*Template machining* utilizes a simple, single-point cutting tool that is guided by a template. However, the equipment is specialized, and the method is seldom used except for making large-bevel gears.

The *generating process* is used to produce most high-quality gears. This process is based on the principle that any two involute gears, or any gear and a rack, of the same diametral pitch will mesh together. Applying this principle, one of the gears (or the rack) is made into a cutter by proper sharpening and is used to cut into a mating gear blank and thus generate teeth on the blank. Gear shapers (pinion or rack), gear-hobbing machines, and bevel-gear generating machines are good examples of the gear generating machines.

### 33.9.2 Gear Finishing

To operate efficiently and have satisfactory life, gears must have accurate tooth profile and smooth and hard faces. Gears are usually produced from relatively soft blanks and are subsequently heat-treated to obtain greater hardness, if it is required. Such heat treatment usually results in some slight distortion and surface roughness. *Grinding and lapping* are used to obtain very accurate teeth on hardened gears. Gear-shaving and burnishing methods are used in gear finishing. Burnishing is limited to unhardened gears.

## 33.10 THREAD CUTTING AND FORMING

Three basic methods are used for the manufacturing of threads; *cutting, rolling,* and *casting.* Die casting and molding of plastics are good examples of casting. The largest number of threads are made by rolling, even though it is restricted to standardized and simple parts, and ductile materials. Large numbers of threads are cut by the following methods:

1. Turning
2. Dies: manual or automatic (external)
3. Milling
4. Grinding (external)
5. Threading machines (external)
6. Taps (internal)

### 33.10.1 Internal Threads

In most cases, the hole that must be made before an internal thread is tapped is produced by drilling. The hole size determines the depth of the thread, the forces required for tapping, and the tap life. In most applications, a drill size is selected that will result in a thread having about 75% of full thread depth. This practice makes tapping much easier, increases the tap's life, and only slightly reduces the resulting strength. Table 33.13 gives the drill sizes used to produce 75% thread depth for several sizes of UNC threads. The feed of a tap depends on the lead of the screw and is equal to 1/lead ipr.

*Cutting speeds* depend on many factors, such as

1. Material hardness
2. Depth of cut
3. Thread profile

**Table 33.13 Recommended Tap-Drill Sizes for Standard Screw-Thread Pitches (American National Coarse-Thread Series)**

| Number or Diameter | Threads per Inch | Outside Diameter of Screw | Tap Drill Sizes | Decimal Equivalent of Drill |
|---|---|---|---|---|
| 6 | 32 | 0.138 | 36 | 0.1065 |
| 8 | 32 | 0.164 | 29 | 0.1360 |
| 10 | 24 | 0.190 | 25 | 0.1495 |
| 12 | 24 | 0.216 | 16 | 0.1770 |
| 1/4 | 20 | 0.250 | 7 | 0.2010 |
| 3/8 | 16 | 0.375 | 5/16 | 0.3125 |
| 1/2 | 13 | 0.500 | 27/64 | 0.4219 |
| 3/4 | 10 | 0.750 | 21/32 | 0.6562 |
| 1 | 8 | 1.000 | 7/8 | 0.875 |

4. Tooth depth
5. Hole depth
6. Fineness of pitch
7. Cutting fluid

Cutting speeds can range from lead 3 ft/min (1 m/min) for high-strength steels to 150 ft/min (45 m/min) for aluminum alloys. Long-lead screws with different configurations can be cut successfully on milling machines, as in Fig. 33.24. The feed per tooth is given by the following equation:

$$f_t = \frac{\pi d S}{nN} \tag{33.56}$$

where $d$ = diameter of thread
$n$ = number of teeth in cutter
$N$ = rpm of cutter
$S$ = rpm of work

### 33.10.2 Thread Rolling

In thread rolling, the metal on the cylindrical blank is cold-forged under considerable pressure by either rotating cylindrical dies or reciprocating flat dies. The advantages of thread rolling include improved strength, smooth surface finish, less material used (~19%), and high production rate. The limitations are that blank tolerance must be close, it is economical only for large quantities, it is limited to external threads, and it is applicable only for ductile materials, less than Rockwell C37.

## 33.11 BROACHING

Broaching is unique in that it is the only one of the basic machining processes in which the feed of the cutting edges is built into the tool. The machined surface is always the inverse of the profile of the broach. The process is usually completed in a single, linear stroke. A broach is composed of a series of single-point cutting edges projecting from a rigid bar, with successive edges protruding farther from the axis of the bar. Figure 33.25 illustrates the parts and nomenclature of the broach. Most broaching machines are driven hydraulically and are of the pull or push type.

The maximum force an internal pull broach can withstand without damage is given by

$$P = \frac{A_y F_y}{s} \text{ lb} \tag{33.57}$$

where $A_y$ = minimum tool selection, in.$^2$
$F_y$ = tensile yield strength of tool steel, psi
$s$ = safety factor

The maximum push force is determined by the minimum tool diameter ($D_y$), the length of the broach ($L$), and the minimum compressive yield strength ($F_y$). The ratio $L/D_y$ should be less than 25 so that the tool will not bend under load. The maximum allowable pushing force is given by

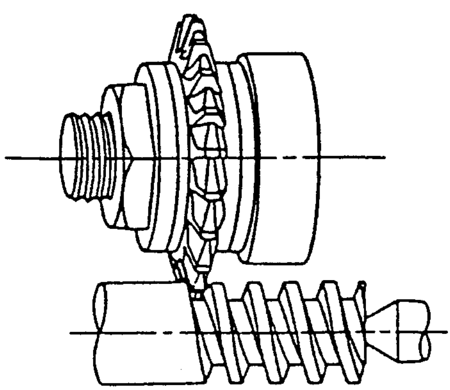


**Fig. 33.24** Single-thread milling cutter.

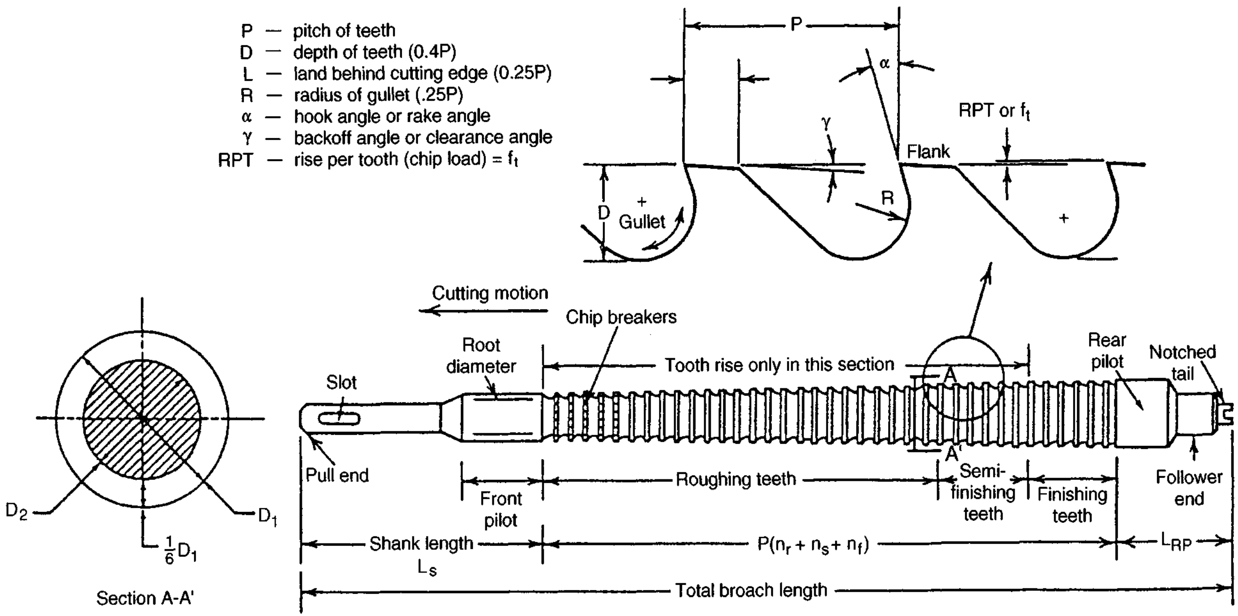



**Fig. 33.25** Standard broach part and nomenclature.

$$P = \frac{A_y F_y}{s} \quad \text{lb} \tag{33.58}$$

where $F_y$ is minimum compressive yield strength.

If $L/D_y$ ratio is greater than 25 (long broach), the *Tool and Manufacturing Engineers Handbook* gives the following formula:

$$P = \frac{5.6 \times 10^7 D_r^4}{sL^2} \quad \text{lb} \tag{33.59}$$

$D_r$ and $L$ are given in inches.

Alignment charts were developed for determining metal removal rate (MRR) and motor power in surface broaching. Figures 33.26 and 33.27 show the application of these charts for either English or metric units.

Broaching speeds are relatively low, seldom exceeding 50 fpm, but, because a surface is usually completed in one stroke, the productivity is high.

## 33.12 SHAPING, PLANING, AND SLOTTING

The shaping and planing operations generate surfaces with a single-point tool by a combination of a reciprocating motion along one axis and a feed motion normal to that axis (Fig. 33.28). Slots and limited inclined surfaces can also be produced. In shaping, the tool is mounted on a reciprocating ram and the table is fed at each stroke of the ram. Planers handle large, heavy workpieces. In planing, the workpiece reciprocates and the feed increment is provided by moving the tool at each reciprocation. To reduce the lost time on the return stroke, they are provided with a quick-return mechanism. For mechanically driven shapers, the ratio of cutting time to return stroke averages 3:2, and for hydraulic shapers the ratio is 2:1. The average cutting speed may be determined by the following formula:

$$CS = \frac{LN}{12C} \quad \text{fpm} \tag{33.60}$$

where $N$ = strokes per minute
$L$ = stroke length, in.
$C$ = cutting time ratio, cutting time divided by total time

For mechanically driven shapers, the cutting speed reduces to

$$CS = \frac{LN}{7.2} \quad \text{fpm} \tag{33.61}$$

or

$$CS = \frac{L_1 N}{600} \quad \text{m/min} \tag{33.62}$$

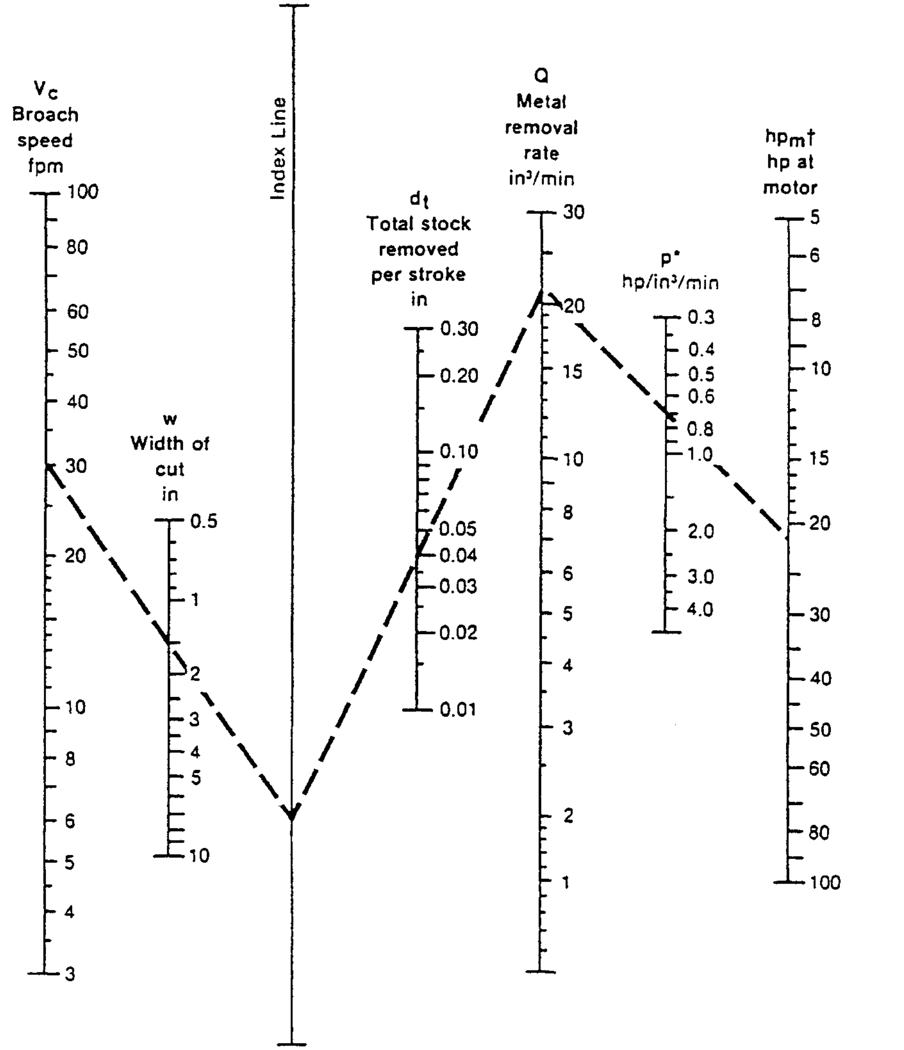
where $L_1$ is the stroke length in millimeters. For hydraulically driven shapers,

$$CS = \frac{LN}{8} \quad \text{fpm} \tag{33.63}$$

or

$$CS = \frac{L_1 N}{666.7} \quad \text{m/min} \tag{33.64}$$

The time $T$ required to machine a workpiece of width $W$ (in.) is calculated by




**Example:**

Material: Cast iron — HSS tools

Chipload 0.005 in/tooth

$V_c$ = 30 fpm    w = 1.5 in

$d_t$ = 0.040 in    Q = 22 in³/min

P = 0.7 hp/in³/min    $hp_m$ = 22 hp

$$Q = 12\,V_c \times w \times d_t \text{ in}^3/\text{min}$$

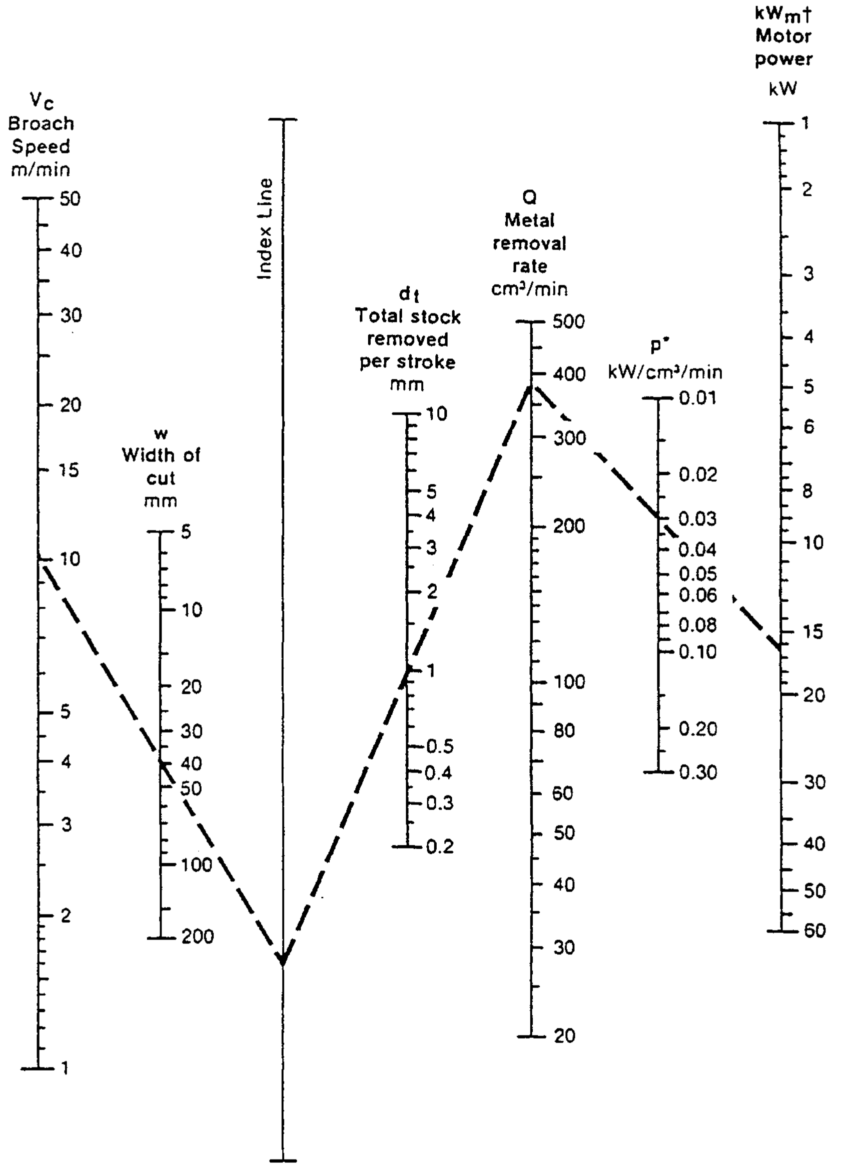
$$hp_m = \frac{Q \times P}{E} = \frac{Q \times P}{0.7}$$

**Fig. 33.26** Alignment chart for determining metal removal rate and motor horsepower in surface broaching with high-speed steel broaching tools—English units.

$$T = \frac{W}{N \times f} \text{ min} \tag{33.65}$$

where $f$ = feed, in. per stroke

The number of strokes ($S$) required to complete a job is then




Example:

Material: Cast iron — HSS tools

Chipload 0.13 mm/tooth

$V_c$ = 10 m/min  w = 38 mm

$d_t$ = 1 mm  Q = 380 cm³/min

P = 0.03 kW/cm³/min  $P_m$ = 16.3 kW

$$Q = V_c \times w \times d_t \text{ cm}^3/\text{min}$$

$$P_m = \frac{Q \times P}{E} = \frac{Q \times P}{0.7}$$

**Fig. 33.27** Alignment chart for determining metal removal rate and motor power in surface broaching with high-speed steel broaching tools—metric units.

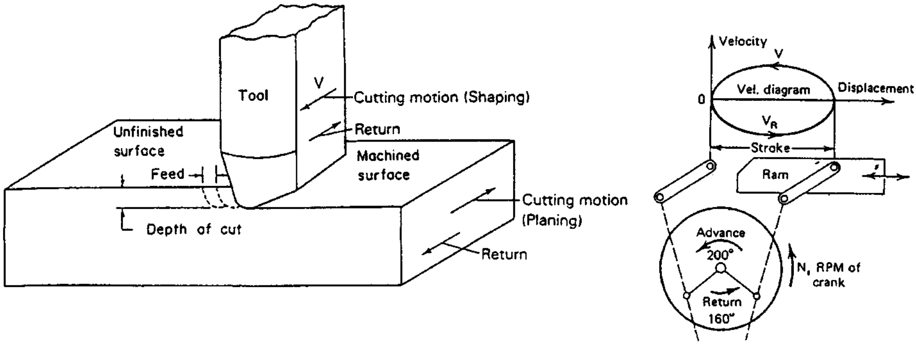



**Fig. 33.28** Basic relationships of tool motion, feed, and depth of cut in shaping and planing.

$$S = \frac{W}{f} \tag{33.66}$$

The power required can be approximated by

$$HP_c = Kdf(CS) \tag{33.67}$$

where $d$ = depth of cut, in.
$CS$ = cutting speed, fpm
$K$ = cutting constant, for medium cast iron, 3; free-cutting steel, 6; and bronze, 1.5 or

$$HP_c = 12f \times d \times CS \times HP_\mu$$

$$F_c = \frac{33{,}000\ HP_c}{CS}$$

## 33.13 SAWING, SHEARING, AND CUTTING OFF

Saws are among the most common of machine tools, even though the surfaces they produce often require further finishing operations. Saws have two general areas of applications: contouring and cutting off. There are three basic types of saws: hacksaw, circular, and band saw.

The *reciprocating power hacksaw* machines can be classified as either positive or uniform-pressure feeds. Most of the new machines are equipped with a quick-return action to reduce idle time.

The machining time required to cut a workpiece of width $W$ in. is calculated as follows:

$$T = \frac{W}{fN} \text{ min} \tag{33.68}$$

where $F$ = feed, in./stroke
$N$ = number of strokes per min

*Circular saws* are made of three types: metal saws, steel friction disks, and abrasive disks. Solid metal saws are limited in size, not exceeding 16 in. in diameter. Large circular saws have either replaceable inserted teeth or segmented-type blades. The machining time required to cut a workpiece of width $W$ in. is calculated as follows:

$$T = \frac{W}{f_t nN} \text{ min} \tag{33.69}$$

where $f_t$ = feed per tooth
$n$ = number of teeth
$N$ = rpm

*Steel friction* disks operate at high peripheral speeds ranging from 18,000–25,000 fpm (90–125 m/sec). The heat of friction quickly softens a path through the part. The disk, which is sometimes provided with teeth or notches, pulls and ejects the softened metal. About 0.5 min are required to cut through a 24-in. I-beam.

*Abrasive disks* are mainly aluminum oxide grains or silicon carbide grains bonded together. They will cut ferrous or nonferrous metals. The finish and accuracy is better than steel friction blades, but they are limited in size compared to steel friction blades.

*Band saw* blades are of the continuous type. Band sawing can be used for cutting and contouring. Band-sawing machines operate with speeds that range from 50–1500 fpm. The time required to cut a workpiece of width $W$ in. can be calculated as follows:

$$T = \frac{W}{12 f_t n V} \quad \text{min} \tag{33.70}$$

where $f_t$ = feed, in. per tooth
$n$ = number of teeth per in.
$V$ = cutting speed, fpm

Cutting can also be achieved by band-friction cutting blades with a surface speed up to 15,000 fpm. Other band tools include band filing, diamond bands, abrasive bands, spiral bands, and special-purpose bands.

## 33.14 MACHINING PLASTICS

Most plastics are readily formed, but some machining may be required. Plastic's properties vary widely. The general characteristics that affect their machinability are discussed below.

First, all plastics are poor heat conductors. Consequently, little of the heat that results from chip formation will be conducted away through the material or carried away in the chips. As a result, cutting tools run very hot and may fail more rapidly than when cutting metal. Carbide tools frequently are more economical to use than HSS tools if cuts are of moderately long duration or if high-speed cutting is to be done.

Second, because considerable heat and high temperatures do develop at the point of cutting, thermoplastics tend to soften, swell, and bind or clog the cutting tool. Thermosetting plastics give less trouble in this regard.

Third, cutting tools should be kept very sharp at all times. Drilling is best done by means of straight-flute drills or by "dubbing" the cutting edge of a regular twist drill to produce a zero rake angle. Rotary files and burrs, saws, and milling cutters should be run at high speeds in order to improve cooling, but with feed carefully adjusted to avoid jamming the gullets. In some cases, coolants can be used advantageously if they do not discolor the plastic or cause gumming. Water, soluble oil and water, and weak solutions of sodium silicate in water are used. In turning and milling plastics, diamond tools provide the best accuracy, surface finish, and uniformity of finish. Surface speeds of 500–600 fpm with feeds of 0.002–0.005 in. are typical.

Fourth, filled and laminated plastics usually are quite abrasive and may produce a fine dust that may be a health hazard.

## 33.15 GRINDING, ABRASIVE MACHINING, AND FINISHING

Abrasive machining is the basic process in which chips are removed by very small edges of abrasive particles, usually synthetic. In many cases, the abrasive particles are bonded into wheels of different shapes and sizes. When wheels are used mainly to produce accurate dimensions and smooth surfaces, the process is called *grinding.* When the primary objective is rapid metal removal to obtain a desired shape or approximate dimensions, it is termed *abrasive machining.* When fine abrasive particles are used to produce very smooth surfaces and to improve the metallurgical structure of the surface, the process is called *finishing.*

### 33.15.1 Abrasives

*Aluminum oxide* ($Al_2O_3$), usually synthetic, performs best on carbon and alloy steels, annealed malleable iron, hard bronze, and similar metals. $Al_2O_3$ wheels are not used in grinding very hard materials, such as tungsten carbide, because the grains will get dull prior to fracture. Common trade names for aluminum oxide abrasives are *Alundum* and *Aloxite.*

*Silicon carbide* (SiC), usually synthetic, crystals are very hard, being about 9.5 on the Moh's scale, where diamond hardness is 10. SiC crystals are brittle, which limits their use. Silicon carbide wheels are recommended for materials of low tensile strength, such as cast iron, brass, stone, rubber, leather, and cemented carbides.

*Cubic boron nitride* (CBN) is the second-hardest natural or manmade substance. It is good for grinding hard and tough-hardened tool-and-die steels.

*Diamonds* may be classified as natural or synthetic. Commercial diamonds are now manufactured in high, medium, and low impact strength.

### Grain Size

To have uniform cutting action, abrasive grains are graded into various sizes, indicated by the numbers 4–600. The number indicates the number of openings per linear inch in a standard screen through which most of the particles of a particular size would pass. Grain sizes from 4–24 are termed coarse; 30–60, medium; and 70–600, fine. Fine grains produce smoother surfaces than coarse ones but cannot remove as much metal.

*Bonding materials* have the following effects on the grinding process: (1) they determine the strength of the wheel and its maximum speed; (2) they determine whether the wheel is rigid or flexible; and (3) they determine the force available to pry the particles loose. If only a small force is needed to release the grains, the wheel is said to be soft. Hard wheels are recommended for soft materials and soft wheels for hard materials. The bonding materials used are vitrified, silicate, rubber, resinoid, shellac, and oxychloride.

### Structure or Grain Spacing

Structure relates to the spacing of the abrasive grain. Soft, ductile materials require a wide spacing to accommodate the relatively large chips. A fine finish requires a wheel with a close spacing. Figure 33.29 shows the standard system of grinding wheels as adopted by the American National Standards Institute.

### Speeds

Wheel speed depends on the wheel type, bonding material, and operating conditions. Wheel speeds range between 4500 and 18,000 sfpm (22.86 and 27.9 m/s). 5500 sfpm (27.9 m/s) is generally recommended as best for all disk-grinding operations. Work speeds depend on type of material, grinding operation, and machine rigidity. Work speeds range between 15 and 200 fpm.

### Feeds

Cross feed depends on the width of grinding wheel. For rough grinding, the range is one-half to three-quarters of the width of the wheel. Finer feed is required for finishing, and it ranges between one-tenth and one-third of the width of the wheel. A cross feed between 0.125 and 0.250 in. is generally recommended.

### Depth of Cut

Rough-grinding conditions will dictate the maximum depth of cut. In the finishing operation, the depth of cut is usually small, 0.0002–0.001 in. (0.005–0.025 mm). Good surface finish and close tolerance can be achieved by "sparking out" or letting the wheel run over the workpiece without increasing the depth of cut till sparks die out. The *grinding ratio* ($G$-ratio) refers to the ratio of the cubic inches of stock removed to the cubic inches of grinding wheel worn away. $G$-ratio is important in calculating grinding and abrasive machining cost, which may be calculated by the following formula:

$$C = \frac{C_a}{G} + \frac{L}{tq} \tag{33.71}$$

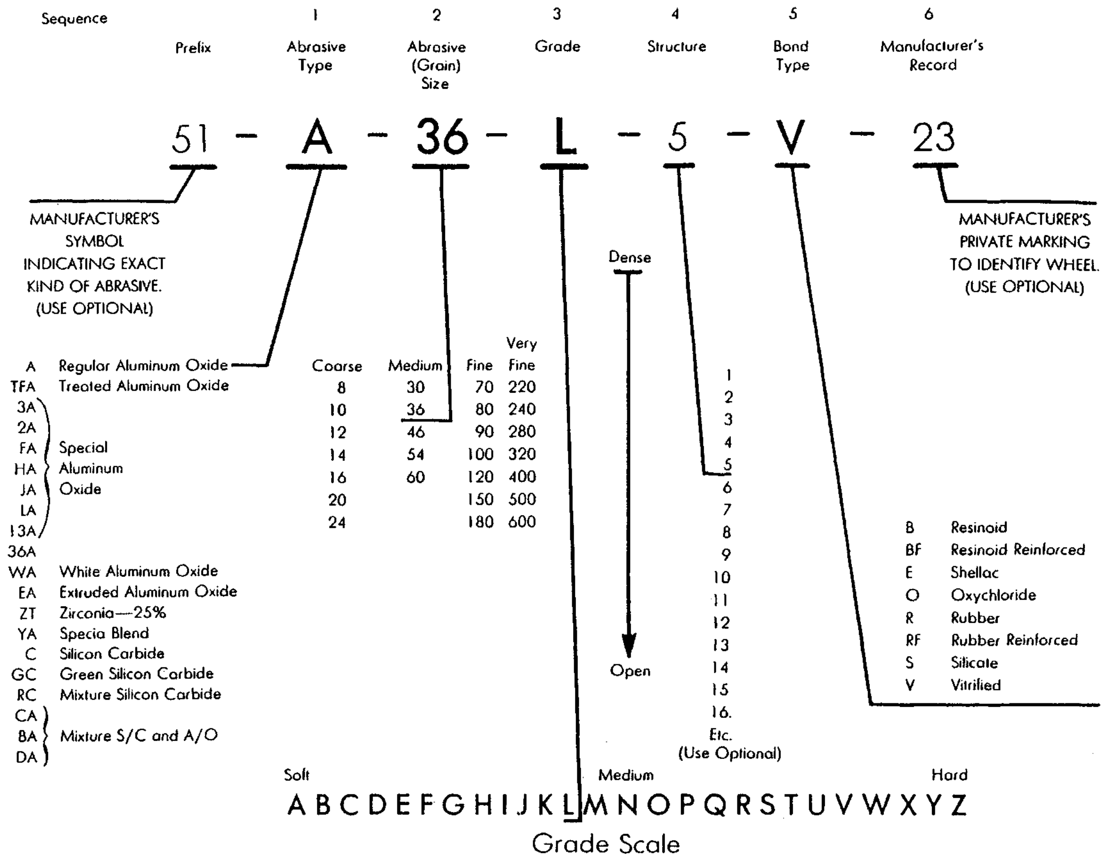
where $C$ = specific cost of removing a cu in. of material
$C_a$ = cost of abrasive, \$/in.$^3$
$G$ = grinding ratio
$L$ = labor and overhead charge, \$/hr
$q$ = machining rate, in.$^3$/hr
$t$ = fraction of time the wheel is in contact with workpiece

### Power Requirement

$$\text{Power} = (u)(\text{MRR}) = F_c \times R \times 2\pi N$$

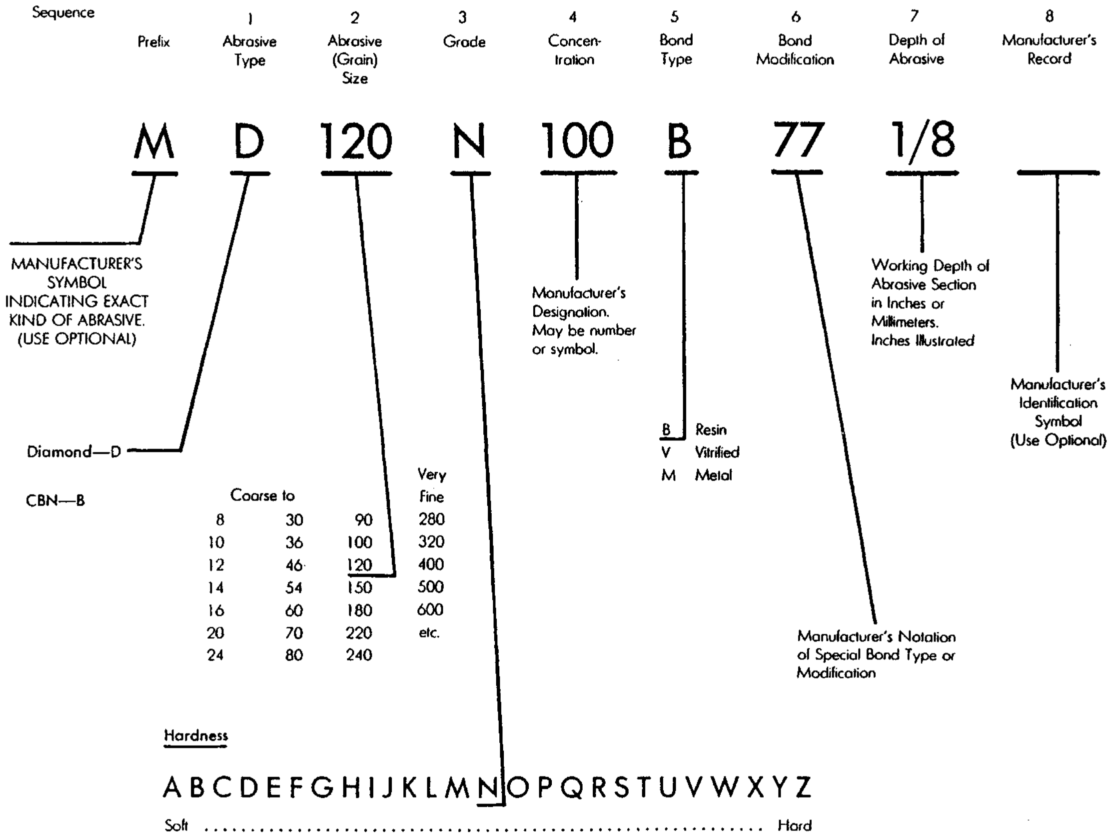
$$\text{MRR} = \text{material removal rate} = d \times w \times v$$

where $d$ = depth of cut
$w$ = width of cut
$v$ = work speed
$u$ = specific energy for surface grinding. Table 33.14 gives the approximate specific energy requirement for certain metals.
$R$ = radius of wheel
$N$ = rev/unit time



Sequence
Prefix
1 Abrasive Type
2 Abrasive (Grain) Size
3 Grade
4 Structure
5 Bond Type
6 Manufacturer's Record
51 - A - 36 - L - 5 - V - 23
MANUFACTURER'S SYMBOL INDICATING EXACT KIND OF ABRASIVE. (USE OPTIONAL)
MANUFACTURER'S PRIVATE MARKING TO IDENTIFY WHEEL. (USE OPTIONAL)
A Regular Aluminum Oxide
TFA Treated Aluminum Oxide
3A
2A
FA Special
HA Aluminum
JA Oxide
LA
13A
36A
WA White Aluminum Oxide
EA Extruded Aluminum Oxide
ZT Zirconia—25%
YA Specia Blend
C Silicon Carbide
GC Green Silicon Carbide
RC Mixture Silicon Carbide
CA
BA Mixture S/C and A/O
DA
Coarse 8 10 12 14 16 20 24
Medium 30 36 46 54 60
Fine 70 80 90 100 120 150 180
Very Fine 220 240 280 320 400 500 600
Dense
Open
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16. Etc.
(Use Optional)
B Resinoid
BF Resinoid Reinforced
E Shellac
O Oxychloride
R Rubber
RF Rubber Reinforced
S Silicate
V Vitrified
Soft
Medium
Hard
A B C D E F G H I J K L M N O P Q R S T U V W X Y Z
Grade Scale

(a)




(*b*)

**Fig. 33.29** Standard systems for grinding wheels. (*a*) aluminum oxide, silicon carbide; (*b*) diamond, CBN.

**Table 33.14 Approximate Specific Energy Required for Surface Grinding**

| Workpiece Material | Hardness | hp (in.$^3$/min) | W/(mm$^3$/sec) |
|---|---|---|---|
| Aluminum | 150 HB | 3–10 | 8–27 |
| Steel | (110–220) HB | 6–24 | 16–66 |
| Cast iron | (140–250) HB | 5–22 | 14–60 |
| Titanium alloy | 300 HB | 6–20 | 16–55 |
| Tool steel | 62–67 HRC | 7–30 | 19–82 |

### 33.15.2 Temperature

Temperature rise affects the surface properties and causes residual stresses on the workpiece. It is related to process variables by the following relation:

$$\text{temperature rise} \propto D^{1/4} d^{3/4} \left(\frac{V}{v}\right)^{1/2} \tag{33.72}$$

where $D$ = wheel diameter
$V$ = wheel speed

#### Grinding Fluids

Grinding fluids are water-base emulsions for general guiding and oils for thread and gear grinding. Advantages include:

1. Machining hard materials > RC50.
2. Fine surface finish, 10–80 $\mu$in. (0.25–2 $\mu$m).
3. Accurate dimensions and close tolerances I.0002 in. (I.005 mm) can be easily achieved.
4. Grinding pressure is light.

#### Machines

Grinding and abrasive machines include

1. Surface grinders, reciprocating or rotating table
2. Cylindrical grinders, work between centers, centerless, crankshaft, thread and gear form work, and internal and other special applications
3. Jig grinders
4. Tool and cutter grinders
5. Snagging, foundry rough work
6. Cutting off and profiling
7. Abrasive grinding, belt, disk and loose grit
8. Mass media, barrel tumbling, and vibratory

#### Ultrasonic Machining

In ultrasonic machining, material is removed from the workpiece by microchipping or erosion through high-velocity bombardment by abrasive particles, in the form of a slurry, through the action of an ultrasonic transducer. It is used for machining hard and brittle materials and can produce very small and accurate holes 0.015 in. (0.4 mm).

#### Surface Finishing

Finishing processes produce an extra-fine surface finish; in addition, tool marks are removed and very close tolerances are achieved. Some of these processes follow.

*Honing* is a low-velocity abrading process. It uses fine abrasive stones to remove very small amounts of metals usually left from previous grinding processes. The amount of metal removed is usually less than 0.005 in. (0.13 mm). Because of low cutting speeds, heat and pressure are minimized, resulting in excellent sizing and metallurgical control.

*Lapping* is an abrasive surface-finishing process wherein fine abrasive particles are charged in some sort of a vehicle, such as grease, oil, or water, and are embedded into a soft material, called a *lap.* Metal laps must be softer than the work and are usually made of close-grained gray cast iron. Other materials, such as steel, copper, and wood, are used where cast iron is not suitable. As the charged lap is rubbed against a surface, small amounts of material are removed from the harder surface. The amount of material removed is usually less than 0.001 in. (0.03 mm).

*Superfinishing* is a surface-improving process that removes undesirable fragmentation, leaving a base of solid crystalline metal. It uses fine abrasive stones, like honing, but differs in the type of motion. Very rapid, short strokes, very light pressure, and low-viscosity lubricant–coolant are used in superfinishing. It is essentially a finishing process and not a dimensional one, and can be superimposed on other finishing operations.

### Buffing

*Buffing* wheels are made from a variety of soft materials. The most widely used is muslin, but flannel, canvas, sisal, and heavy paper are used for special applications. Buffing is usually divided into two operations: cutting down and coloring. The first is used to smooth the surface and the second to produce a high luster. The abrasives used are extremely fine powders of aluminum oxide, tripoli (an amorphous silicon), crushed flint or quartz, silicon carbide, and red rouge (iron oxide). Buffing speeds range between 6,000 and 12,000 fpm.

*Electropolishing* is the reverse of electroplating; that is, the work is the anode instead of the cathode and metal is removed rather than added. The electrolyte attacks projections on the workpiece surface at a higher rate, thus producing a smooth surface.

## 33.16 NONTRADITIONAL MACHINING

Nontraditional, or nonconventional, machining processes are material-removal processes that have recently emerged or are new to the user. They have been grouped for discussion here according to their primary energy mode; that is, mechanical, electrical, thermal, or chemical, as shown in Table 33.15.

Nontraditional processes provide manufacturing engineers with additional choices or alternatives to be applied where conventional processes are not satisfactory, such as when

- Shapes and dimensions are complex or very small
- Hardness of material is very high (>400 HB)
- Tolerances are tight and very fine surface finish is desired
- Temperature rise and residual stresses must be avoided
- Cost and production time must be reduced

Figure 33.30 and Table 33.16 demonstrate the relationships among the conventional and the nontraditional machining processes with respect to surface roughness, dimensional tolerance, and metal-removal rate.

The *Machinery Handbook*[6] is an excellent reference for nontraditional machining processes, values, ranges, and limitations.

### 33.16.1 Abrasive Flow Machining

Abrasive flow machining (AFM) is the removal of material by a viscous, abrasive medium flowing, under pressure, through or across a workpiece. Figure 33.31 contains a schematic presentation of the AFM process. Generally, the putty-like medium is extruded through or over the workpiece with motion usually in both directions. Aluminum oxide, silicon carbide, boron carbide, or diamond abrasives are used. The movement of the abrasive matrix erodes away burrs and sharp corners and polishes the part.

### 33.16.2 Abrasive Jet Machining

Abrasive jet machining (AJM) is the removal of material through the action of a focused, high-velocity stream of fine grit or powder-loaded gas. The gas should be dry, clean, and under modest pressure. Figure 33.32 shows a schematic of the AJM process. The mixing chamber sometimes uses a vibrator to promote a uniform flow of grit. The hard nozzle is directed close to the workpiece at a slight angle.

### 33.16.3 Hydrodynamic Machining

Hydrodynamic machining (HDM) removes material by the stroking of high-velocity fluid against the workpiece. The jet of fluid is propelled at speeds up to Mach 3. Figure 33.33 shows a schematic of the HDM operation.

### 33.16.4 Low-Stress Grinding

Low-stress grinding (LSG) is an abrasive material-removal process that leaves a low-magnitude, generally compressive residual stress in the surface of the workpiece. Figure 33.34 shows a schematic of the LSG process. The thermal effects from conventional grinding can produce high tensile stress

**Table 33.15 Current Commercially Available Nontraditional Material Removal Processes**

| Mechanical | | Electrical | | Thermal | | Chemical | |
|---|---|---|---|---|---|---|---|
| AFM | Abrasive flow machining | ECD | Electrochemical deburring | EBM | Electron-beam machining | CHM | Chemical machining: chemical milling, chemical blanking |
| AJM | Abrasive jet machining | ECDG | Electrochemical discharge grinding | EDG | Electrical discharge grinding | | |
| HDM | Hydrodynamic machining | | | | | | |
| LSG | Low-stress grinding | ECG | Electrochemical grinding | EDM | Electrical discharge machining | ELP | Electropolish |
| RUM | Rotary ultrasonic machining | ECH | Electrochemical honing | | | PCM | Photochemical machining |
| | | ECM | Electrochemical machining | EDS | Electrical discharge sawing | TCM | Thermochemical machining (or TEM, thermal energy method) |
| TAM | Thermally assisted machining | ECP | Electrochemical polishing | EDWC | Electrical discharge wire cutting | | |
| | | ECS | Electrochemical sharpening | | | | |
| TFM | Total form machining | ECT | Electrochemical turning | LBM | Laser-beam machining | | |
| USM | Ultrasonic machining | ES | Electro-stream™ | LBT | Laser-beam torch | | |
| WJM | Water-jet machining | STEM™ | Shaped tube electrolytic machining | PBM | Plasma-beam machining | | |

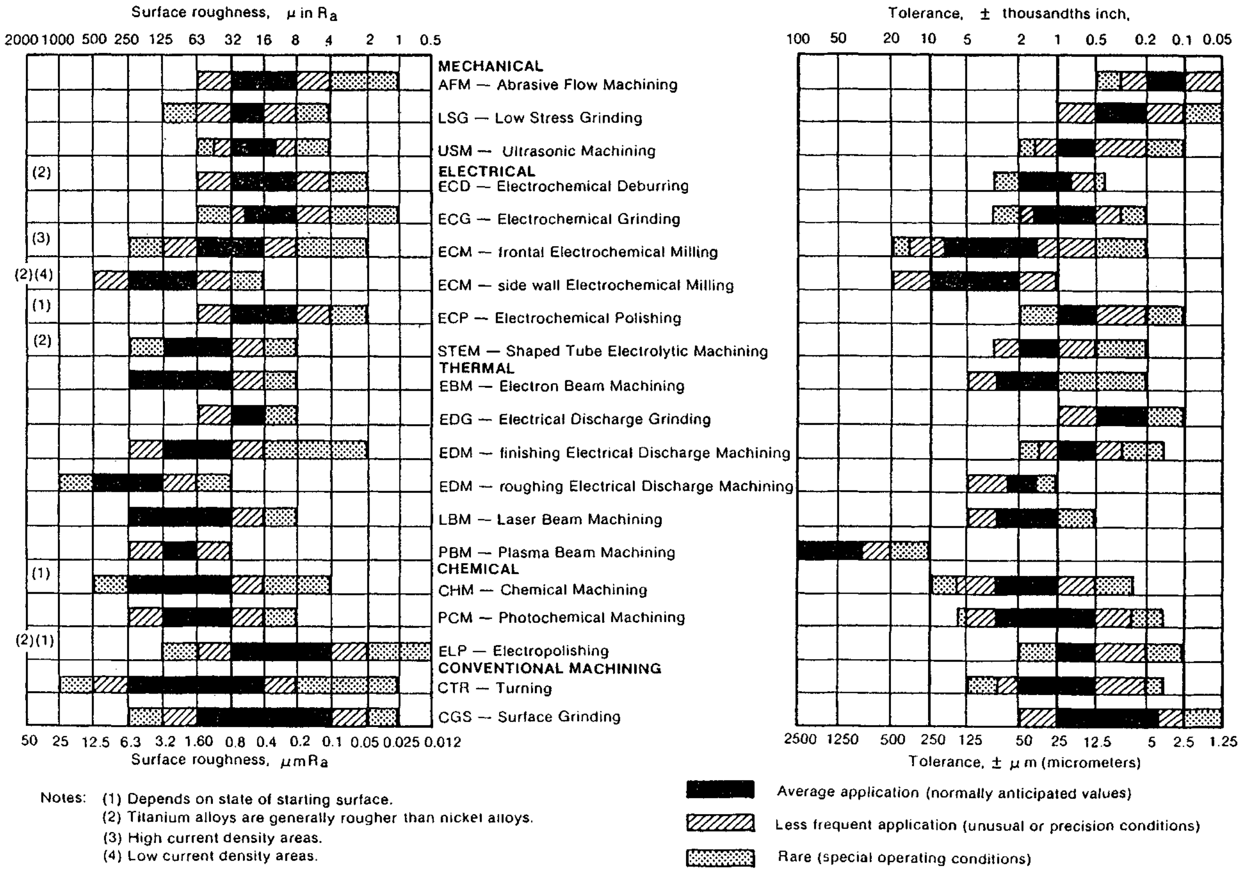



**Fig. 33.30** Typical surface roughness and tolerances produced by nontraditional machining.

**Table 33.16 Material Removal Rates and Dimensional Tolerances**

| Process | Maximum Rate of Material Removal in.$^3$/min cm$^3$/min | Typical Power Consumption hp/in.$^3$/min kW/cm$^3$/min | Cutting Speed fpm m/min | Penetration Rate per Minute in. mm | Accuracy ± Attainable in. mm | Accuracy ± At Maximum Material Removal Rate in. mm | Typical Machine Input hp kW |
|---|---|---|---|---|---|---|---|
| Conventional turning | 200 | 1 | 250 | — | 0.0002 | 0.005 | 30 |
| | 3300 | 0.046 | 76 | — | 0.005 | 0.13 | 22 |
| Conventional grinding | 50 | 10 | 10 | — | 0.0001 | 0.002 | 25 |
| | 820 | 0.46 | 3 | — | 0.0025 | 0.05 | 20 |
| CHM | 30 | — | — | 0.001 | 0.0005 | 0.003 | — |
| | 490 | — | — | 0.025 | 0.013 | 0.075 | — |
| PBM | 10 | 20 | 50 | 10 | 0.02 | 0.1 | 200 |
| | 164 | 0.91 | 15 | 254 | 0.5 | 2.54 | 150 |
| ECG | 2 | 2 | 0.25 | — | 0.0002 | 0.0025 | 4 |
| | 33 | 0.019 | 0.08 | — | 0.005 | 0.063 | 3 |
| ECM | 1 | 160 | — | 0.5 | 0.0005 | 0.006 | 200 |
| | 16.4 | 7.28 | — | 12.7 | 0.013 | 0.15 | 150 |
| EDM | 0.3 | 40 | — | 0.5 | 0.00015 | 0.002 | 15 |
| | 4.9 | 1.82 | — | 12.7 | 0.004 | 0.05 | 11 |
| USM | 0.05 | 200 | — | 0.02 | 0.0002 | 0.0015 | 15 |
| | 0.82 | 9.10 | — | 0.50 | 0.005 | 0.040 | 11 |
| EBM | 0.0005 | 10,000 | 200 | 6 | 0.0002 | 0.002 | 10 |
| | 0.0082 | 455 | 60 | 150 | 0.005 | 0.050 | 7.5 |
| LBM | 0.0003 | 60,000 | — | 4 | 0.0005 | 0.005 | 20 |
| | 0.0049 | 2,731 | — | 102 | 0.013 | 0.13 | 15 |

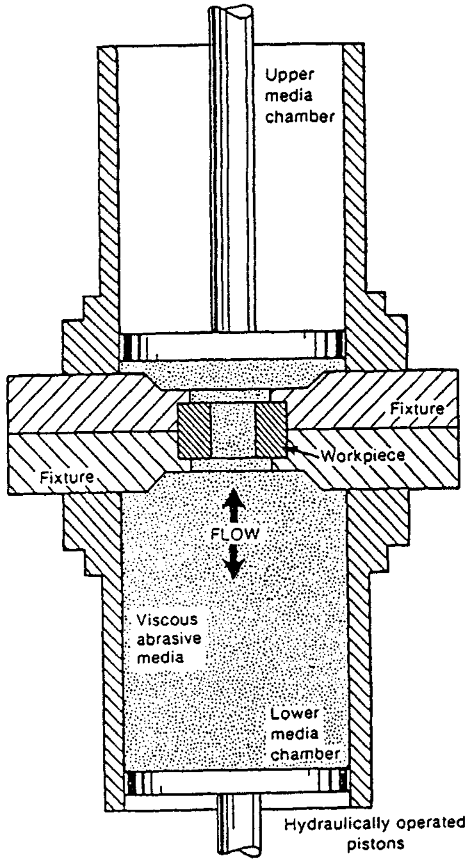



**Fig. 33.31** Abrasive flow machining.

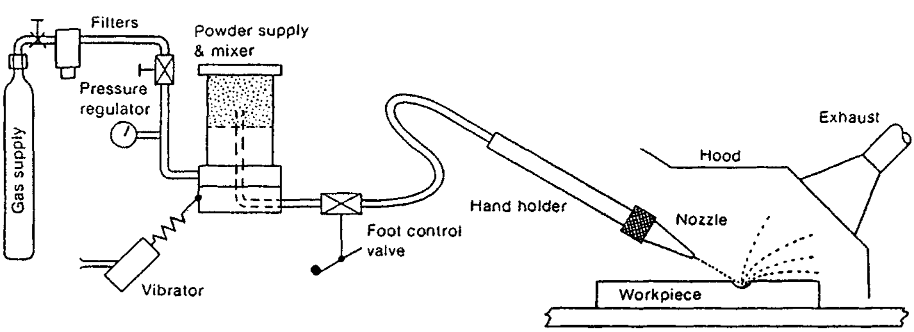



**Fig. 33.32** Abrasive jet machining.

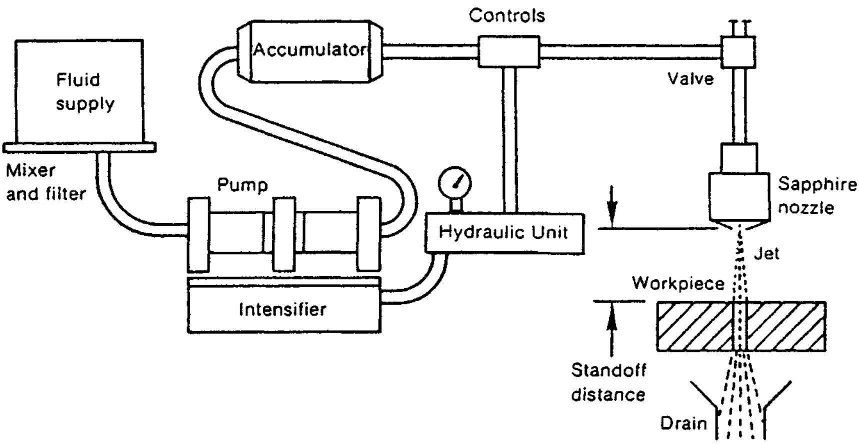



**Fig. 33.33** Hydrodynamic machining.

in the workpiece surface. The process parameter guidelines can be applied to any of the grinding modes: surface, cylindrical, centerless, internal, and so on.

### 33.16.5 Thermally Assisted Machining

Thermally assisted machining (TAM) is the addition of significant amounts of heat to the workpiece immediately prior to single-point cutting so that the material is softened but the strength of the tool bit is unimpaired (Fig. 33.35). While resistive heating and induction heating offer possibilities, the plasma arc has a core temperature of 14,500°F (8000°C) and a surface temperature of 6500°F (3600°C). The torch can produce 2000°F (1100°C) in the workpiece in approximately one-quarter revolution of the workpiece between the point of application of the torch and the cutting tool.

### 33.16.6 Electromechanical Machining

Electromechanical machining (EMM) is a process in which the metal removal is effected in a conventional manner except that the workpiece is electrochemically polarized. When the applied voltage

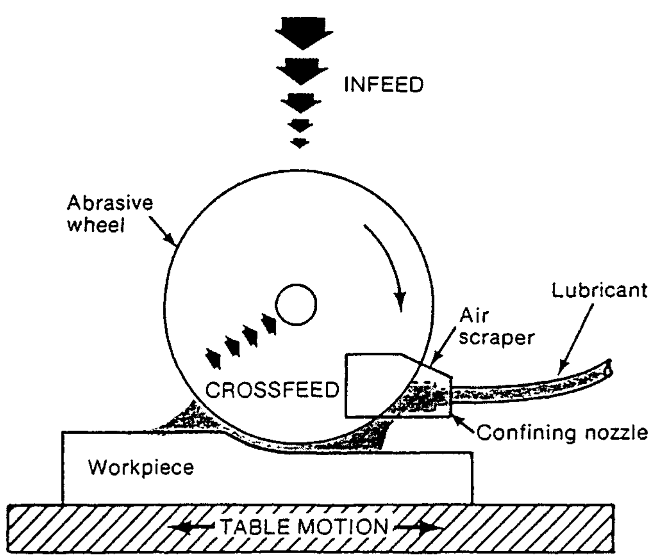



**Fig. 33.34** Low-stress grinding.

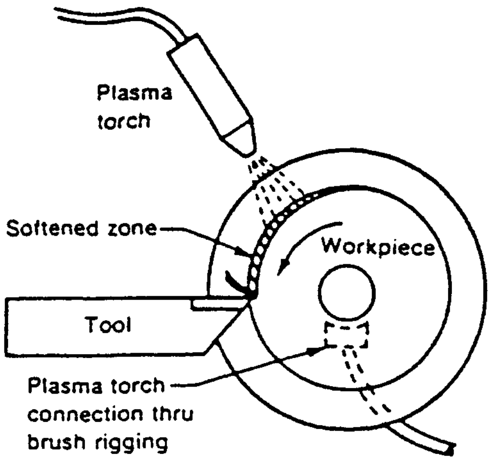



**Fig. 33.35** Thermally assisted machining.

and the electrolytic solution are controlled, the surface of the workpiece can be changed to achieve the characteristics suitable for the machining operation.

### 33.16.7 Total Form Machining

Total form machining (TFM) is a process in which an abrasive master abrades its full three-dimensional shape into the workpiece by the application of force while a full-circle, orbiting motion is applied to the workpiece via the worktable (Fig. 33.36). The cutting master is advanced into the work until the desired depth of cut is achieved. Uniformity of cutting is promoted by the fluid that continuously transports the abraded particles out of the working gap. Adjustment of the orbiting cam drive controls the precision of the overcut from the cutting master. Cutting action takes place simultaneously over the full surface of abrasive contact.

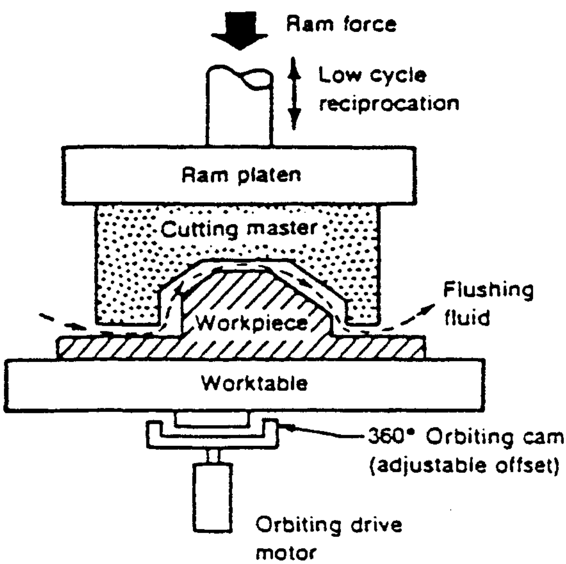



**Fig. 33.36** Total form machining.

### 33.16.8 Ultrasonic Machining

Ultrasonic machining (USM) is the removal of material by the abrading action of a grit-loaded liquid slurry circulating between the workpiece and a tool vibrating perpendicular to the workface at a frequency above the audible range (Fig. 33.37). A high-frequency power source activates a stack of magnetostrictive material, which produces a low-amplitude vibration of the toolholder. This motion is transmitted under light pressure to the slurry, which abrades the workpiece into a conjugate image of the tool form. A constant flow of slurry (usually cooled) is necessary to carry away the chips from the workface. The process is sometimes called *ultrasonic abrasive machining* (UAM) or *impact machining*.

A prime variation of USM is the addition of ultrasonic vibration to a rotating tool—usually a diamond-plated drill. *Rotary ultrasonic machining* (RUM) substantially increases the drilling efficiency. A piezoelectric device built into the rotating head provides the needed vibration. Milling, drilling, turning, threading, and grinding-type operations are performed with RUM.

### 33.16.9 Water-Jet Machining

Water-jet machining (WJM) is low-pressure hydrodynamic machining. The pressure range for WJM is an order of magnitude below that used in HDM. There are two versions of WJM: one for mining, tunneling, and large-pipe cleaning that operates in the region from 250–1000 psi (1.7–6.9 Mpa); and one for smaller parts and production shop situations that uses pressures below 250 psi (1.7 Mpa).

The first version, or high-pressure range, is characterized by use of a pumped water supply with hoses and nozzles that generally are hand-directed. In the second version, more production-oriented and controlled equipment, such as that shown in Fig. 33.38, is involved. In some instances, abrasives are added to the fluid flow to promote rapid cutting. Single or multiple-nozzle approaches to the workpiece depend on the size and number of parts per load. The principle is that WJM is high-volume, not high-pressure.

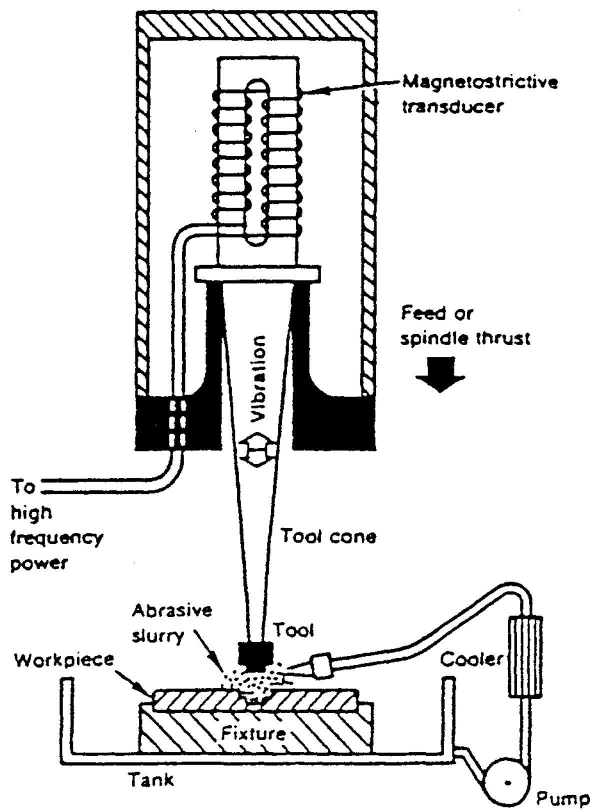



**Fig. 33.37** Ultrasonic machining.

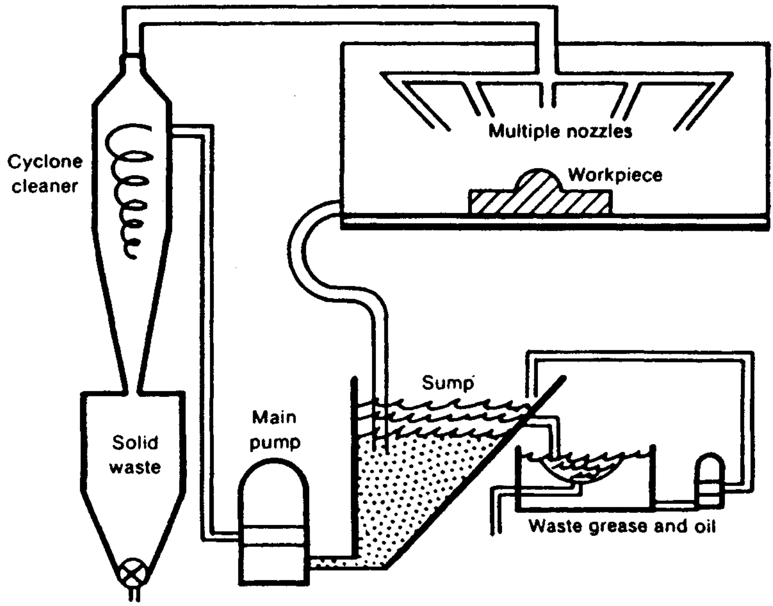



**Fig. 33.38** Water-jet machining.

### 33.16.10 Electrochemical Deburring

Electrochemical deburring (ECD) is a special version of ECM (Fig. 33.39). ECD was developed to remove burrs and fins or to round sharp corners. Anodic dissolution occurs on the workpiece burrs in the presence of a closely placed cathodic tool whose configuration matches the burred edge. Normally, only a small portion of the cathode is electrically exposed, so a maximum concentration of the electrolytic action is attained. The electrolyte flow usually is arranged to carry away any burrs that may break loose from the workpiece during the cycle. Voltages are low, current densities are high, electrolyte flow rate is modest, and electrolyte types are similar to those used for ECM. The electrode (tool) is stationary, so equipment is simpler than that used for ECM. Cycle time is short for deburring. Longer cycle time produces a natural radiusing action.

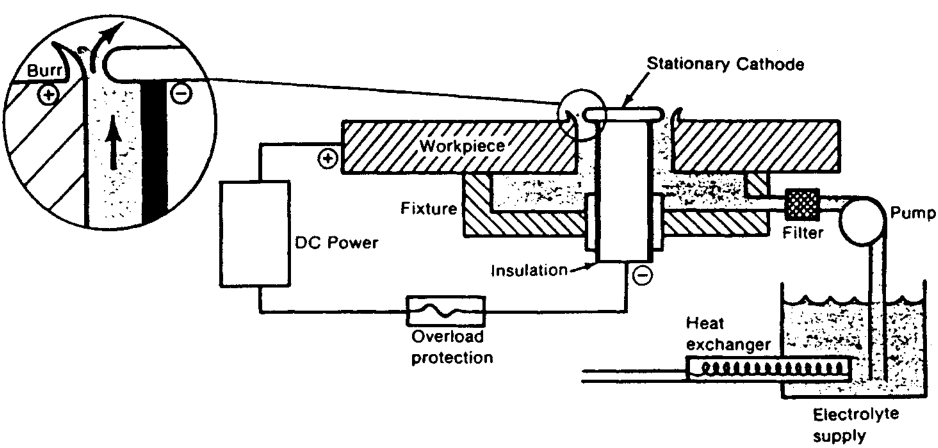



**Fig. 33.39** Electrochemical deburring.

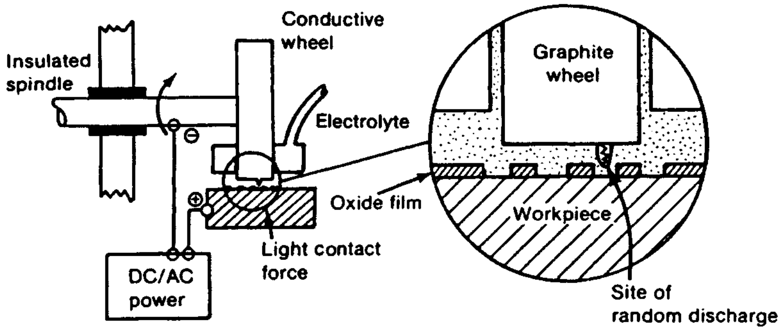



**Fig. 33.40** Electrochemical discharge grinding.

### 33.16.11 Electrochemical Discharge Grinding

Electrochemical discharge grinding (ECDG) combines the features of both electrochemical and electrical discharge methods of material removal (Fig. 33.40). ECDG has the arrangement and electrolytes of electrochemical grinding (ECG), but uses a graphite wheel without abrasive grains. The random spark discharge is generated through the insulating oxide film on the workpiece by the power generated in an ac source or by a pulsating dc source. The principal material removal comes from the electrolytic action of the low-level dc voltages. The spark discharges erode the anodic films to allow the electrolytic action to continue.

### 33.16.12 Electrochemical Grinding

Electrochemical grinding (ECG) is a special form of electrochemical machining in which the conductive workpiece material is dissolved by anodic action, and any resulting films are removed by a rotating, conductive, abrasive wheel (Fig. 33.41). The abrasive grains protruding from the wheel form the insulating electrical gap between the wheel and the workpiece. This gap must be filled with electrolyte at all times. The conductive wheel uses conventional abrasives—aluminum oxide (because it is nonconductive) or diamond (for intricate shapes)—but lasts substantially longer than wheels used in conventional grinding. The reason for this is that the bulk of material removal (95–98%) occurs by deplating, while only a small amount (2–5%) occurs by abrasive mechanical action. Maximum wheel contact arc lengths are about ¾–1 in. (19–25 mm) to prevent overheating the electrolyte. The fastest material removal is obtained by using the highest attainable current densities without boiling the electrolyte. The corrosive salts used as electrolytes should be filtered and flow rate should be controlled for the best process control.

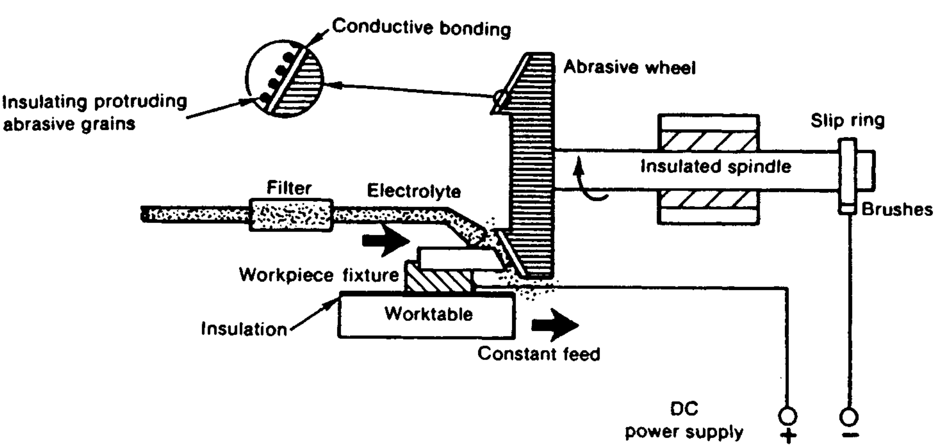



**Fig. 33.41** Electrochemical grinding.

### 33.16.13 Electrochemical Honing

Electrochemical honing (ECH) is the removal of material by anodic dissolution combined with mechanical abrasion from a rotating and reciprocating abrasive stone (carried on a spindle, which is the cathode) separated from the workpiece by a rapidly flowing electrolyte (Fig. 33.42). The principal material removal action comes from electrolytic dissolution. The abrasive stones are used to maintain size and to clean the surfaces to expose fresh metal to the electrolyte action. The small electrical gap is maintained by the nonconducting stones that are bonded to the expandable arbor with cement. The cement must be compatible with the electrolyte and the low dc voltage. The mechanical honing action uses materials, speeds, and pressures typical of conventional honing.

### 33.16.14 Electrochemical Machining

Electrochemical machining (ECM) is the removal of electrically conductive material by anodic dissolution in a rapidly flowing electrolyte, which separates the workpiece from a shaped electrode (Fig. 33.43). The filtered electrolyte is pumped under pressure and at controlled temperature to bring a controlled-conductivity fluid into the narrow gap of the cutting area. The shape imposed on the workpiece is nearly a mirror or conjugate image of the shape of the cathodic electrode. The electrode is advanced into the workpiece at a constant feed rate that exactly matches the rate of dissolution of the work material. Electrochemical machining is basically the reverse of electroplating.

#### Calculation of Metal Removal and Feed Rates in ECM

$$\text{current } I = \frac{V}{R} \text{ amp}$$

$$\text{resistance } R = \frac{g \times r}{A}$$

where $g$ = length of gap (cm)
$r$ = electrolyte resistivity
$A$ = area of current path ($cm^2$)
$V$ = voltage
$R$ = resistance

$$\text{current density } S = \frac{I}{A} = \frac{V}{r \times g} \text{ amp/cm}^2$$

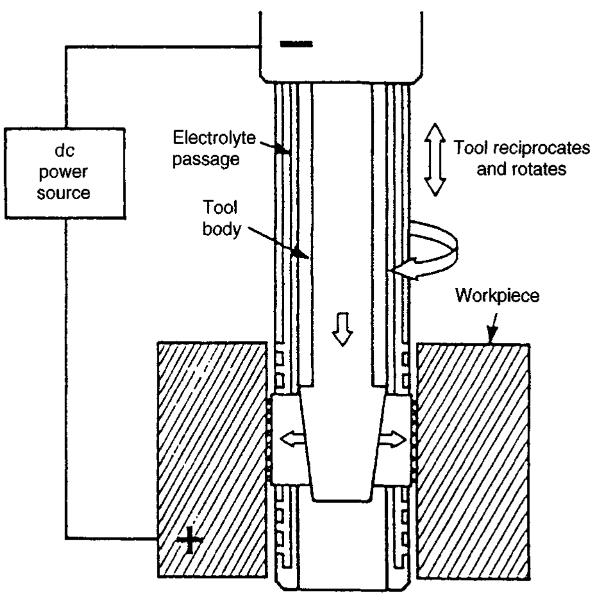



**Fig. 33.42** Electrochemical honing.

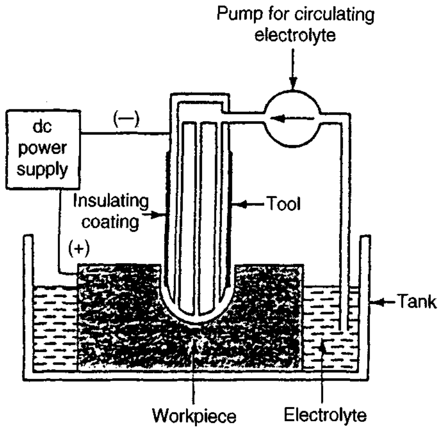



**Fig. 33.43** Electrochemical machining.

The amount of material deposited or dissolved is proportional to the quantity of electricity passed (current × time).

$$\text{amount of material} = C \times I \times t$$

where $C$ = constant
$t$ = time, sec

The amount removed or deposited by one faraday (96,500 coulombs = 96,500 amp–sec) is 1 gram-equivalent weight ($G$)

$$G = \frac{N}{n} \quad \text{(for 1 faraday)}$$

where $N$ = atomic weight
$n$ = valence

$$\text{volume of metal removed} = \frac{I \times t}{96{,}500} \times \frac{N}{n} \times \frac{1}{d} \times h$$

where $d$ = density, $g/cm^3$
$h$ = current efficiency

$$\text{specific removal rate } s = \frac{N}{n} \times \frac{1}{96{,}500} \times h \quad cm^3/\text{amp–sec}$$

$$\text{cathode feed rate } F = S \times s \quad \text{cm/sec.}$$

### 33.16.15 Electrochemical Polishing

Electrochemical polishing (ECP) is a special form of electrochemical machining arranged for cutting or polishing a workpiece (Fig. 33.44). Polishing parameters are similar in range to those for cutting, but without the feed motion. ECP generally uses a larger gap and a lower current density than does ECM. This requires modestly higher voltages. (In contrast, electropolishing (ELP) uses still lower current densities, lower electrolyte flow, and more remote electrodes.)

### 33.16.16 Electrochemical Sharpening

Electrochemical sharpening (ECS) is a special form of electrochemical machining arranged to accomplish sharpening or polishing by hand (Fig. 33.45). A portable power pack and electrolyte reservoir supply a finger-held electrode with a small current and flow. The fixed gap incorporated on the several styles of shaped electrodes controls the flow rate. A suction tube picks up the used electrolyte for recirculation after filtration.

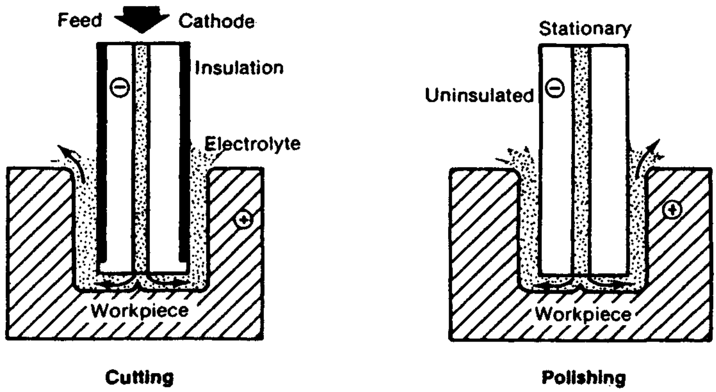



**Fig. 33.44** Electrochemical polishing.

### 33.16.17 Electrochemical Turning

Electrochemical turning (ECT) is a special form of electrochemical machining designed to accommodate rotating workpieces (Fig. 33.46). The rotation provides additional accuracy but complicates the equipment with the method of introducing the high currents to the rotating part. Electrolyte control may also be complicated because rotating seals are needed to direct the flow properly. Otherwise, the parameters and considerations of electrochemical machining apply equally to the turning mode.

### 33.16.18 Electro-stream

Electro-stream (ES) is a special version of electrochemical machining adapted for drilling very small holes using high voltages and acid electrolytes (see Fig. 33.47). The voltages are more than 10 times those employed in ECM or STEM, so special provisions for containment and protection are required. The tool is a drawn-glass nozzle, 0.001–0.002 in. smaller than the desired hole size. An electrode inside the nozzle or the manifold ensures electrical contact with the acid. Multiple-hole drilling is achieved successfully by ES.

### 33.16.19 Shaped-Tube Electrolytic Machining

Shaped-tube electrolytic machining (STEM™) is a specialized ECM technique for "drilling" small, deep holes by using acid electrolytes (Fig. 33.48). Acid is used so that the dissolved metal will go into the solution rather than form a sludge, as is the case with the salt-type electrolytes of ECM. The electrode is a carefully straightened acid-resistant metal tube. The tube is coated with a film of enamel-type insulation. The acid is pressure-fed through the tube and returns via a narrow gap between the tube insulation and the hole wall. The electrode is fed into the workpiece at a rate exactly equal to the rate at which the workpiece material is dissolved. Multiple electrodes, even of varying

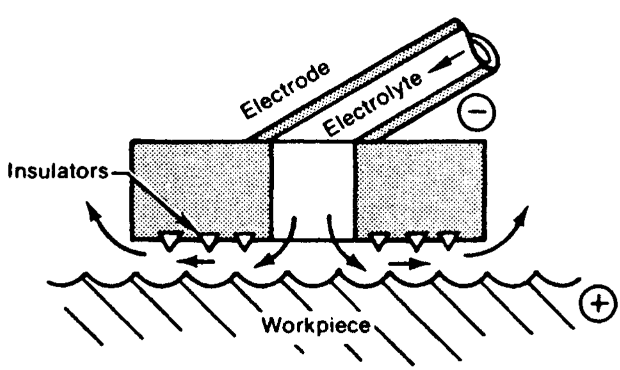



**Fig. 33.45** Electrochemical sharpening.

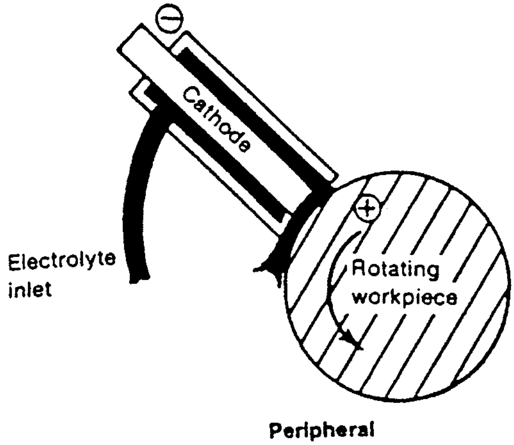



**Fig. 33.46** Electrochemical turning.

diameters or shapes, may be used simultaneously. A solution of sulfuric acid is frequently used as the electrolyte when machining nickel alloys. The electrolyte is heated and filtered, and flow monitors control the pressure. Tooling is frequently made of plastics, ceramics, or titanium alloys to withstand the electrified hot acid.

### 33.16.20 Electron-Beam Machining

Electron-beam machining (EBM) removes material by melting and vaporizing the workpiece at the point of impingement of a focused stream of high-velocity electrons (Fig. 33.49). To eliminate scattering of the beam of electrons by contact with gas molecules, the work is done in a high-vacuum chamber. Electrons emanate from a triode electron-beam gun and are accelerated to three-fourths the speed of light at the anode. The collision of the electrons with the workpiece immediately translates their kinetic energy into thermal energy. The low-inertia beam can be simply controlled by electromagnetic fields. Magnetic lenses focus the electron beam on the workpiece, where a 0.001-in. (0.025-mm) diameter spot can attain an energy density of up to $10^9$ W/in.$^2$ ($1.55 \times 10^8$ W/cm$^2$) to melt and vaporize any material. The extremely fast response time of the beam is an excellent companion for three-dimensional computer control of beam deflection, beam focus, beam intensity, and workpiece motion.

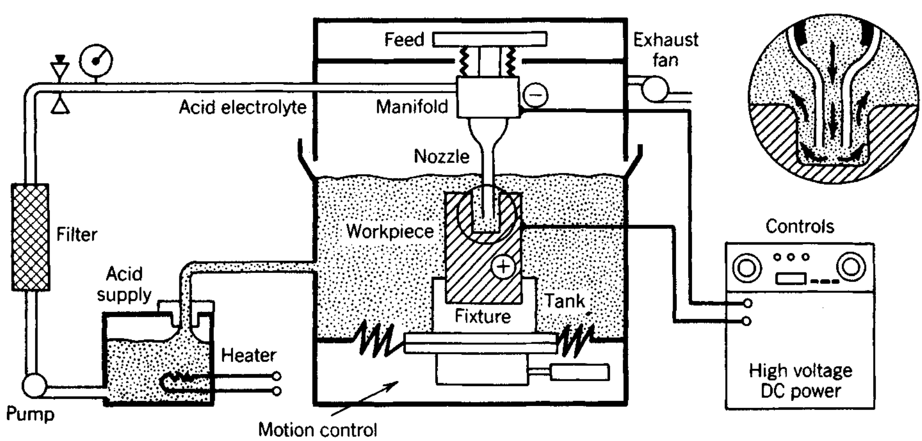



**Fig. 33.47** Electro-stream.

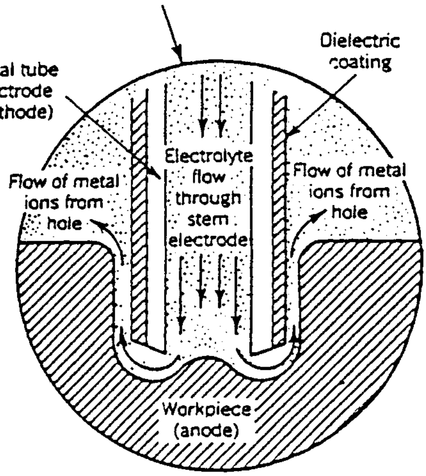



**Fig. 33.48** Shaped-tube electrolytic machining.

### 33.16.21 Electrical Discharge Grinding

Electrical discharge grinding (EDG) is the removal of a conductive material by rapid, repetitive spark discharges between a rotating tool and the workpiece, which are separated by a flowing dielectric fluid (Fig. 33.50). (EDG is similar to EDM except that the electrode is in the form of a grinding wheel and the current is usually lower.) The spark gap is servocontrolled. The insulated wheel and the worktable are connected to the dc pulse generator. Higher currents produce faster cutting, rougher finishes, and deeper heat-affected zones in the workpiece.

### 33.16.22 Electrical Discharge Machining

Electrical discharge machining (EDM) removes electrically conductive material by means of rapid, repetitive spark discharges from a pulsating dc power supply with dielectric flowing between the workpiece and the tool (Fig. 33.51). The cutting tool (electrode) is made of electrically conductive material, usually carbon. The shaped tool is fed into the workpiece under servocontrol. A spark discharge then breaks down the dielectric fluid. The frequency and energy per spark are set and

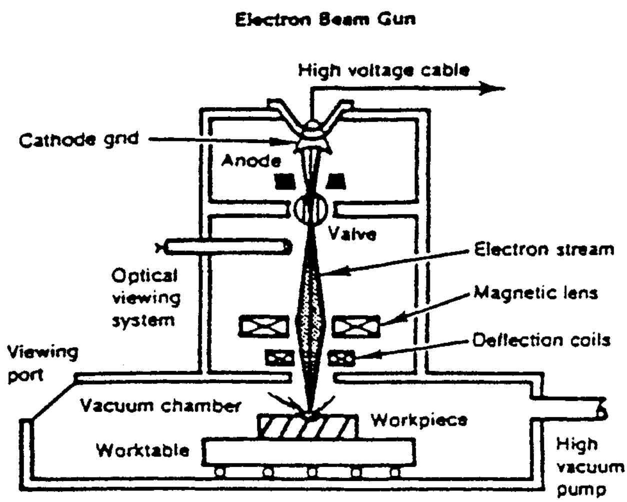



**Fig. 33.49** Electron-beam machining.

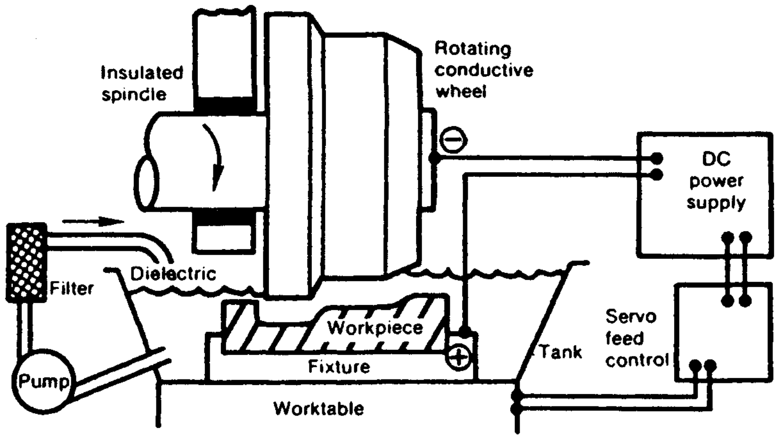



**Fig. 33.50** Electrical discharge grinding.

controlled with a dc power source. The servocontrol maintains a constant gap between the tool and the workpiece while advancing the electrode. The dielectric oil cools and flushes out the vaporized and condensed material while reestablishing insulation in the gap. Material removal rate ranges from 16–245 $cm^3/h$. EDM is suitable for cutting materials regardless of their hardness or toughness. Round or irregular-shaped holes 0.002 in. (0.05 mm) diameter can be produced with L/D ratio of 20:1. Narrow slots as small as 0.002–0.010 in. (0.05–0.25 mm) wide are cut by EDM.

### 33.16.23 Electrical Discharge Sawing

Electrical discharge sawing (EDS) is a variation of electrical discharge machining (EDM) that combines the motion of either a band saw or a circular disk saw with electrical erosion of the workpiece (Fig. 33.52). The rapid-moving, untoothed, thin, special steel band or disk is guided into the workpiece by carbide-faced inserts. A kerf only 0.002–0.005 in. (0.050–0.13 mm) wider than the blade or disk is formed as they are fed into the workpiece. Water is used as a cooling quenchant for the tool, swarf, and workpiece. Circular cutting is usually performed under water, thereby reducing noise and fumes. While the work is power-fed into the band (or the disk into the work), it is not subjected to appreciable forces because the arc does the cutting, so fixturing can be minimal.

### 33.16.24 Electrical Discharge Wire Cutting (Traveling Wire)

Electrical discharge wire cutting (EDWC) is a special form of electrical discharge machining wherein the electrode is a continuously moving conductive wire (Fig. 33.53). EDWC is often called *traveling*

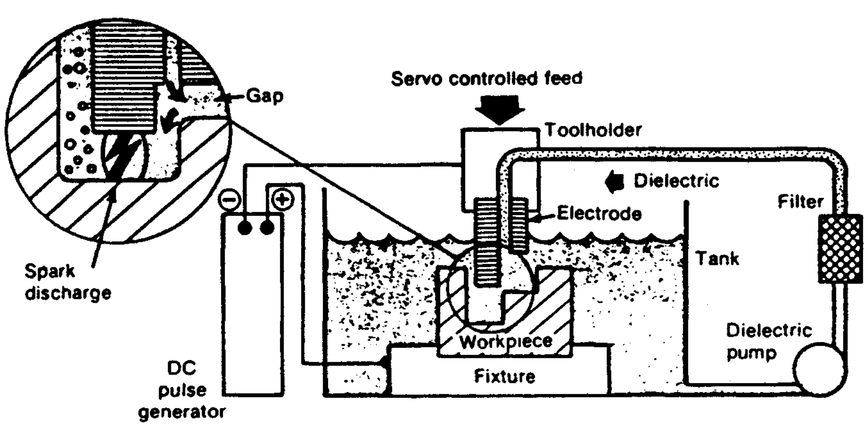



**Fig. 33.51** Electrical discharge machining.

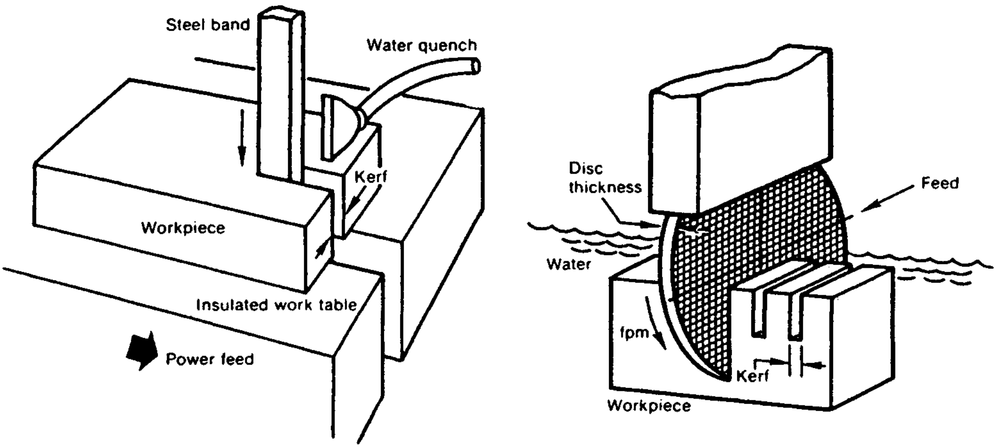



**Fig. 33.52** Electrical discharge sawing.

*wire* EDM. A small-diameter tension wire, 0.001–0.012 in. (0.03–0.30 mm), is guided to produce a straight, narrow-kerf size 0.003–0.015 in. (0.075–0.375 mm). Usually, a programmed or numerically controlled motion guides the cutting, while the width of the kerf is maintained by the wire size and discharge controls. The dielectric is oil or deionized water carried into the gap by motion of the wire. Wire EDM is able to cut plates as thick as 12 in. (300 mm) and issued for making dies from hard metals. The wire travels with speed in the range of 6–300 in./min (0.15–8 mm/min). A typical cutting rate is 1 in.$^2$ (645 mm$^2$) of cross-sectional area per hour.

### 33.16.25 Laser-Beam Machining

Laser-beam machining (LBM) removes material by melting, ablating, and vaporizing the workpiece at the point of impingement of a highly focused beam of coherent monochromatic light (Fig. 33.54). Laser is an acronym for "light amplification by stimulated emission of radiation." The electromagnetic radiation operates at wavelengths from the visible to the infrared. The principal lasers used for material removal are the ND:glass (neodymium–glass), the Nd:YAG (neodymium:yttrium-aluminum-garnet), the ruby and the carbon dioxide ($CO_2$). The last is a gas laser (most frequently used as a torch with an assisting gas—see LBT, laser-beam torch), while others are solid-state lasing materials.

For pulsed operation, the power supply produces short, intense bursts of electricity into the flash lamps, which concentrate their light flux on the lasing material. The resulting energy from the excited

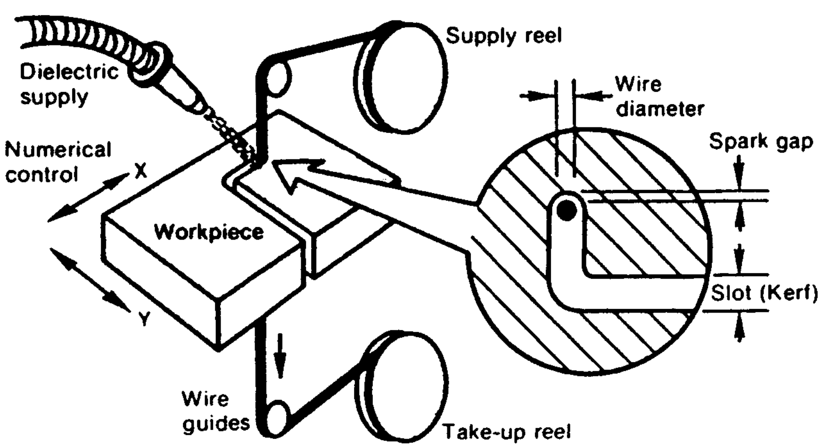



**Fig. 33.53** Electrical discharge wire cutting.

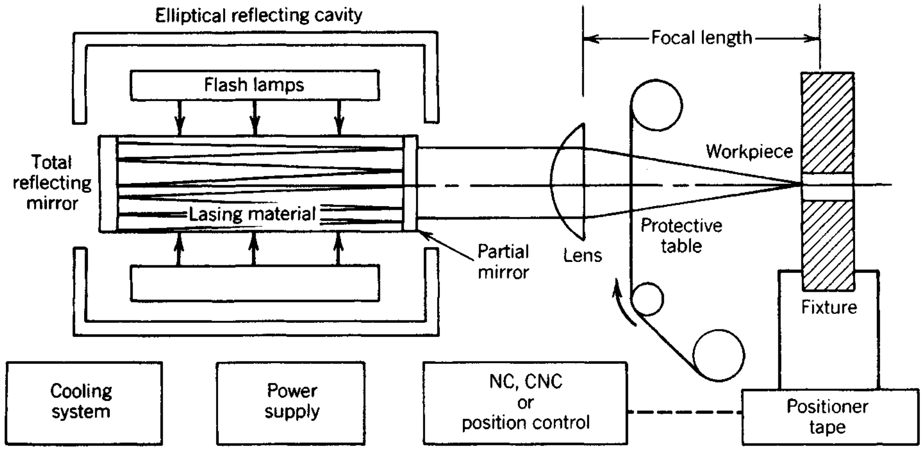



**Fig. 33.54** Laser-beam machining.

atoms is released at a characteristic, constant frequency. The monochromatic light is amplified during successive reflections from the mirrors. The thoroughly collimated light exits through the partially reflecting mirror to the lens, which focuses it on or just below the surface of the workpiece. The small beam divergence, high peak power, and single frequency provide excellent, small-diameter spots of light with energy densities up to $3 \times 10^{10}$ W/in.$^2$ ($4.6 \times 10^9$ W/cm$^2$), which can sublime almost any material. Cutting requires energy densities of $10^7$–$10^9$ W/in.$^2$ ($1.55 \times 10^6$–$1.55 \times 10^8$ W/cm$^2$), at which rate the thermal capacity of most materials cannot conduct energy into the body of the workpiece fast enough to prevent melting and vaporization. Some lasers can instantaneously produce 41,000°C (74,000°F). Holes of 0.001 in. (0.025 mm), with depth-to-diameter 50 to 1 are typically produced in various materials by LBM.

### 33.16.26 Laser-Beam Torch

Laser-beam torch (LBT) is a process in which material is removed by the simultaneous focusing of a laser beam and a gas stream on the workpiece (see Fig. 33.55). A continuous-wave (CW) laser or a pulsed laser with more than 100 pulses per second is focused on or slightly below the surface of the workpiece, and the absorbed energy causes localized melting. An oxygen gas stream promotes an exothermic reaction and purges the molten material from the cut. Argon or nitrogen gas is sometimes used to purge the molten material while also protecting the workpiece.

Argon or nitrogen gas is often used when organic or ceramic materials are being cut. Close control of the spot size and the focus on the workpiece surface is required for uniform cutting. The type of gas used has only a modest effect on laser penetrating ability. Typically, short laser pulses with high peak power are used for cutting and welding. The $CO_2$ laser is the laser most often used for cutting. Thin materials are cut at high rates, ⅛–⅜ in. (3.2–9.5 mm) thickness is a practical limit.

### 33.16.27 Plasma-Beam Machining

Plasma-beam machining (PBM) removes material by using a superheated stream of electrically ionized gas (Fig. 33.56). The 20,000–50,000°F (11,000–28,000°C) plasma is created inside a water-cooled nozzle by electrically ionizing a suitable gas, such as nitrogen, hydrogen, or argon, or mixtures of these gases. Since the process does not rely on the heat of combustion between the gas and the workpiece material, it can be used on almost any conductive metal. Generally, the arc is transferred to the workpiece, which is made electrically positive. The plasma—a mixture of free electrons, positively charged ions, and neutral atoms—is initiated in a confined, gas-filled chamber by a high-frequency spark. The high-voltage dc power sustains the arc, which exits from the nozzle at near-sonic velocity. The high-velocity gases 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. PBM is sometimes called *plasma-arc cutting* (PAC). PBM can cut plates up to 6.0 in. (152 mm) thick. Kerf width can be as small as 0.06 in. (1.52 mm) in cutting thin plates.

### 33.16.28 Chemical Machining: Chemical Milling, Chemical Blanking

Chemical machining (CHM) is the controlled dissolution of a workpiece material by contact with a strong chemical reagent (Fig. 33.57). The thoroughly cleaned workpiece is covered with a strippable,

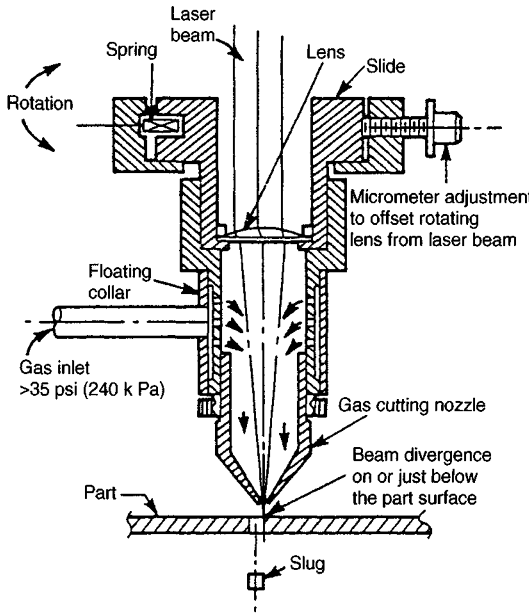



**Fig. 33.55** Laser-beam torch.

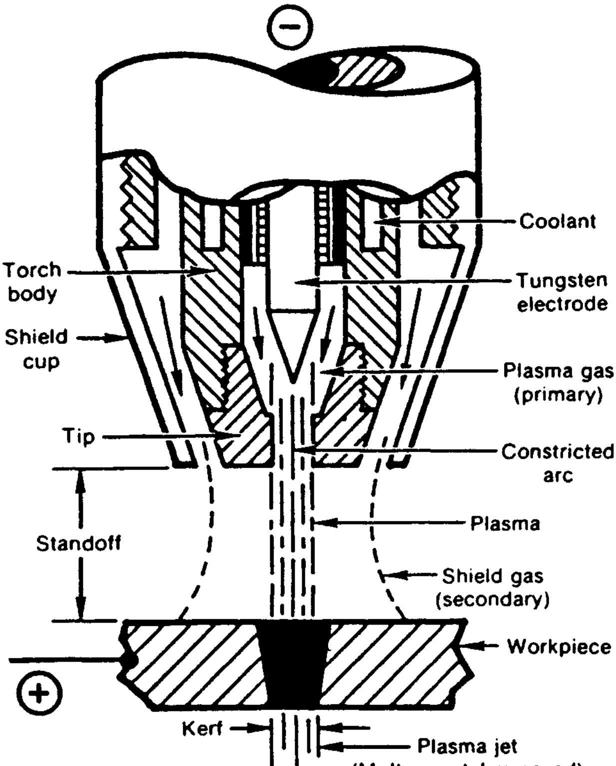



**Fig. 33.56** Plasma-beam machining.

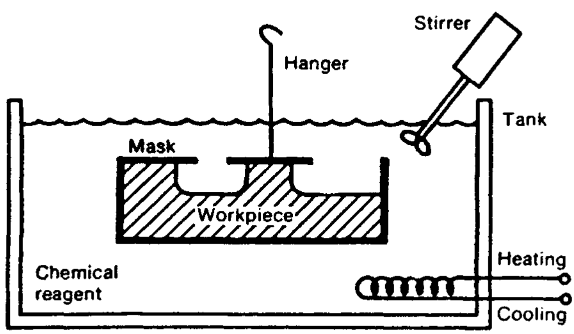



Fig. 33.57 Chemical machining.

chemically resistant mask. Areas where chemical action is desired are outlined on the workpiece with the use of a template and then stripped off the mask. The workpiece is then submerged in the chemical reagent to remove material simultaneously from all exposed surfaces. The solution should be stirred or the workpiece should be agitated for more effective and more uniform action. Increasing the temperatures will also expedite the action. The machined workpiece is then washed and rinsed, and the remaining mask is removed. Multiple parts can be maintained simultaneously in the same tank. A wide variety of metals can be chemically machined; however, the practical limitations for depth of cut are 0.25–0.5 in. (6.0–12.0 mm) and typical etching rate is 0.001 in./min (0.025 mm/min).

In chemical blanking, the material is removed by chemical dissolution instead of shearing. The operation is applicable to production of complex shapes in thin sheets of metal.

### 33.16.29 Electropolishing

Electropolishing (ELP) is a specialized form of chemical machining that uses an electrical deplating action to enhance the chemical action (Fig. 33.58). The chemical action from the concentrated heavy acids does most of the work, while the electrical action smooths or polishes the irregularities. A metal cathode is connected to a low-voltage, low-amperage dc power source and is installed in the chemical bath near the workpiece. Usually, the cathode is not shaped or conformed to the surface being polished. The cutting action takes place over the entire exposed surface; therefore, a good flow of heated, fresh chemicals is needed in the cutting area to secure uniform finishes. The cutting action will concentrate first on burrs, fins, and sharp corners. Masking, similar to that used with CHM, prevents cutting in unwanted areas. Typical roughness values range from 4–32 $\mu$in. (0.1–0.8 $\mu$m).

### 33.16.30 Photochemical Machining

Photochemical machining (PCM) is a variation of CHM where the chemically resistant mask is applied to the workpiece by a photographic technique (Fig. 33.59). A photographic negative, often a reduced image of an oversize master print (up to 100 ×), is applied to the workpiece and developed.

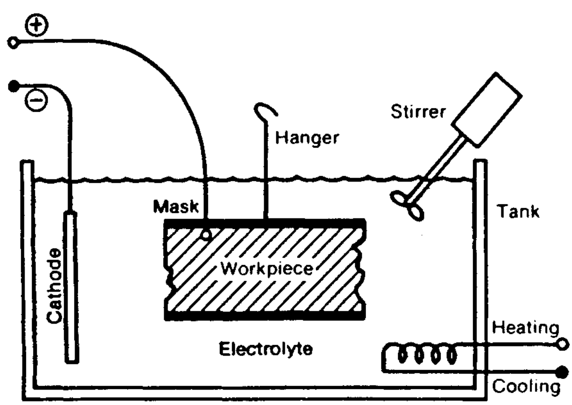



Fig. 33.58 Electropolishing.

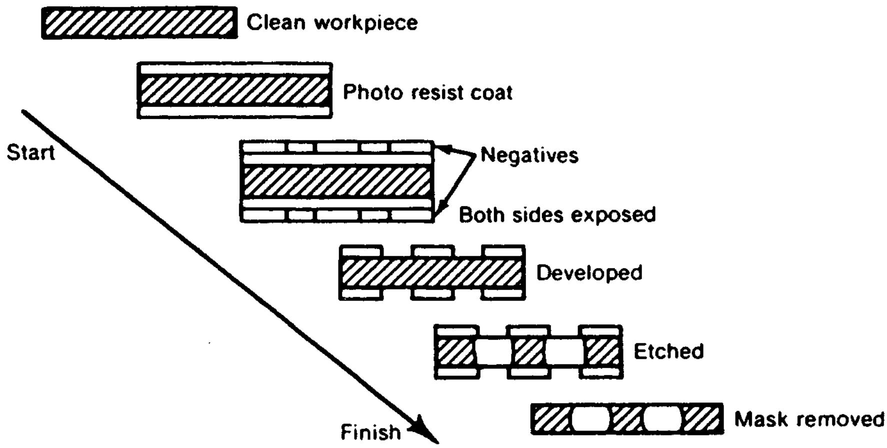



**Fig. 33.59** Photochemical machining.

Precise registry of duplicate negatives on each side of the sheet is essential for accurately blanked parts. Immersion or spray etching is used to remove the exposed material. The chemicals used must be active on the workpiece, but inactive against the photoresistant mask. The use of PCM is limited to thin materials—up to 1/16 in. (1.5 mm).

### 33.16.31 Thermochemical Machining

Thermochemical machining (TCM) removes the workpiece material—usually only burrs and fins—by exposure of the workpiece to hot, corrosive gases. The process is sometimes called *combustion machining, thermal deburring,* or *thermal energy method* (TEM). The workpiece is exposed for a very short time to extremely hot gases, which are formed by detonating an explosive mixture. The ignition of the explosive—usually hydrogen or natural gas and oxygen—creates a transient thermal wave that vaporizes the burrs and fins. The main body of the workpiece remains unaffected and relatively cool because of its low surface-to-mass ratio and the shortness of the exposure to high temperatures.

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