recast layer on top of a ground surface. Note the small spheres in the lower-right corner attached to the surface, representing chips that did not escape the surface. Below the recast layer is a heat-affected zone on the order of 0.0254 mm.

FIGURE: SEM micrograph of EDM surface (right) on top of a ground surface in steel. The spheroidal nature of debris on the surface is in evidence around the craters (300x).

The effect of the recast layer and heat-affected zone is poor surface finish as well as poor surface integrity and poor fatigue strength. MRR and surface finish are both controlled by the spark energy. In modern EDM equipment, the spark energy is controlled by a DC power supply. The power supply works by pulsing the current on and off at certain frequencies (between 10 and 500 kHz). The on-time as a percentage of the total cycle time (inverse of the frequency) is called the duty cycle. EDM power supplies must be able to control the pulse voltage, current, duration, duty cycle, frequency, and electrode polarity. The power supply controls the spark energy mainly by two parameters: current on-time and discharge current. Figure [below] shows the effect of current on-time and discharge current on size. Larger craters are good for high MRRs. Conversely, small craters are good for finishing operations. Therefore, generally, higher duty cycles and lower frequencies are used to maximize MRR. Further, higher frequencies and lower discharge currents are used to improve surface finish while reducing the MRR.

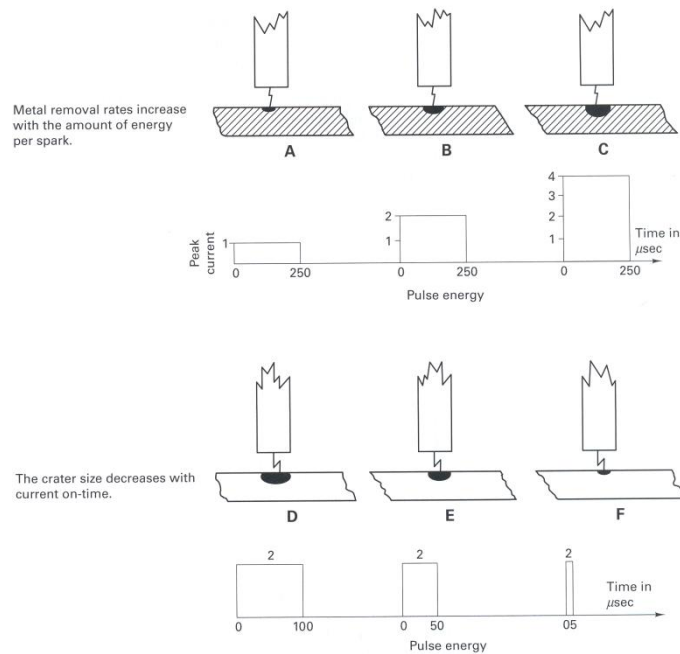


FIGURE: The principles of metal removal for EDM.

## Advantages and Disadvantages of EDM

EDM is applicable to all materials that are fairly good electrical conductors, including metals, alloys, and most carbides. The hardness, toughness, or brittleness of the material imposes no limitations. EDM provides a relatively simple method for making holes and pockets of any desired cross section in materials that are too hard or too brittle to be machined by most other methods.

The process leaves no burrs on the edges. About 80 to 90% of the EDM work performed in the world is in the manufacture of tool and die sets for injection molding, forging, stamping, and extrusions. The absence of almost all mechanical forces makes it possible to EDM fragile or delicate parts without distortion. EDM has been used in micromachining to make feature sizes as small as 0.01 mm.

On most materials, the process produces a thin, hard recast surface, which may be an advantage or a disadvantage, depending on the use. When the work piece material is one that tends to be brittle at room temperature, the surface may contain fine cracks caused by the thermally induced stresses. Consequently, some other finishing process is often used subsequent to EDM to remove the thin recast and heat-affected layers, particularly if the product will be fatigued. Fumes, resulting from the bubbles produced during spark erosion, are given off during the EDM process. Fumes can be toxic when electrical discharge machining boron carbide, titanium boride, and beryllium, posing a significant safety issue, although machining of these materials is hazardous in other processes as well.

## ELECTRON AND ION MACHINING

As a metals-processing tool, the electron beam is used mainly for welding, to some extent for surface hardening, and occasionally for cutting (mainly drilling). **Electron-beam machining (EBM)** is a thermal process that uses a beam of high-energy electrons focused on the work piece to melt and vaporize metal. This process shown in Figure is performed in a vacuum chamber.



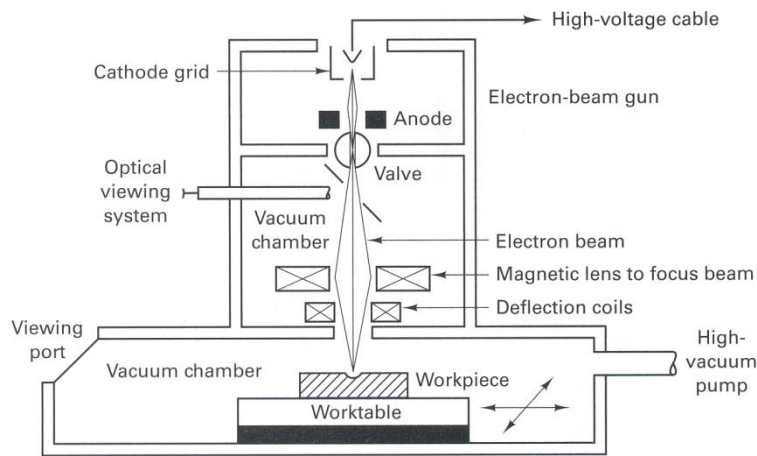


FIGURE: Electron-beam machining uses a high-energy electron beam ( $10^9 \text{ W/mm}^2$ ).

The electron beam is produced in the electron gun (also under vacuum) by thermionic emission. In its simplest form, a filament (tungsten or lanthanum-hexaboride) is heated to temperatures in excess of  $2000^\circ\text{C}$ , where a stream (beam) of electrons (more than 1 billion per second) is emitted from the tip of the filament. Electrostatic optics are used to focus and direct the beam. The desired beam path can be programmed with a computer to produce any desired pattern in the work piece. The diameter of the beam is on the order of 0.012 to 0.025 mm, and holes or narrow slits with depth-to-width ratios of 100:1 can be "machined" with great precision in any material. The interaction of the beam with the surface produces dangerous X-rays; therefore, electromagnetic shielding of the process is necessary. The layer of recast material and the depth of the heat damage are very small. For micromachining applications, MRRs can exceed that of EDM or ECM. Typical tolerances are about 10% of the hole diameter or slot width. These machines require high voltages (50 to 200 k V) to accelerate the electrons to speeds of 0.5 to 0.8 the speed of light and should be operated by fully trained personnel.

**Ion-beam machining (IBM)** is a nanoscale ( $10^{-9}$ ) machining technology used in the microelectronics industry to cleave defective wafers for characterization and failure analysis. IBM uses a focused ion beam created by thermionic emission similar to EBM to machine features as small as 50 nm. The ion beam may be focused down to a 50-nm diameter and is focused and positioned by an electrostatic optics column. Current densities up to  $5 \text{ A/cm}^2$  and

voltages between 4 and 150 kV provide ion energies up to 300 A/cm<sup>2</sup>/keV. Target substrates as large as 180 mm x 180 mm x 6mm thick can be processed.

## LASER-BEAM MACHINING

Laser stands for "light amplification by stimulated emission of radiation." Lasers were invented five decades ago and are used everywhere. Semiconductor lasers are found inside laptops and DVD players. For manufacturing processes, like **laser-beam machining (LBM)**, an intensely focused, coherent stream of light called a laser is used to vaporize or chemically *ablate* materials. A schematic of the LBM process is shown in Figure. Lasers are also used for joining (welding, brazing, soldering), heat-treating materials, inspection, and free-form manufacturing.

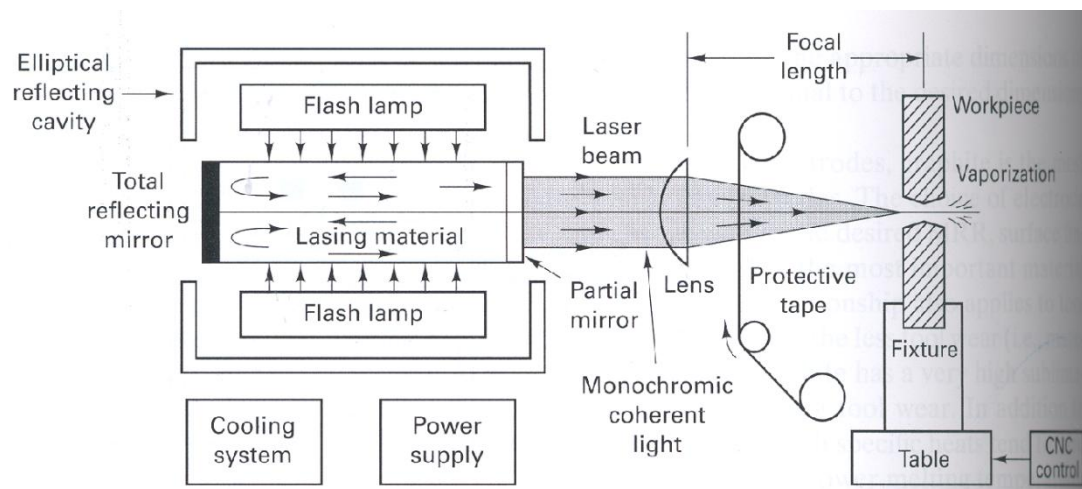


FIGURE: Schematic of a laser-beam machine, a thermal NTM process that can micro-machine any material.

Power density and interaction time are the basic parameters in laser applications, as shown in Figure. Drilling requires high power densities and shorter interaction times compared to most other applications. .

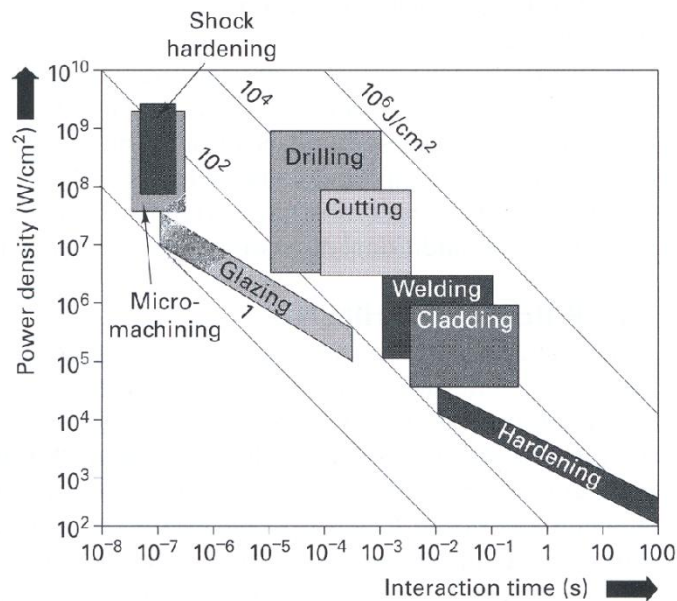


FIGURE: Power densities and interaction times in laser processing vary with the application.

The material removal mechanism in LBM is dependent on the wavelength of laser used. At UV wavelengths (i.e., between about 200 and 400 nm), the material removal mechanism in polymers (for example) is generally thermal evaporation. Below 400 nm, polymeric material is typically removed by chemical ablation. In *ablation*, the chemical bonds between atoms are broken by the excess amount of laser energy absorbed by the valence electrons in the material. The advantage of chemical ablation is that because it is not a thermal process, it does not result in a heat-affected zone.

Here is how the laser works. Laser light is produced within a laser cavity, which is a highly reflective cavity containing a laser rod and a high-intensity light source, or laser lamp. The light source is used to "pump up" the laser rod, which includes atoms of a lasing media that is capable of absorbing the particular wavelength of light produced by the light source. When an atom of lasing media is struck by a photon of light, it becomes energized. When a second photon strikes the energized atom, the atom gives off two photons of identical wavelength, moving in the same direction and with the same phase. This process is called **stimulated emission**. As the two photons now stimulate further emission from other energized atoms, a cascading of stimulated emission ensues. To increase the number of stimulated emissions, the

laser rod has mirrors on both ends that are precisely parallel to one another. Only photons moving perpendicular to these two mirrors stay within the laser rod, causing additional stimulated emission. One of the mirrors is partially transmissive and permits some percent of the laser energy to escape the cavity. The energy leaving the laser rod is the laser beam.

Lasers produce highly collimated, coherent (in-phase) light, which, when focused to a small diameter, produces high-power densities that are good for machining. It is generally accepted that in order to evaporate materials, infrared power densities in excess of  $10^5 \text{ W/mm}^2$  are needed. For CO<sub>2</sub> lasers, these levels are directly achievable. However, in Nd:YAG lasers, these high power conditions would significantly decrease the life of the laser lamp. Therefore, Nd:YAG lasers break up the continuous light stream into a series of higher power pulses.

## **PLASMA ARC CUTTING**

Plasma arc cutting (PAC) uses a superheated stream of electrically ionized gas to melt and remove material (Figure). The 11,000° to 28,000°C plasma is created inside a water-cooled nozzle by electrically ionizing a suitable gas such as nitrogen, hydrogen, argon, or mixtures of these gases. The process can be used on almost any conductive metal. The plasma arc is a mixture of free electrons, positively charged ions, and neutral atoms. The arc is initiated in a confined gas-filled chamber by a high-frequency spark.

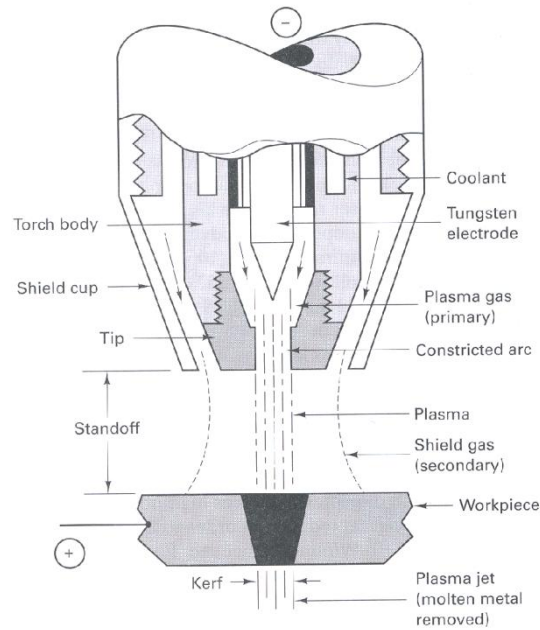


FIGURE: Plasma arc machining or cutting.

The high-voltage, DC power sustains the arc, which exits from the nozzle at near-sonic velocity. The work piece is electrically positive. The high-velocity gases melt and blow away the molten metal "chips." Dual-flow torches use a secondary gas or water shield to assist in blowing the molten metal out of the kerf, giving a cleaner cut. The process may be performed underwater, using a large tank to hold the plates being cut. The water assists in confining the arc and reducing smoke. The main advantage of PAC is speed.

Mild steel 6 mm thick can be cut at 3m/ min. Speed decreases with thickness. Greater nozzle life and faster cutting speeds accompany the use of water-injection-type torches. Control of nozzle stand-off from the work piece is important. One electrode size can be used to machine a wide variety of materials and thicknesses by suitable adjustments to the power level, gas type, gas flow rate, traverse speed, and flame angle. PAC is sometimes called plasma-beam machining.

PAC can machine exotic materials at high rates. Profile cutting of metals, particularly of stainless steel and aluminum, has been the most prominent commercial application. However,

mild steel, alloy steel, titanium, bronze, and most metals can be cut cleanly and rapidly. Multiple-torch cuts are possible on programmed or tracer-controlled cutting tables on plates up to 150 mm thick in stainless steel. Smooth cuts free from contaminants are a PAC advantage.

Some of the drawbacks of the PAC process include poor tolerances, tapered cuts, and double arcing, leading to premature wear on the nozzle.