25 Nontraditional Machining and Thermal Cutting Processes

Chapter Contents

Conventional machining processes (i.e., turning, drilling, milling) use a sharp cutting tool to form a chip from the work by shear deformation. In addition to these conventional methods, there is a group of processes that uses other mechanisms to remove material. The term ***nontraditional machining*** refers to this group that removes excess material by various techniques involving mechanical, thermal, electrical, or chemical energy (or combinations of these energies). They do not use a sharp cutting tool in the conventional sense.

The nontraditional processes have been developed since World War II largely in response to new and unusual machining requirements that could not be satisfied by conventional methods. These requirements, and the resulting commercial and technological importance of the nontraditional processes, include:

- The need to machine newly developed metals and nonmetals. These new materials often have special properties (e.g., high strength, high hardness, high toughness) that make them difficult or impossible to machine by conventional methods.
- The need for unusual and/or complex part geometries that cannot easily be accomplished and in some cases are impossible to achieve by conventional machining.
- The need to avoid surface damage that often accompanies the stresses created by conventional machining.

Many of these requirements are associated with the aerospace and electronics industries, which have become increasingly important in recent decades.

There are literally dozens of nontraditional machining processes, most of which are unique in their range of applications. In the present chapter, the most important are discussed. More detailed discussions of these nontraditional methods are presented in several of the references.

The nontraditional processes are often classified according to principal form of energy used to effect material removal. By this classification, there are four types:

1. ***Mechanical***. Mechanical energy in some form other than the action of a conventional cutting tool is used in these nontraditional processes. Erosion of the work material by a high velocity stream of abrasives or fluid (or both) is a typical form of mechanical action in these processes.
2. ***Electrical***. These nontraditional processes use electrochemical energy to remove material; the mechanism is the reverse of electroplating.
3. ***Thermal***. These processes use thermal energy to cut or shape the work part. The thermal energy is generally applied to a very small portion of the work surface, causing that portion to be removed by fusion and/or vaporization. The thermal energy is generated by the conversion of electrical energy.
4. ***Chemical***. Most materials (metals particularly) are susceptible to chemical attack by certain acids or other etchants. In chemical machining, chemicals selectively remove material from portions of the work part, while other portions of the surface are protected by a mask.

25.1 Mechanical Energy Processes

This section examines several of the nontraditional processes that use mechanical energy other than a sharp cutting tool: (1) ultrasonic machining, (2) water jet processes, and (3) other abrasive processes.

25.1.1 ULTRASONIC MACHINING

Ultrasonic machining (USM) is a nontraditional machining process in which abrasives contained in a slurry are driven at high velocity against the work by a tool vibrating at low amplitude and high frequency. The amplitudes are around 0.075 mm (0.003 in), and the frequencies are approximately 20,000 Hz. The tool oscillates in a direction perpendicular to the work surface, and is fed slowly into the work, so that the shape of the tool is formed in the part. However, it is the action of the abrasives, impinging against the work surface, that performs the cutting. The general arrangement of the USM process is depicted in Figure 25.1.

Common tool materials used in USM include soft steel and stainless steel. Abrasive materials in USM include boron nitride, boron carbide, aluminum oxide, silicon carbide, and diamond. Grit size (Section 16.1.1) ranges between 100 and 2000. The vibration amplitude should be set approximately equal to the grit size, and the gap size should be maintained at about two times grit size. To a significant degree, grit size determines the surface finish on the new work surface. In addition to surface finish, material removal rate is an important performance variable in ultrasonic machining. For a given work material, the removal rate in USM increases with increasing frequency and amplitude of vibration.

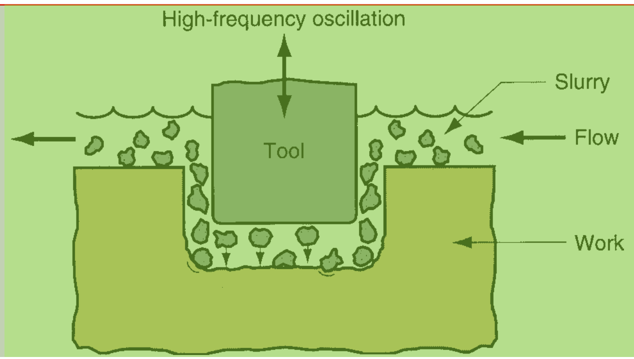


FIGURE 25.1 Ultrasonic machining.

The cutting action in USM operates on the tool as well as the work. As the abrasive particles erode the work surface, they also erode the tool, thus affecting its shape. It is therefore important to know the relative volumes of work material and tool material removed during the process—similar to the grinding ratio (Section 25.1.2). This ratio of stock removed to tool wear varies for different work materials, ranging from around 100:1 for cutting glass down to about 1:1 for cutting tool steel.

The slurry in USM consists of a mixture of water and abrasive particles. Concentration of abrasives in water ranges from 20% to 60% [5]. The slurry must be continuously circulated to bring fresh grains into action at the tool–work gap. It also washes away chips and worn grits created by the cutting process.

The development of ultrasonic machining was motivated by the need to machine hard, brittle work materials, such as ceramics, glass, and carbides. It is also successfully used on certain metals such as stainless steel and titanium. Shapes obtained by USM include nonround holes, holes along a curved axis, and coining operations, in which an image pattern on the tool is imparted to a flat work surface.

25.1.2 PROCESSES USING WATER JETS

The two processes described in this section remove material by means of high-velocity streams of water or a combination of water and abrasives.

Water Jet Cutting Water jet cutting (WJC) uses a fine, high-pressure, high-velocity stream of water directed at the work surface to cause cutting of the work, as illustrated in Figure 25.2. To obtain the fine stream of water a small nozzle opening of diameter 0.1 to 0.4 mm (0.004–0.016 in) is used. To provide the stream with sufficient energy for cutting, pressures up to 400 MPa (60,000 lb/in^2) are used, and the jet reaches velocities up to 900 m/s (3000 ft/sec). The fluid is pressurized to the desired level by a hydraulic pump. The nozzle unit consists of a holder made of stainless steel, and a jewel nozzle made of sapphire, ruby, or diamond. Diamond lasts the longest but costs the most. Filtration systems must be used in WJC to separate the swarf produced during cutting.

Cutting fluids in WJC are polymer solutions, preferred because of their tendency to produce a coherent stream. Cutting fluids have been discussed before in the context of conventional machining (Section 22.4), but never has the term been more appropriately applied than in WJC.

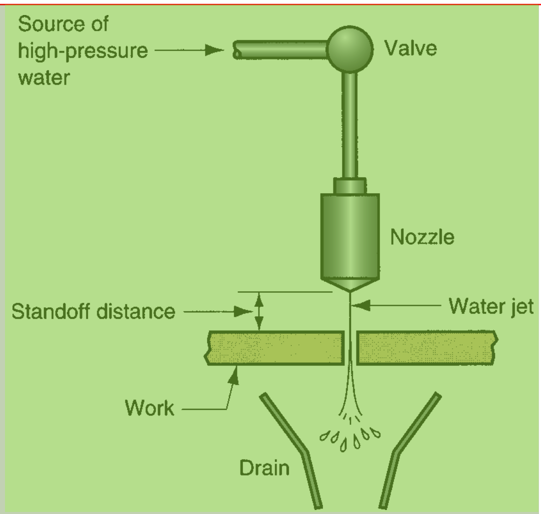


FIGURE 25.2 Water jet cutting.

Important process parameters include standoff distance, nozzle opening diameter, water pressure, and cutting feed rate. As in Figure 25.2, the ***standoff distance*** is the separation between the nozzle opening and the work surface. It is generally desirable for this distance to be small to minimize dispersion of the fluid stream before it strikes the surface. A typical standoff distance is 3.2 mm (0.125 in). Size of the nozzle orifice affects the precision of the cut; smaller openings are used for finer cuts on thinner materials. To cut thicker stock, thicker jet streams and higher pressures are required. The cutting feed rate refers to the velocity at which the WJC nozzle is traversed along the cutting path. Typical feed rates range from 5 mm/s (12 in/min) to more than 500 mm/s (1200 in/min), depending on work material and its thickness [5]. The WJC process is usually automated using computer numerical control or industrial robots to manipulate the nozzle unit along the desired trajectory.

Water jet cutting can be used effectively to cut narrow slits in flat stock such as plastic, textiles, composites, floor tile, carpet, leather, and cardboard. Robotic cells have been installed with WJC nozzles mounted as the robot's tool to follow cutting patterns that are irregular in three dimensions, such as cutting and trimming of automobile dashboards before assembly [9]. In these applications, advantages of WJC include (1) no crushing or burning of the work surface typical in other mechanical or thermal processes, (2) minimum material loss because of the narrow cut slit, (3) no environmental pollution, and (4) ease of automating the process. A limitation of WJC is that the process is not suitable for cutting brittle materials (e.g., glass) because of their tendency to crack during cutting.

Abrasive Water Jet Cutting When WJC is used on metallic work parts, abrasive particles must usually be added to the jet stream to facilitate cutting. This process is therefore called ***abrasive water jet cutting*** (AWJC). Introduction of abrasive particles into the stream complicates the process by adding to the number of parameters that must be controlled. Among the additional parameters are abrasive type, grit size, and flow rate. Aluminum oxide, silicon dioxide, and garnet (a silicate mineral) are typical abrasive materials, at grit sizes ranging between 60 and 120. The abrasive particles are added to the water stream at approximately 0.25 kg/min (0.5 lb/min) after it has exited the WJC nozzle.

The remaining process parameters include those that are common to WJC: nozzle opening diameter, water pressure, and standoff distance. Nozzle orifice diameters are 0.25 to 0.63 mm (0.010–0.025 in)—somewhat larger than in water jet cutting to permit higher flow rates and more energy to be contained in the stream before injection of abrasives. Water pressures are about the same as in WJC. Standoff distances are somewhat less to minimize the effect of dispersion of the cutting fluid that now contains abrasive particles. Typical standoff distances are between 1/4 and 1/2 of those in WJC.

25.1.3 OTHER NONTRADITIONAL ABRASIVE PROCESSES

Two additional mechanical energy processes use abrasives to accomplish deburring, polishing, or other operations in which very little material is removed.

Abrasive Jet Machining Not to be confused with AWJC is the process called abrasive jet machining (AJM), a material removal process caused by the action of a high-velocity stream of gas containing small abrasive particles, as in Figure 25.3. The gas is dry, and pressures of 0.2 to 1.4 MPa (25–200 lb/in^2) are used to propel it through nozzle orifices of diameter 0.075 to 1.0 mm (0.003–0.040 in) at velocities of 2.5 to 5.0 m/s (500–1000 ft/min). Gases include dry air, nitrogen, carbon dioxide, and helium.

The process is usually performed manually by an operator who directs the nozzle at the work. Typical distances between nozzle tip and work surface range from 3 to 75 mm (0.125–3 in). The workstation must be set up to provide proper ventilation for the operator.

AJM is normally used as a finishing process rather than a production cutting process. Applications include deburring, trimming and deflashing, cleaning, and polishing. Cutting is accomplished successfully on hard, brittle materials (e.g., glass, silicon, mica, and ceramics) that are in the form of thin flat stock. Typical abrasives used in AJM include aluminum oxide (for aluminum and brass), silicon carbide (for stainless steel and ceramics), and glass beads (for polishing). Grit sizes are small, 15 to 40 μm (0.0006–0.0016 in) in diameter, and must be uniform in size for a given application. It is important not to recycle the abrasives because used grains become fractured (and therefore smaller in size), worn, and contaminated.

Abrasive Flow Machining This process was developed in the 1960s to deburr and polish difficult-to-reach areas using abrasive particles mixed in a viscoelastic polymer

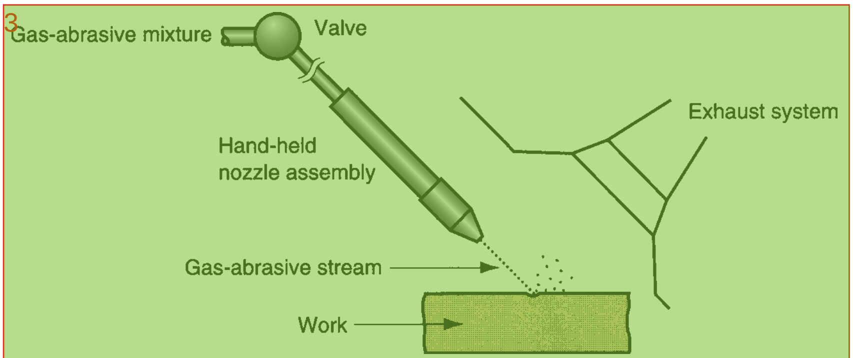


FIGURE 25.3 Abrasive jet machining (AJM).

that is forced to flow through or around the part surfaces and edges. The polymer has the consistency of putty. Silicon carbide is a typical abrasive. Abrasive flow machining (AFM) is particularly well-suited for internal passageways that are often inaccessible by conventional methods. The abrasive-polymer mixture, called the media, flows past the target regions of the part under pressures ranging from 0.7 to 20 MPa (100–3000 lb/in^2). In addition to deburring and polishing, other AFM applications include forming radii on sharp edges, removing rough surfaces on castings, and other finishing operations. These applications are found in industries such as aerospace, automotive, and die-making. The process can be automated to economically finish hundreds of parts per hour.

A common setup is to position the work part between two opposing cylinders, one containing media and the other empty. The media is forced to flow through the part from the first cylinder to the other, and then back again, as many times as necessary to achieve the desired material removal and finish.

25.2 Electrochemical Machining Processes

An important group of nontraditional processes use electrical energy to remove material. This group is identified by the term ***electrochemical processes***, because electrical energy is used in combination with chemical reactions to accomplish material removal. In effect, these processes are the reverse of electroplating (Section 27.3.1). The work material must be a conductor in the electrochemical machining processes.

25.2.1 ELECTROCHEMICAL MACHINING

The basic process in this group is electrochemical machining (ECM). Electrochemical machining removes metal from an electrically conductive workpiece by anodic dissolution, in which the shape of the workpiece is obtained by a formed electrode tool in close proximity to, but separated from, the work by a rapidly flowing electrolyte. ECM is basically a deplating operation. As illustrated in Figure 25.4, the workpiece is the anode, and the tool is the cathode. The principle underlying the process is that material

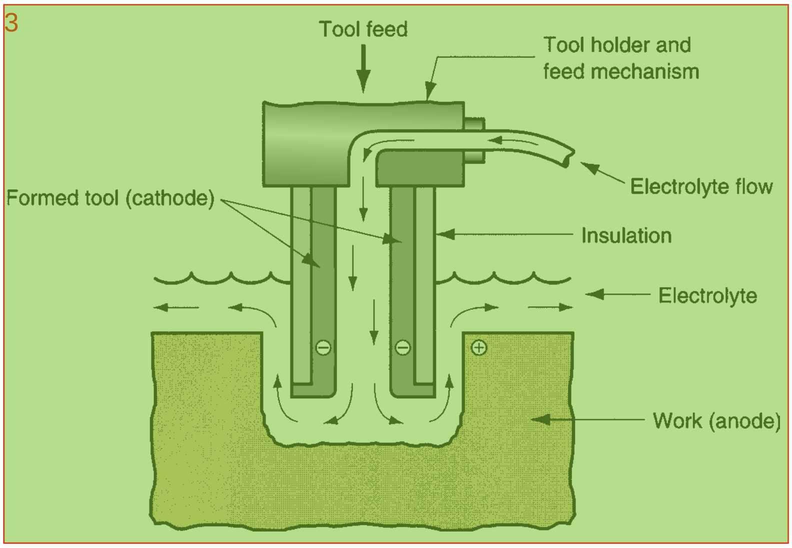


FIGURE 25.4 Electrochemical machining (ECM).

is deplated from the anode (the positive pole) and deposited onto the cathode (the negative pole) in the presence of an electrolyte bath (Section 4.5). The difference in ECM is that the electrolyte bath flows rapidly between the two poles to carry off the deplated material, so that it does not become plated onto the tool.

The electrode tool, usually made of copper, brass, or stainless steel, is designed to possess approximately the inverse of the desired final shape of the part. An allowance in the tool size must be provided for the gap that exists between the tool and the work. To accomplish metal removal, the electrode is fed into the work at a rate equal to the rate of metal removal from the work. Metal removal rate is determined by Faraday's First Law, which states that the amount of chemical change produced by an electric current (i.e., the amount of metal dissolved) is proportional to the quantity of electricity passed (current $\times$ time):

$$V = CIt \tag{25.1}$$

where V = volume of metal removed, mm^3 (in^3); C = a constant called the specific removal rate that depends on atomic weight, valence, and density of the work material, mm^3/amp- s (in^3/amp-min); I = current, amps; and t = time, s (min).

Based on Ohm's law, current $I = E/R$, where E = voltage and R = resistance. Under the conditions of the ECM operation, resistance is given by

$$R = \frac{gr}{A} \tag{25.2}$$

where g = gap between electrode and work, mm (in); r = resistivity of electrolyte, ohm-mm (ohm-in); and A = surface area between work and tool in the working frontal gap, mm^2 (in^2). Substituting this expression for R into Ohm's law,

$$I = \frac{EA}{gr} \tag{25.3}$$

And substituting this equation back into the equation defining Faraday's law,

$$V = \frac{C(EAt)}{gr} \tag{25.4}$$

It is convenient to convert this equation into an expression for feed rate, the rate at which the electrode (tool) can be advanced into the work. This conversion can be accomplished in two steps. First, divide both sides of Equation (25.4) by At (area $\times$ time) to convert volume of metal removed into a linear travel rate:

$$\frac{V}{At} = f_r = \frac{CE}{gr} \tag{25.5}$$

where f_r = feed rate, mm/s (in/min). Second, substitute I/A in place of $E/(gr)$, as provided by Equation (25.3). Thus, feed rate in ECM is

$$f_r = \frac{CI}{A} \tag{25.6}$$

where A = the frontal area of the electrode, mm^2 (in^2). This is the projected area of the tool in the direction of the feed into the work. Values of specific removal rate C are presented in Table 25.1 for various work materials. Note that this equation assumes 100% efficiency of metal removal. The actual efficiency is in the range 90% to 100% and depends on tool shape, voltage and current density, and other factors.

TABLE • 25.1 Typical values of specific removal rate C for selected work materials in electrochemical machining.

Work Material[a]	Specific Removal Rate C mm³/amp-sec	Specific Removal Rate C in³/amp-min	Work Material[a]	Specific Removal Rate C mm³/amp-sec	Specific Removal Rate C in³/amp-min
Aluminum (3)	3.44×10^{-2}	1.26×10^{-4}	Steels:		
Copper (1)	7.35×10^{-2}	2.69×10^{-4}	Low alloy	3.0×10^{-2}	1.1×10^{-4}
Iron (2)	3.69×10^{-2}	1.35×10^{-4}	High alloy	2.73×10^{-2}	1.0×10^{-4}
Nickel (2)	3.42×10^{-2}	1.25×10^{-4}	Stainless	2.46×10^{-2}	0.9×10^{-4}
			Titanium (4)	2.73×10^{-2}	1.0×10^{-4}

Compiled from data in [8].

[a]Most common valence given in parentheses () is assumed in determining specific removal rate C. For different valence, multiply C by most common valence and divide by actual valence.

Example 25.1 Electrochemical machining

An ECM operation is to be used to cut a hole into a plate of aluminum that is 12 mm thick. The hole has a rectangular cross section, 10 mm by 30 mm. The ECM operation will be accomplished at a current = 1200 amps. Efficiency is expected to be 95%. Determine feed rate and time required to cut through the plate.

Solution From Table 25.1, specific removal rate C for aluminum = 3.44×10^{-2} mm³/A-s. The frontal area of the electrode A = 10 mm × 30 mm = 300 mm². At a current level of 1200 amps, feed rate is

$$f_r = 0.0344 \text{ mm}^3/\text{A-s} = 0.1376 \text{ mm/s}$$

At an efficiency of 95%, the actual feed rate is

$$f_r = 0.1376 \text{ mm/s } (0.95) = \mathbf{0.1307 \text{ mm/s}}$$

Time to machine through the 12-mm plate is

$$T_m = \frac{12.0}{0.1307} = 91.8 \text{ s} = \mathbf{1.53 \text{ min}}$$

The preceding equations indicate the important process parameters for determining metal removal rate and feed rate in electrochemical machining: gap distance g, electrolyte resistivity r, current I, and electrode frontal area A. Gap distance needs to be controlled closely. If g becomes too large, the electrochemical process slows down. However, if the electrode touches the work, a short circuit occurs, which stops the process altogether. As a practical matter, gap distance is usually maintained within a range 0.075 to 0.75 mm (0.003–0.030 in).

Water is used as the base for the electrolyte in ECM. To reduce electrolyte resistivity, salts such as NaCl or $NaNO_3$ are added in solution. In addition to carrying off the material that has been removed from the workpiece, the flowing electrolyte also serves the function of removing heat and hydrogen bubbles created in the chemical reactions of the process. The removed work material is in the form of microscopic particles that must be separated from the electrolyte through centrifuge, sedimentation, or other means. The separated particles form a thick sludge whose disposal is an environmental problem associated with ECM.

Large amounts of electrical power are required to perform ECM. As the equations indicate, rate of metal removal is determined by electrical power, specifically the current density that can be supplied to the operation. The voltage in ECM is kept relatively low to minimize arcing across the gap.

Electrochemical machining is generally used in applications in which the work metal is very hard or difficult to machine, or the work part geometry is difficult (or impossible) to accomplish by conventional machining methods. Work hardness makes no difference in ECM, because the metal removal is not mechanical. Typical ECM applications include (1) ***die sinking***, which involves the machining of irregular shapes and contours into forging dies, plastic molds, and other shaping tools; (2) multiple hole drilling, in which many holes can be drilled simultaneously with ECM and conventional drilling would probably require the holes to be made sequentially; (3) holes that are not round, because ECM does not use a rotating drill; and (4) deburring.

Advantages of ECM include (1) little surface damage to the work part, (2) no burrs as in conventional machining, (3) low tool wear (the only tool wear results from the flowing electrolyte), and (4) relatively high metal removal rates for hard and difficult-to-machine metals. Disadvantages of ECM are (1) significant cost of electrical power to drive the operation and (2) problems of disposing of the electrolyte sludge.

25.2.2 ELECTROCHEMICAL DEBURRING AND GRINDING

Electrochemical deburring (ECD) is an adaptation of ECM designed to remove burrs or to round sharp corners on metal work parts by anodic dissolution. One possible setup for ECD is shown in Figure 25.5. The hole in the work part has a sharp burr of the type that is produced in a conventional through-hole drilling operation. The electrode tool is designed to focus the metal removal action on the burr. Portions of the tool not being used for machining are insulated. The electrolyte flows through the hole to carry away the burr particles. The same ECM principles of operation also apply to ECD. However, since much less material is removed in electrochemical deburring, cycle times are much shorter. A typical cycle time in ECD is less than a minute. The time can be increased if it is desired to round the corner in addition to removing the burr.

Electrochemical grinding (ECG) is a special form of ECM in which a rotating grinding wheel with a conductive bond material is used to augment the anodic dissolution

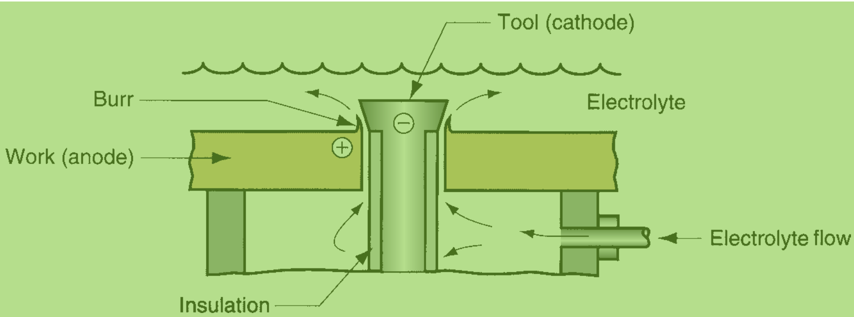


FIGURE 25.5 Electrochemical deburring (ECD).

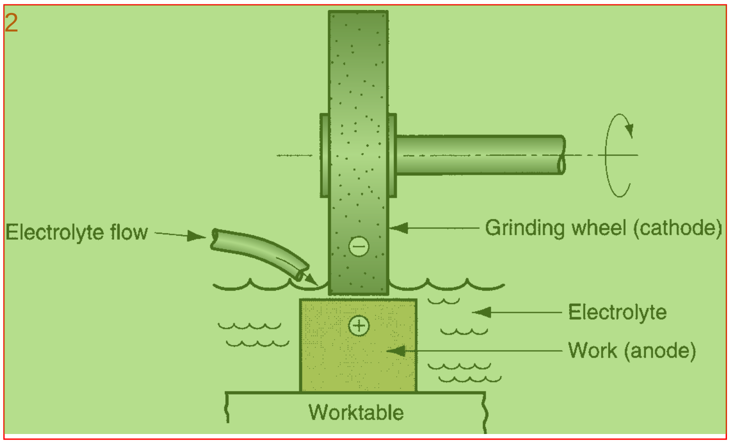


FIGURE 25.6 Electrochemical grinding (ECG).

of the metal work part surface, as illustrated in Figure 25.6. Abrasives used in ECG include aluminum oxide and diamond. The bond material is either metallic (for diamond abrasives) or resin bond impregnated with metal particles to make it electrically conductive (for aluminum oxide). The abrasive grits protruding from the grinding wheel at the contact with the work part establish the gap distance in ECG. The electrolyte flows through the gap between the grains to play its role in electrolysis.

Deplating is responsible for 95% or more of the metal removal in ECG, and the abrasive action of the grinding wheel removes the remaining 5% or less, mostly in the form of salt films that have been formed during the electrochemical reactions at the work surface. Because most of the machining is accomplished by electrochemical action, the grinding wheel in ECG lasts much longer than a wheel in conventional grinding. The result is a much higher grinding ratio. In addition, dressing of the grinding wheel is required much less frequently. These are the significant advantages of the process. Applications of ECG include sharpening of cemented carbide tools and grinding of surgical needles, other thin wall tubes, and fragile parts.

25.3 Thermal Energy Processes

Material removal processes based on thermal energy are characterized by very high local temperatures—hot enough to remove material by fusion or vaporization. Because of the high temperatures, these processes cause physical and metallurgical damage to the new work surface. In some cases, the resulting finish is so poor that subsequent processing is required to smooth the surface. This section examines several thermal energy processes that are commercially important: (1) electric discharge machining and electric discharge wire cutting, (2) electron beam machining, (3) laser beam machining, (4) arc cutting processes, and (5) oxyfuel cutting processes.

25.3.1 ELECTRIC DISCHARGE PROCESSES

Electric discharge processes remove metal by a series of discrete electrical discharges (sparks) that cause localized temperatures high enough to melt or vaporize the metal in the immediate vicinity of the discharge. The two main processes in this category are (1) electric discharge machining and (2) wire electric discharge machining. These processes can be used only on electrically conducting work materials.

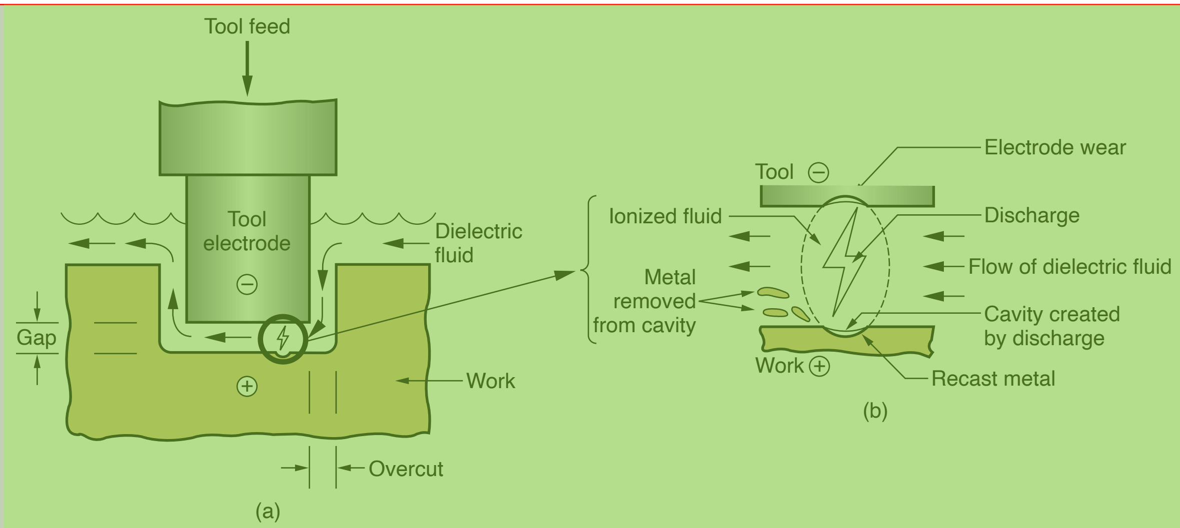
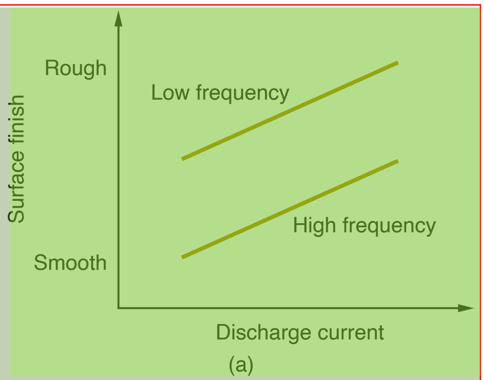


FIGURE 25.7 Electric discharge machining (EDM): (a) overall setup, and (b) close-up view of gap, showing discharge and metal removal.

Electric Discharge Machining Electric discharge machining (EDM) is one of the most widely used nontraditional processes. An EDM setup is illustrated in Figure 25.7. The shape of the finished work surface is produced by a formed electrode tool. The sparks occur across a small gap between tool and work surface. The EDM process must take place in the presence of a dielectric fluid, which creates a path for each discharge as the fluid becomes ionized in the gap. The discharges are generated by a pulsating direct current power supply connected to the work and the tool.

Figure 25.7(b) shows a close-up view of the gap between the tool and the work. The discharge occurs at the location where the two surfaces are closest. The dielectric fluid ionizes at this location to create a path for the discharge. The region in which discharge occurs is heated to extremely high temperatures, so that a small portion of the work surface is suddenly melted and removed. The flowing dielectric then flushes away the small particle (call it a "chip"). Because the surface of the work at the location of the previous discharge is now separated from the tool by a greater distance, this location is less likely to be the site of another spark until the surrounding regions have been reduced to the same level or below. Although the individual discharges remove metal at very localized points, they occur hundreds or thousands of times per second so that a gradual erosion of the entire surface occurs in the area of the gap.

Two important process parameters in EDM are discharge current and frequency of discharges. As either of these parameters is increased, metal removal rate increases. Surface roughness is also affected by current and frequency, as shown in Figure 25.8(a). The best surface finish is obtained in EDM by operating at high frequencies and low discharge currents. As the electrode tool penetrates into the work, overcutting occurs. ***Overcut*** in EDM is the distance by which the machined cavity in the work part exceeds the size of the tool on each side of the tool, as illustrated in Figure 25.7(a). It is produced because the electrical discharges occur at the sides of the tool as well as its frontal area. Overcut is a function of current and frequency, as seen in Figure 25.8(b), and can amount to several hundredths of a millimeter.



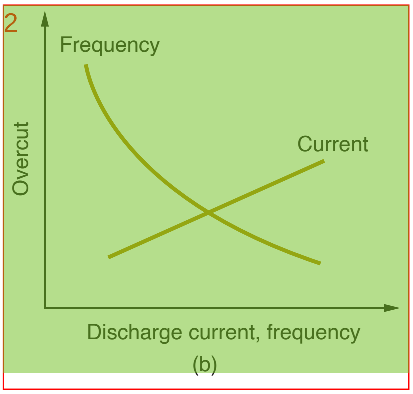


FIGURE 25.8 (a) Surface finish in EDM as a function of discharge current and frequency of discharges. (b) Overcut in EDM as a function of discharge current and frequency of discharges.

The high spark temperatures that melt the work also melt the tool, creating a small cavity in the surface opposite the cavity produced in the work. Tool wear is usually measured as the ratio of work material removed to tool material removed (similar to the grinding ratio). This wear ratio ranges between 1.0 and 100 or slightly above, depending on the combination of work and electrode materials. Electrodes are made of graphite, copper, brass, copper tungsten, silver tungsten, and other materials. The selection depends on the type of power supply circuit available on the EDM machine, the type of work material that is to be machined, and whether roughing or finishing is to be done. Graphite is preferred for many applications because of its melting characteristics. In fact, graphite does not melt. It vaporizes at very high temperatures, and the cavity created by the spark is generally smaller than for most other EDM electrode materials. Consequently, a high ratio of work material removed to tool wear is usually obtained with graphite tools.

The hardness and strength of the work material are not factors in EDM, because the process is not a contest of hardness between tool and work. The melting point of the work material is an important property, and metal removal rate can be related to melting point approximately by the following empirical formula, based on an equation described in Weller [18]:

$$R_{MR} = \frac{KI}{T_m^{1.23}} \tag{25.7}$$

where R_{MR} = metal removal rate, mm³/s (in³/min); K = constant of proportionality whose value = 664 in SI units (5.08 in U.S. customary units); I = discharge current, amps; and T_m = melting temperature of work metal, °C (°F). Melting points of selected metals are listed in Table 4.1.

Example 25.2 Electric discharge machining

Copper is to be machined in an EDM operation. If discharge current = 25 amps, what is the expected metal removal rate?

Solution From Table 4.1, the melting point of copper is found to be 1083°C. Using Equation (25.7), the anticipated metal removal rate is

$$R_{MR} = \frac{664(25)}{1083^{1.23}} = \mathbf{3.07\ mm^3/s}$$

Dielectric fluids used in EDM include hydrocarbon oils, kerosene, and distilled or deionized water. The dielectric fluid serves as an insulator in the gap except when ionization occurs in the presence of a spark. Its other functions are to flush debris out of the gap and remove heat from tool and work part.

Applications of electric discharge machining include both tool fabrication and parts production. The tooling for many of the mechanical processes discussed in this book are often made by EDM, including molds for plastic injection molding, extrusion dies, wire drawing dies, forging and heading dies, and sheet metal stamping dies. As in ECM, the term ***die sinking*** is used for operations in which a mold cavity is produced, and the EDM process is sometimes referred to as ***ram EDM***. For many of the applications, the materials used to fabricate the tooling are difficult (or impossible) to machine by conventional methods. Certain production parts also call for application of EDM. Examples include delicate parts that are not rigid enough to withstand conventional cutting forces, hole drilling where the axis of the hole is at an acute angle to the surface so that a conventional drill would be unable to start the hole, and production machining of hard and exotic metals.

Electric Discharge Wire Cutting Electric discharge wire cutting (EDWC), commonly called ***wire EDM***, is a special form of electric discharge machining that uses a small diameter wire as the electrode to cut a narrow kerf in the work. The cutting action in wire EDM is achieved by thermal energy from electric discharges between the electrode wire and the workpiece. Wire EDM is illustrated in Figure 25.9. The workpiece is fed past the wire to achieve the desired cutting path, somewhat in the manner of a bandsaw operation. Numerical control is used to control the work part motions during cutting. As it cuts, the wire is slowly and continuously advanced between a supply spool and a take-up spool to present a fresh electrode of constant diameter to the work. This helps to maintain a constant kerf width during cutting. As in EDM, wire EDM must be carried out in the presence of a dielectric. This is applied by nozzles directed at the tool–work interface as in the figure, or the work part is submerged in a dielectric bath.

Wire diameters range from 0.076 to 0.30 mm (0.003–0.012 in), depending on required kerf width. Materials used for the wire include brass, copper, tungsten, and molybdenum. Dielectric fluids include deionized water or oil. As in EDM, an overcut exists in wire EDM that makes the kerf larger than the wire diameter, as shown

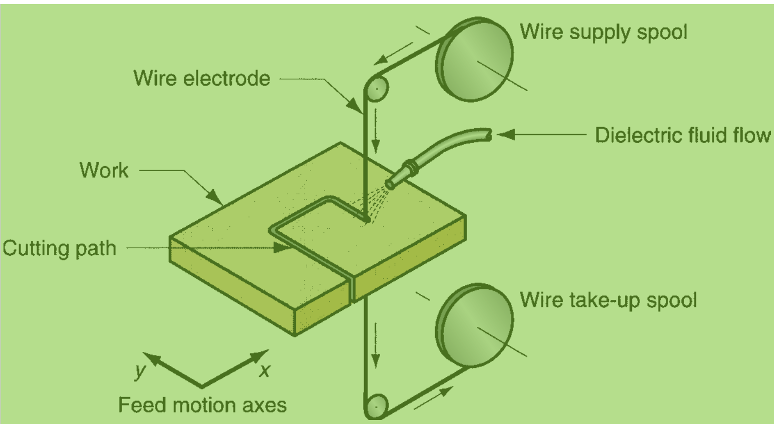


FIGURE 25.9 Electric discharge wire cutting (EDWC), also called wire EDM.

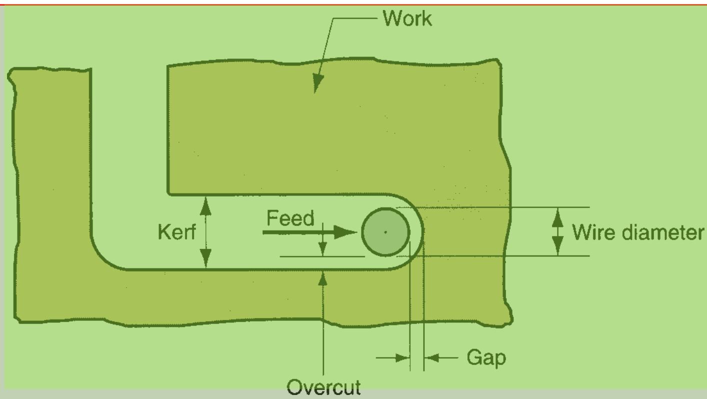


FIGURE 25.10 Definition of kerf and overcut in electric discharge wire cutting.

in Figure 25.10. This overcut is in the range 0.020 to 0.050 mm (0.0008–0.002 in). Once cutting conditions have been established for a given cut, the overcut remains fairly constant and predictable.

Although EDWC seems similar to a bandsaw operation, its precision far exceeds that of a bandsaw. The kerf is much narrower, corners can be made much sharper, and the cutting forces against the work are nil. In addition, hardness and toughness of the work material do not affect cutting performance. The only requirement is that the work material must be electrically conductive.

The special features of wire EDM make it ideal for making components for stamping dies. Because the kerf is so narrow, it is often possible to fabricate punch and die in a single cut, as suggested by Figure 25.11. Other tools and parts with

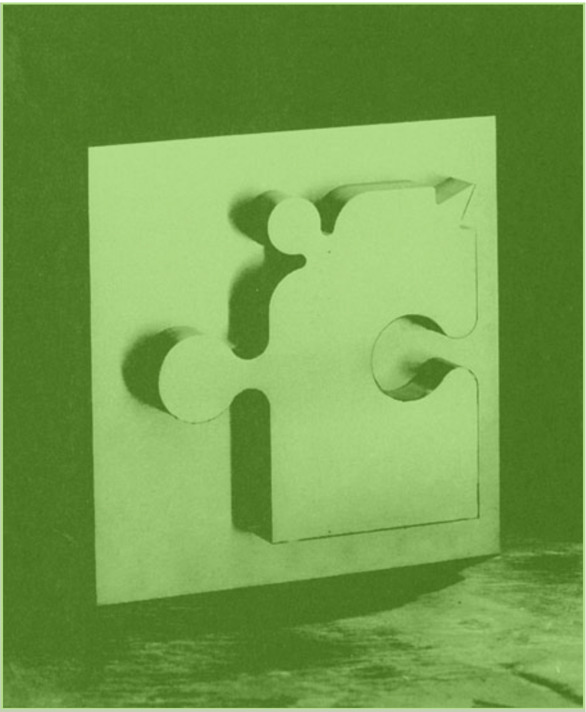


FIGURE 25.11 Irregular outline cut from a solid metal slab by wire EDM. (Photo courtesy of Makino.)

intricate outline shapes, such as lathe form tools, extrusion dies, and flat templates, are made with electric discharge wire cutting.

25.3.2 ELECTRON BEAM MACHINING

Electron beam machining (EBM) is one of several industrial processes that use electron beams. Besides machining, other applications of the technology include heat treating (Section 26.5.2) and welding (Section 29.4). ***Electron beam machining*** uses a high velocity stream of electrons focused on the workpiece surface to remove material by melting and vaporization. A schematic of the EBM process is illustrated in Figure 25.12. An electron beam gun generates a continuous stream of electrons that is accelerated to approximately 75% of the speed of light and focused through an electromagnetic lens on the work surface. The lens is capable of reducing the area of the beam to a diameter as small as 0.025 mm (0.001 in). On impinging the surface, the kinetic energy of the electrons is converted into thermal energy of extremely high density that melts or vaporizes the material in a very localized area.

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 (0.002 in) diameter, drilling of holes with very high depth-to-diameter ratios—more than 100:1, and cutting of slots that are only about 0.001 in (0.025 mm) wide. These cuts can be made to very close tolerances with no cutting forces or tool wear. The process is ideal for micromachining and is generally limited to cutting operations in thin parts—in the range 0.25 to 6.3 mm (0.010–0.250 in) thick. EBM must be carried out in a vacuum chamber to eliminate collision of the electrons with gas molecules. Other limitations include the high energy required and expensive equipment.

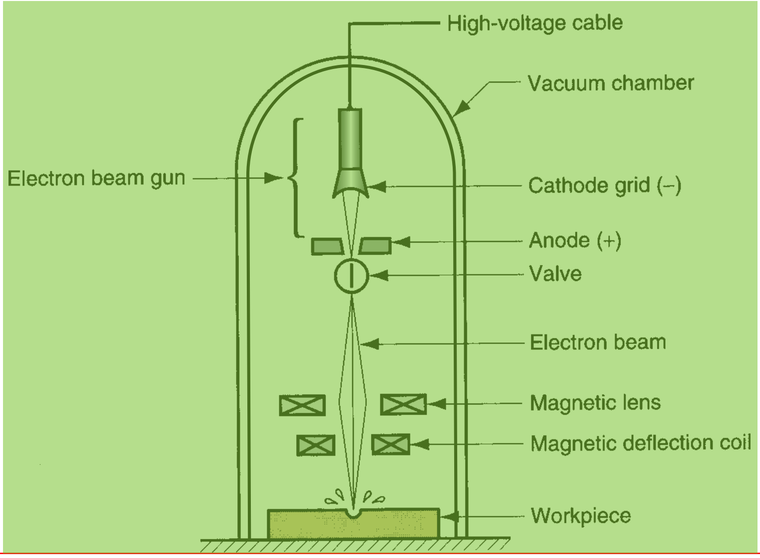


FIGURE 25.12 Electron beam machining (EBM).

25.3.3 LASER BEAM MACHINING

Lasers are being used for a variety of industrial applications, including heat treatment (Section 26.5.2), welding (Section 29.4), rapid prototyping (Section 32.2), measurement (Section 40.6.2), as well as scribing, cutting, and drilling (described here). The term ***laser*** stands for ***l***ight ***a***mplification by ***s***timulated ***e***mission of ***r***adiation. A laser is an optical transducer that converts electrical energy into a highly coherent light beam. A laser light beam has several properties that distinguish it from other forms of light. It is monochromatic (theoretically, the light has a single wave length) and highly collimated (the light rays in the beam are almost perfectly parallel). These properties allow the light generated by a laser to be focused, using conventional optical lenses, onto a very small spot with resulting high power densities. Depending on the amount of energy contained in the light beam, and its degree of concentration at the spot, the various laser processes identified above can be accomplished.

Laser beam machining (LBM) uses the light energy from a laser to remove material by vaporization and ablation. The setup for LBM is illustrated in Figure 25.13. The types of lasers used in LBM are carbon dioxide gas lasers and solid-state lasers (of which there are several types). In laser beam machining, the energy of the coherent light beam is concentrated not only optically but also in terms of time. The light beam is pulsed so that the released energy results in an impulse against the work surface that produces a combination of evaporation and melting, with the melted material evacuating the surface at high velocity.

LBM is used to perform various types of drilling, slitting, slotting, scribing, and marking operations. Drilling small diameter holes is possible—down to 0.025 mm (0.001 in). For larger holes, above 0.50-mm (0.020-in) diameter, the laser beam is controlled to cut the outline of the hole. LBM is not considered a mass production process, and it is generally used on thin stock. The range of work materials that can be machined by LBM is virtually unlimited. Ideal properties of a material for LBM

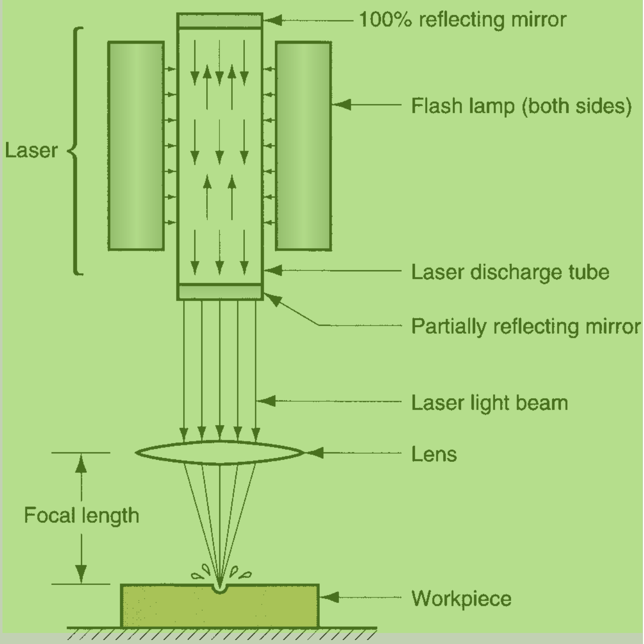


FIGURE 25.13 Laser beam machining (LBM).

FIGURE 25.14 Parts produced by laser beam machining. The model bicycles on the right are about 20 mm (0.8 in) long. (Courtesy of George E. Kane Manufacturing Technology Laboratory, Lehigh University.)

include high light energy absorption, poor reflectivity, good thermal conductivity, low specific heat, low heat of fusion, and low heat of vaporization. Of course, no material has this ideal combination of properties. The actual list of work materials processed by LBM includes metals with high hardness and strength, soft metals, ceramics, glass and glass epoxy, plastics, rubber, cloth, and wood. Figure 25.14 shows several parts cut by LBM.

25.3.4 ARC-CUTTING PROCESSES

The intense heat from an electric arc can be used to melt virtually any metal for the purpose of welding or cutting. Most arc-cutting processes use the heat generated by an arc between an electrode and a metallic work part (usually a flat plate or sheet) to melt a kerf that separates the part. The most common arc-cutting processes are (1) plasma arc cutting and (2) air carbon arc cutting [11].

Plasma Arc Cutting A ***plasma*** is a superheated, electrically ionized gas. Plasma arc cutting (PAC) uses a plasma stream operating at temperatures in the range 10,000°C to 14,000°C (18,000°F–25,000°F) to cut metal by melting, as shown in Figure 25.15. The cutting action operates by directing the high-velocity plasma stream at the work, thus melting it and blowing the molten metal through the kerf. The plasma arc is generated between an electrode inside the torch and the anode workpiece. The plasma flows through a water-cooled nozzle that constricts and directs the stream to the desired location on the work. The resulting plasma jet is a high-velocity, well-collimated stream with extremely high temperatures at its center, hot enough to cut through metal in some cases 150 mm (6 in) thick.

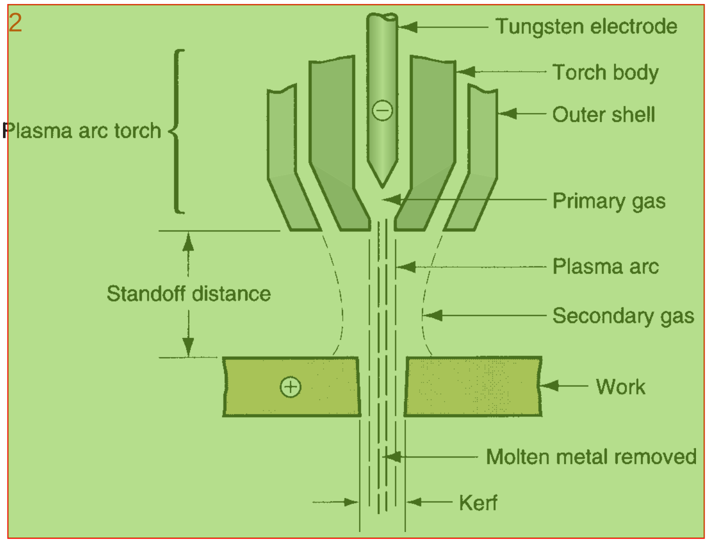


FIGURE 25.15 Plasma arc cutting (PAC).

Gases used to create the plasma in PAC include nitrogen, argon, hydrogen, or mixtures of these gases. These are referred to as the primary gases in the process. Secondary gases or water are often directed to surround the plasma jet to help confine the arc and clean the kerf of molten metal as it forms.

Most applications of PAC involve cutting of flat metal sheets and plates. Operations include hole piercing and cutting along a defined path. The desired path can be cut either by use of a hand-held torch manipulated by a human operator, or by directing the cutting path of the torch under numerical control (NC). For faster production and higher accuracy, NC is preferred because of better control over the important process variables such as standoff distance and feed rate. Plasma arc cutting can be used to cut nearly any electrically conductive metal. Metals frequently cut by PAC include plain carbon steel, stainless steel, and aluminum. The advantage of NC in these applications is high productivity. Feed rates along the cutting path can be as high as 200 mm/s (450 in/min) for 6-mm (0.25-in) aluminum plate and 85 mm/s (200 in/min) for 6-mm (0.25-in) steel plate [8]. Feed rates must be reduced for thicker stock. For example, the maximum feed rate for cutting 100-mm- (4-in)-thick aluminum stock is around 8 mm/s (20 in/min) [8]. Disadvantages of PAC are (1) the cut surface is rough, and (2) metallurgical damage at the surface is the most severe among the nontraditional metalworking processes.

Air Carbon Arc Cutting In this process, the arc is generated between a carbon electrode and the metallic work, and a high-velocity air jet is used to blow away the melted portion of the metal. This procedure can be used to form a kerf for severing the piece, or to gouge a cavity in the part. Gouging is used to prepare the edges of plates for welding, for example to create a U-groove in a butt joint (Section 28.2.1). Air carbon arc cutting is used on a variety of metals, including cast iron, carbon steel, low alloy, and stainless steels, and various nonferrous alloys. Spattering of the molten metal is a hazard and a disadvantage of the process.

Other Arc-Cutting Processes Various other electric arc processes are used for cutting applications, although not as widely as plasma arc and air carbon arc cutting.

These other processes include (1) gas metal arc cutting, (2) shielded metal arc cutting, (3) gas tungsten arc cutting, and (4) carbon arc cutting. The technologies are the same as those used in arc welding (Section 29.1), except that the heat of the electric arc is used for cutting.

25.3.5 OXYFUEL-CUTTING PROCESSES

A widely used family of thermal cutting processes, popularly known as ***flame cutting***, use the heat of combustion of certain fuel gases combined with the exothermic reaction of the metal with oxygen. The cutting torch used in these processes is designed to deliver a mixture of fuel gas and oxygen in the proper amounts, and to direct a stream of oxygen to the cutting region. The primary mechanism of material removal in oxyfuel cutting (OFC) is the chemical reaction of oxygen with the base metal. The purpose of the oxyfuel combustion is to raise the temperature in the region of cutting to support the reaction. These processes are commonly used to cut ferrous metal plates, in which the rapid oxidation of iron occurs according to the following reactions [11]:

$$Fe + O \rightarrow FeO + heat \tag{25.8a}$$

$$3Fe + 2O_2 \rightarrow Fe_3O_4 + heat \tag{25.8b}$$

$$2Fe + 1.5O_2 \rightarrow Fe_2O_3 + heat \tag{25.8c}$$

The second of these reactions, Equation (25.8b), is the most significant in terms of heat generation.

The cutting mechanism for nonferrous metals is somewhat different. These metals are generally characterized by lower melting temperatures than the ferrous metals, and they are more oxidation resistant. In these cases, the heat of combustion of the oxyfuel mixture plays a more important role in creating the kerf. Also, to promote the metal oxidation reaction, chemical fluxes or metallic powders are often added to the oxygen stream.

Fuels used in OFC include acetylene (C_2H_2), MAPP (methylacetylene-propadiene—C_3H_4), propylene (C_3H_6), and propane (C_3H_8). Flame temperatures and heats of combustion for these fuels are listed in Table 29.2. Acetylene burns at the highest flame temperature and is the most widely used fuel for welding and cutting. However, there are certain hazards with the storage and handling of acetylene that must be considered (Section 29.3.1).

OFC processes are performed either manually or by machine. Manually operated torches are used for repair work, cutting of scrap metal, trimming of risers from sand castings, and similar operations that generally require minimal accuracy. For production work, machine flame cutting allows faster speeds and greater accuracies. This equipment is often numerically controlled to allow profiled shapes to be cut.

25.4 Chemical Machining

Chemical machining (CHM) is a nontraditional process in which material is removed by means of a strong chemical etchant. Applications as an industrial process began shortly after World War II in the aircraft industry. The use of chemicals to remove unwanted material from a work part can be accomplished in several ways, and different terms have been developed to distinguish the applications. These terms include chemical milling, chemical blanking, chemical engraving, and photochemical machining (PCM). They all use the same mechanism of material removal, and it is appropriate to discuss the general characteristics of chemical machining before defining the individual processes.

25.4.1 MECHANICS AND CHEMISTRY OF CHEMICAL MACHINING

The chemical machining process consists of several steps. Differences in applications and the ways in which the steps are implemented account for the different forms of CHM. The steps are:

1. ***Cleaning***. The first step is a cleaning operation to ensure that material will be removed uniformly from the surfaces to be etched.
2. ***Masking***. A protective coating called a maskant is applied to certain portions of the part surface. This maskant is made of a material that is chemically resistant to the etchant (the term ***resist*** is used for this masking material). It is therefore applied to those portions of the work surface that are not to be etched.
3. ***Etching***. This is the material removal step. The part is immersed in an etchant that chemically attacks those portions of the part surface that are not masked. The usual method of attack is to convert the work material (e.g., a metal) into a salt that dissolves in the etchant and is thereby removed from the surface. When the desired amount of material has been removed, the part is withdrawn from the etchant and washed to stop the process.
4. ***Demasking***. The maskant is removed from the part.

The two steps in chemical machining that involve significant variations in methods, materials, and process parameters are masking and etching—steps 2 and 3.

Maskant materials include neoprene, polyvinylchloride, polyethylene, and other polymers. Masking can be accomplished by any of three methods: (1) cut and peel, (2) photographic resist, and (3) screen resist. The ***cut and peel*** method applies the maskant over the entire part by dipping, painting, or spraying. The resulting thickness of the maskant is 0.025 to 0.125 mm (0.001–0.005 in). After the maskant has hardened, it is cut using a scribing knife and peeled away in the areas of the work surface that are to be etched. The maskant cutting operation is performed by hand, usually guiding the knife with a template. The cut and peel method is generally used for large work parts, low production quantities, and where accuracy is not a critical factor. This method cannot hold tolerances tighter than ± 0.125 mm (± 0.005 in) except with extreme care.

As the name suggests, the ***photographic resist*** method (called the ***photoresist*** method for short) uses photographic techniques to perform the masking step. The masking materials contain photosensitive chemicals. They are applied to the work surface and exposed to light through a negative image of the desired areas to be etched. These areas of the maskant can then be removed from the surface using photographic developing techniques. This procedure leaves the desired surfaces of the part protected by the maskant and the remaining areas unprotected, vulnerable to chemical etching. Photoresist masking techniques are normally applied where small parts are produced in high quantities, and close tolerances are required. Tolerances closer than ± 0.0125 mm (± 0.0005 in) can be held [18].

The ***screen resist*** method applies the maskant by means of silk screening methods. In these methods, the maskant is painted onto the work part surface through a silk

TABLE • 25.2 Common work materials and etchants in CHM, with typical penetration rates and etch factors.

Work Material	Etchant	Penetration Rates mm/min	Penetration Rates in/min	Etch Factor
Aluminum and alloys	$FeCl_3$	0.020	0.0008	1.75
	$NaOH$	0.025	0.001	1.75
Copper and alloys	$FeCl_3$	0.050	0.002	2.75
Magnesium and alloys	H_2SO_4	0.038	0.0015	1.0
Silicon	$HNO_3 : HF : H_2O$	very slow		NA
Mild steel	$HCl:HNO_3$	0.025	0.001	2.0
	$FeCl_3$	0.025	0.001	2.0
Titanium and alloys	HF	0.025	0.001	1.0
	$HF : HNO_3$	0.025	0.001	1.0

Compiled from [5], [8], and [18].
NA = data not available.

or stainless steel mesh. Embedded in the mesh is a stencil that protects those areas to be etched from being painted. The maskant is thus painted onto the work areas that are not to be etched. The screen resist method is generally used in applications that are between the other two masking methods in terms of accuracy, part size, and production quantities. Tolerances of ±0.075 mm (±0.003 in) can be achieved with this masking method.

Selection of the ***etchant*** depends on work material to be etched, desired depth and rate of material removal, and surface finish requirements. The etchant must also be matched with the type of maskant that is used to ensure that the maskant material is not chemically attacked by the etchant. Table 25.2 lists some of the work materials machined by CHM together with the etchants that are generally used on these materials. Also included in the table are penetration rates and etch factors. These parameters are explained next.

Material removal rates in CHM are generally indicated as penetration rates, mm/min (in/min), because rate of chemical attack of the work material by the etchant is directed into the surface. The penetration rate is unaffected by surface area. Penetration rates listed in Table 25.2 are typical values for the given material and etchant.

Depths of cut in chemical machining are as much as 12.5 mm (0.5 in) for aircraft panels made out of metal plates. However, many applications require depths that are only several hundredths of a millimeter. Along with the penetration into the work, etching also occurs sideways under the maskant, as illustrated in Figure 25.16. The

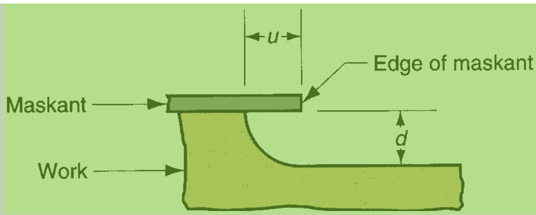


FIGURE 25.16
Undercut in chemical machining.

effect is referred to as the ***undercut***, and it must be accounted for in the design of the mask for the resulting cut to have the specified dimensions. For a given work material, the undercut is directly related to the depth of cut. The constant of proportionality for the material is called the etch factor, defined as

$$F_e = \frac{d}{u} \tag{25.9}$$

where F_e = etch factor; d = depth of cut, mm (in); and u = undercut, mm (in). The dimensions u and d are defined in Figure 25.16. Different work materials have different etch factors in chemical machining. Some typical values are presented in Table 25.2. The etch factor can be used to determine the dimensions of the cutaway areas in the maskant, so that the specified dimensions of the etched areas on the part can be achieved.

25.4.2 CHM PROCESSES

This section describes the principle chemical machining processes: (1) chemical milling, (2) chemical blanking, (3) chemical engraving, and (4) photochemical machining.

Chemical Milling Chemical milling was the first CHM process to be commercialized. During World War II, an aircraft company in the United States began to use chemical milling to remove metal from aircraft components. They referred to their process as the "chem-mill" process. Today, chemical milling is still used largely in the aircraft industry, to remove material from aircraft wing and fuselage panels for weight reduction. It is applicable to large parts where substantial amounts of metal are removed during the process. The cut and peel maskant method is employed. A template is generally used that takes into account the undercut that will result during etching. The sequence of processing steps is illustrated in Figure 25.17.

Chemical milling produces a surface finish that varies with different work materials. Table 25.3 provides a sampling of the values. Surface finish depends on depth of penetration. As depth increases, finish becomes worse, approaching the upper side of the ranges given in the table. Metallurgical damage from chemical milling is very small, perhaps around 0.005 mm (0.0002 in) into the work surface.

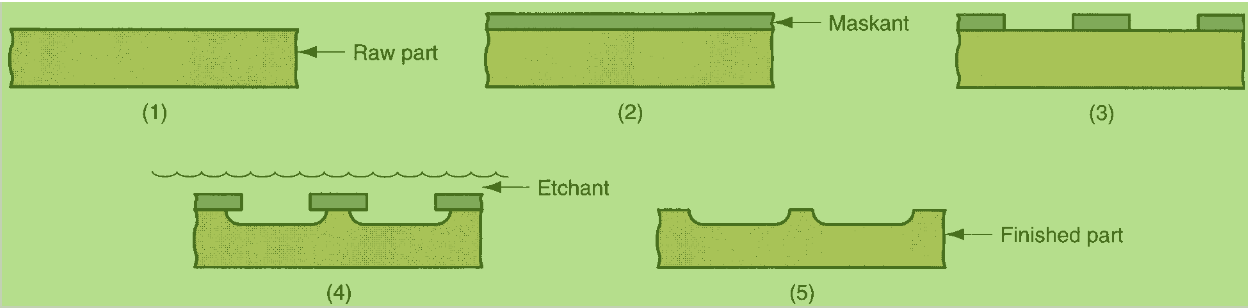


FIGURE 25.17 Sequence of processing steps in chemical milling: (1) clean raw part, (2) apply maskant, (3) scribe, cut, and peel the maskant from areas to be etched, (4) etch, and (5) remove maskant and clean to yield finished part.

TABLE • 25.3 Surface finishes expected in chemical milling.

Work Material	Surface Finishes Range μm	Surface Finishes Range μ-in
Aluminum and alloys	1.8–4.1	70–160
Magnesium	0.8–1.8	30–70
Mild steel	0.8–6.4	30–250
Titanium and alloys	0.4–2.5	15–100

Compiled from [8] and [18].

Chemical Blanking Chemical blanking uses chemical erosion to cut very thin sheetmetal parts—down to 0.025 mm (0.001 in) thick and/or for intricate cutting patterns. In both instances, conventional punch-and-die methods do not work because the stamping forces damage the sheet metal, or the tooling cost would be prohibitive, or both. Chemical blanking produces parts that are burr free, an advantage over conventional shearing operations.

Methods used for applying the maskant in chemical blanking are either the photoresist method or the screen resist method. For small and/or intricate cutting patterns and close tolerances, the photoresist method is used. Tolerances as close as ±0.0025 mm (±0.0001 in) can be held on 0.025-mm (0.001-in)-thick stock using the photoresist method of masking. As stock thickness increases, more generous tolerances must be allowed. Screen resist masking methods are not nearly so accurate as photoresist. The small work size in chemical blanking excludes the cut and peel maskant method.

Using the screen resist method to illustrate, the steps in chemical blanking are shown in Figure 25.18. Because chemical etching takes place on both sides of the part in chemical blanking, it is important that the masking procedure provides accurate registration between the two sides. Otherwise, the erosion into the part from opposite directions will not line up. This is especially critical with small part sizes and intricate patterns.

Application of chemical blanking is generally limited to thin materials and/or intricate patterns for reasons given above. Maximum stock thickness is around

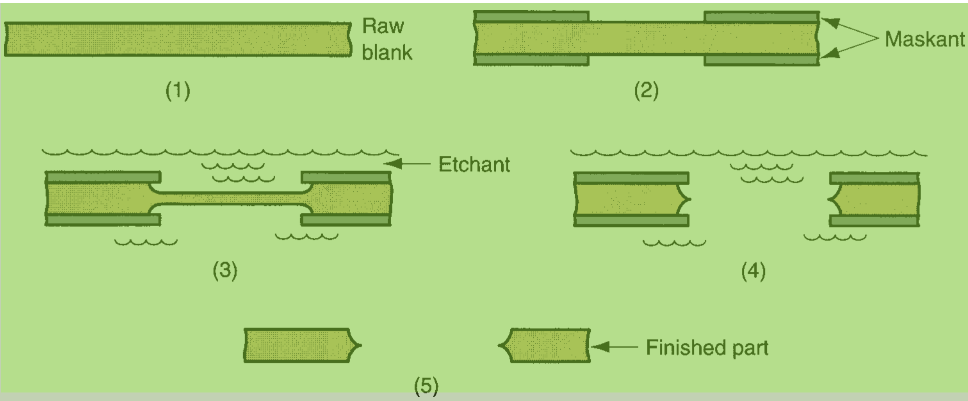


FIGURE 25.18 Sequence of processing steps in chemical blanking: (1) clean raw part, (2) apply resist (maskant) by painting through screen, (3) etch (partially completed), (4) etch (completed), and (5) remove resist and clean to yield finished part.

0.75 mm (0.030 in). Also, hardened and brittle materials can be processed by chemical blanking where mechanical methods would surely fracture the work.

Chemical Engraving Chemical engraving is a chemical machining process for making name plates and other flat panels that have lettering and/or artwork on one side. These plates and panels would otherwise be made using a conventional engraving machine or similar process. Chemical engraving can be used to make panels with either recessed lettering or raised lettering, simply by reversing the portions of the panel to be etched. Masking is done by either the photoresist or screen resist methods. The sequence in chemical engraving is similar to the other CHM processes, except that a filling operation follows etching. The purpose of filling is to apply paint or other coating into the recessed areas that have been created by etching. Then, the panel is immersed in a solution that dissolves the resist but does not attack the coating material. Thus, when the resist is removed, the coating remains in the etched areas but not in the areas that were masked. The effect is to highlight the pattern.

Photochemical Machining Photochemical machining (PCM) is chemical machining in which the photoresist method of masking is used. The term can therefore be applied correctly to chemical blanking and chemical engraving when these methods use the photographic resist method. PCM is employed in metalworking when close tolerances and/or intricate patterns are required on flat parts. Photochemical processes are also used extensively in the electronics industry to produce intricate circuit designs on semiconductor wafers (Section 33.3). Figure 25.19 shows several parts produced by photochemical blanking and photochemical engraving.

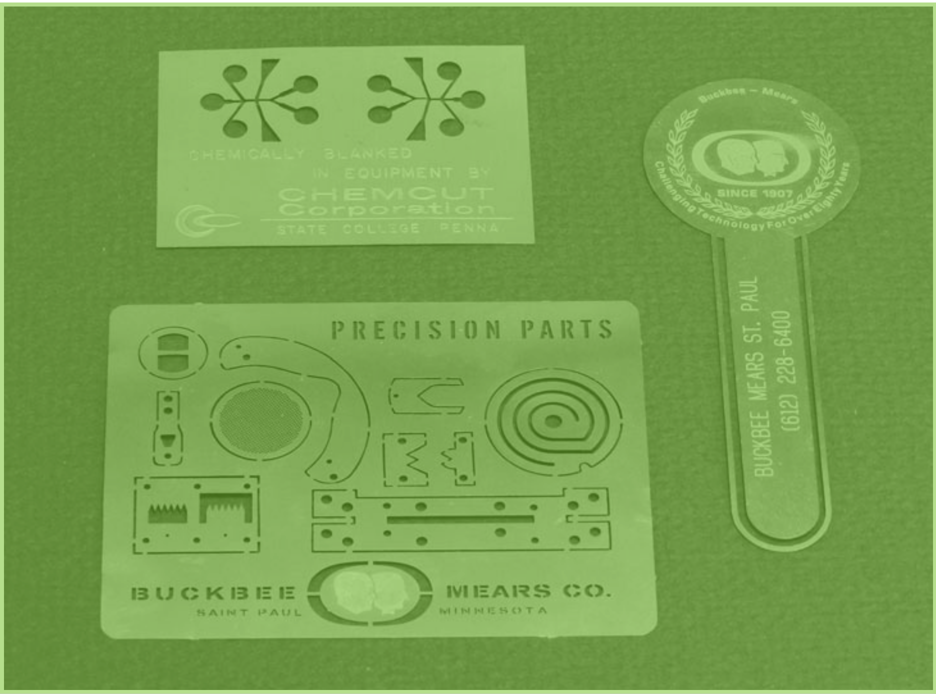


FIGURE 25.19 Parts made by photochemical blanking and photochemical engraving. (Courtesy of George E. Kane Manufacturing Technology Laboratory, Lehigh University.)

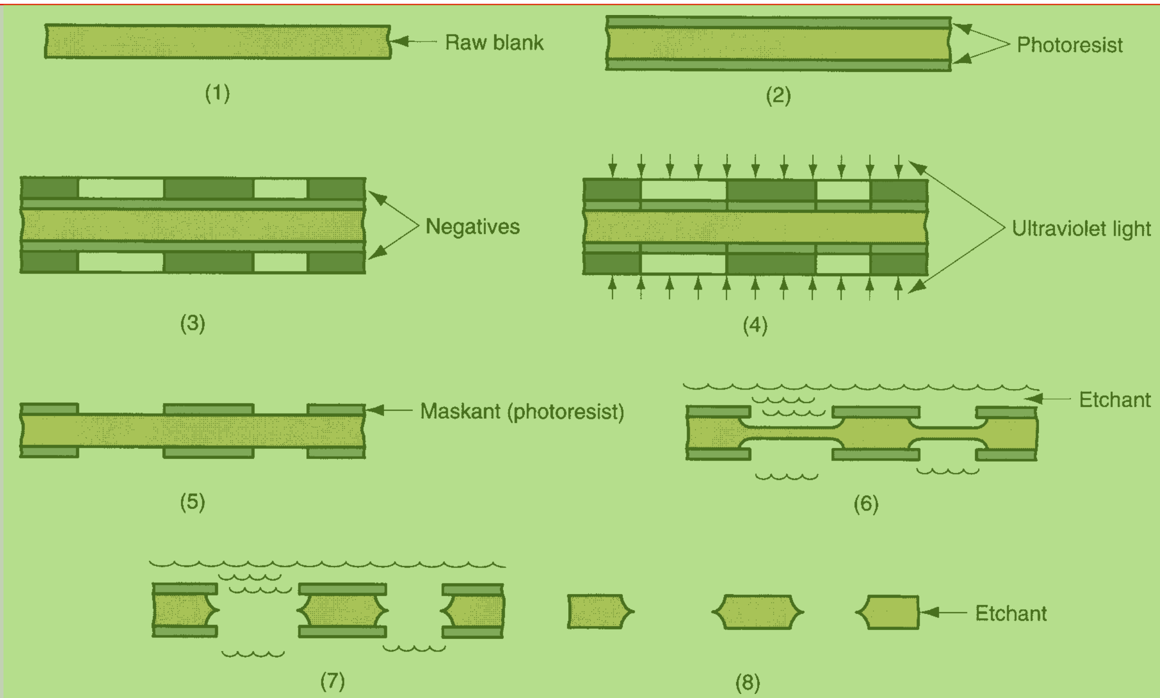


FIGURE 25.20 Sequence of processing steps in photochemical machining: (1) clean raw part, (2) apply resist (maskant) by dipping, spraying, or painting, (3) place negative on resist, (4) expose to ultraviolet light, (5) develop to remove resist from areas to be etched, (6) etch (shown partially etched), (7) etch (completed), (8) remove resist and clean to yield finished part.

Figure 25.20 shows the sequence of steps in photochemical machining as it is applied to chemical blanking. There are various ways to photographically expose the desired image onto the resist. The figure shows the negative in contact with the surface of the resist during exposure. This is contact printing, but other photographic printing methods are available that expose the negative through a lens system to enlarge or reduce the size of the pattern printed on the resist surface. Photoresist materials in current use are sensitive to ultraviolet light but not to light of other wavelengths. Therefore, with proper lighting in the factory, there is no need to carry out the processing steps in a dark room environment. Once the masking operation is accomplished, the remaining steps in the procedure are similar to the other chemical machining methods.

In photochemical machining, the term corresponding to etch factor is ***anisotropy***, which is defined as the depth of cut d divided by the undercut u (see Figure 25.16). This is the same definition as in Equation (25.9).

25.5 Application Considerations

Typical applications of nontraditional processes include special geometric features and work materials that cannot be readily processed by conventional techniques. This section examines these issues and summarizes the general performance characteristics of nontraditional processes.

TABLE • 25.4 Work part geometric features and appropriate nontraditional processes.

Geometric Feature	Likely Process
Very small holes. Diameters less than 0.125 mm (0.005 in), in some cases down to 0.025 mm (0.001 in), generally smaller than the diameter range of conventional drill bits.	EBM, LBM
Holes with large depth-to-diameter ratios, e.g., $d/D > 20$. Except for gun drilling, these holes cannot be machined in conventional drilling operations.	ECM, EDM
Holes that are not round. Nonround holes cannot be drilled with a rotating drill bit.	EDM, ECM
Narrow slots in slabs and plates of various materials. The slots are not necessarily straight. In some cases, the slots have extremely intricate shapes.	EBM, LBM, WJC, wire EDM, AWJC
Micromachining. In addition to cutting small holes and narrow slits, there are other material removal applications in which the work part and/or areas to be cut are very small.	PCM, LBM, EBM
Shallow pockets and surface details in flat parts. There is a significant range in the sizes of the parts in this category, from microscopic integrated circuit chips to large aircraft panels.	CHM
Special contoured shapes for mold and die applications. These applications are sometimes referred to as die-sinking.	EDM, ECM

Work part Geometry and Work Materials Some of the special work part shapes for which nontraditional processes are well suited are listed in Table 25.4 along with the nontraditional processes that are likely to be appropriate.

As a group, the nontraditional processes can be applied to nearly all work materials, metals and nonmetals. However, certain processes are not suited to certain work materials. Table 25.5 relates applicability of the nontraditional processes to various types of materials. Several of the processes can be used on metals but not nonmetals. For example, ECM, EDM, and PAM require work materials that are electrical conductors. This generally limits their applicability

TABLE • 25.5 Applicability of selected nontraditional machining processes to various work materials. For comparison, conventional milling and grinding are included in the compilation.

	Nontraditional Processes								Conventional Processes	
	Mech		Elec		Thermal		Chem			
Work Material	USM	WJC	ECM	EDM	EBM	LBM	PAC	CHM	Milling	Grinding
Aluminum	C	C	B	B	B	B	A	A	A	A
Steel	B	D	A	A	B	B	A	A	A	A
Super alloys	C	D	A	A	B	B	A	B	B	B
Ceramic	A	D	D	D	A	A	D	C	D	C
Glass	A	D	D	D	B	B	D	B	D	C
Silicon[a]			D	D	B	B	D	B	D	B
Plastics	B	B	D	D	B	B	D	C	B	C
Cardboard[b]	D	A	D	D			D	D	D	D
Textiles[c]	D	A	D	D			D	D	D	D

Compiled from [18] and other sources. Key: A = good application, B = fair application, C = poor application, D = not applicable, and blank entries indicate no data available during compilation.
[a]Refers to silicon used in fabricating integrated circuit chips.
[b]Includes other paper products.
[c]Includes felt, leather, and similar materials.

TABLE • 25.6 Machining characteristics of the nontraditional machining processes.

	Nontraditional Processes								Conventional Processes	
	Mech		Elec		Thermal		Chem			
Work Material	**USM**	**WJC**	**ECM**	**EDM**	**EBM**	**LBM**	**PAC**	**CHM**	**Milling**	**Grinding**
Material removal rates	C	C	B	C	D	D	A	B–D[a]	A	B
Dimensional control	A	B	B	A–D[b]	A	A	D	A–B[b]	B	A
Surface finish	A	A	B	B–D[b]	B	B	D	B	B–C[b]	A
Surface damage[c]	B	B	A	D	D	D	D	A	B	B–C[b]

Compiled from [18]. Key: A = excellent, B = good, C = fair, and D = poor.
[a]Rating depends on size of work and masking method.
[b]Rating depends on cutting conditions.
[c]In surface damage a good rating means low surface damage and poor rating means deep penetration of surface damage; thermal processes can cause damage up to 0.020 in (0.50 mm) below the new work surface.

to metal parts. Chemical machining depends on the availability of an appropriate etchant for the given work material. Because metals are more susceptible to chemical attack by various etchants, CHM is commonly used to process metals. With some exceptions, USM, AJM, EBM, and LBM can be used on both metals and nonmetals. WJC is generally limited to the cutting of plastics, cardboards, textiles, and other materials that do not possess the strength of metals.

Performance of Nontraditional Processes The nontraditional processes are generally characterized by low material removal rates and high specific energies relative to conventional machining operations. The capabilities for dimensional control and surface finish of the nontraditional processes vary widely, with some of the processes providing high accuracies and good finishes, and others yielding poor accuracies and finishes. Surface damage is also a consideration. Some of these processes produce very little metallurgical damage at and immediately below the work surface, whereas others (mostly the thermal-based processes) do considerable damage to the surface. Table 25.6 compares these features of the prominent nontraditional methods, using conventional milling and surface grinding for comparison. Inspection of the data reveals wide differences in machining characteristics. In comparing the characteristics of nontraditional and conventional machining, it must be remembered that nontraditional processes are generally used where conventional methods are not practical or economical.

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