Manufacturing Processes for Engineering Materials

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Stratus Ex. 2044

Manufacturing Processes for Engineering Materials

FOURTH EDITION

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Illinois Institute of Technology, Chicago, Illinois

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EXAMPLE 9.5 Machining time in electrochemical machining vs. drilling

A round hole 12.5 mm in diameter is being produced in a titanium-alloy block by electrochemical machining. Using a current density of 6 A/mm^2, estimate the time required for machining a 20-mm-deep hole. Assume that the efficiency is 90%. Compare this time with that required for ordinary drilling.

Solution. We note from Eqs. (9.14) and (9.15) that the feed rate can be expressed by the equation

$$f = \frac{CI\eta}{A_o}.$$

Letting $C = 1.6\ \text{mm}^3/\text{A}\cdot\text{min}$ and $I/A_o = 6\ \text{A/mm}^2$, we find that the feed rate is $f = (1.6)(6)(0.9) = 8.64$ mm/min. Since the hole is 20 mm deep,

$$\text{Machining time} = \frac{20}{8.64} = 2.3\ \text{min}.$$

To determine the drilling time, we refer to Table 8.10 and note the data for titanium alloys. Let's select the following values for a 12.5-mm drill: drill rpm = 300 and feed = 0.15 mm/rev. From these values, we calculate that the feed rate will be (300 rev/min)(0.15 mm/rev) = 45 mm/min. Since the hole is 20 mm deep,

$$\text{Drilling time} = \frac{20}{45} = 0.45\ \text{min},$$

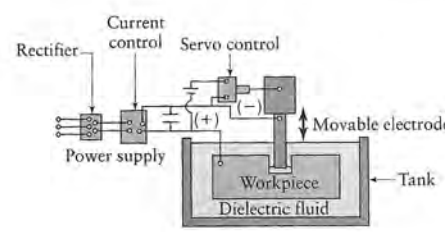
which is about 20% of the time for ECM.

9.13 Electrical-Discharge Machining

The principle of *electrical-discharge machining* (EDM), also called *electrodischarge* or *sparkerosion machining*, is based on erosion of metals by spark discharges (Table 9.4). We know that when two current-conducting wires are allowed to touch each other, an arc is produced. If we look closely at the point of contact between the two wires, we note that a small portion of the metal has been eroded away, leaving a small crater. Although this phenomenon has been known since the discovery of electricity, it was not until the 1940s that a machining process based on this principle was developed. The EDM process has become one of the most important and widely accepted production technologies in manufacturing industries.

The EDM system (Fig. 9.32) consists of a shaped tool (**electrode**) and the workpiece, which are connected to a dc power supply and placed in a **dielectric** (electrically

FIGURE 9.32 Schematic illustration of the electrical-discharge-machining process.



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nonconducting) **fluid**. When a voltage is applied to the tool, a magnetic field causes suspended particles in the dielectric fluid to concentrate, eventually forming a bridge for current to flow to the workpiece. An intense electrical arc is then generated, causing sufficient heating to melt a portion of the workpiece and usually some of the cooling material as well. In addition, the dielectric fluid is heated rapidly, causing evaporation of the fluid in the arc gap; this evaporation, in turn, increases the resistance of the interface, until the arc can no longer be maintained. Once the arc is interrupted, heat is removed from the gas bubble by the surrounding dielectric fluid, and the bubble collapses (cavitates). The associated shock wave and flow of dielectric fluid flush debris from the surface and entrain any molten workpiece material into the dielectric fluid. The capacitor discharge is repeated at rates of between 50 kHz and 500 kHz, with voltages usually ranging between 50 V and 380 V and currents from 0.1 A to 500 A.

The dielectric fluid (1) acts as an insulator until the potential is sufficiently high, (2) acts as a flushing medium and carries away the debris in the gap, and (3) provides a cooling medium. The gap between the tool and the workpiece (called *overcut*) is critical; thus, the downward feed of the tool is controlled by a servomechanism, which automatically maintains a constant gap. The most common dielectric fluids are mineral oils, although kerosene and distilled and deionized water may be used in specialized applications. The workpiece is fixtured within the tank containing the dielectric fluid, and its movements are controlled by numerically controlled systems. The machines are equipped with a pump and filtering system for the dielectric fluid.

The EDM process can be used on any material that is an electrical conductor. The melting point and latent heat of melting are important physical properties that determine the volume of metal removed per discharge; as these values increase, the rate of material removal slows. The volume of material removed per discharge is typically in the range of 10^{-6} to 10^{-4} mm^3 (10^{-10} to 10^{-8} in^3). Since the process doesn't involve mechanical energy, the hardness, strength, and toughness of the workpiece material do not necessarily influence the removal rate. The frequency of discharge or the energy per discharge is usually varied to control the removal rate, as are the voltage and current. The rate and surface roughness increase with increasing current density and decreasing frequency of sparks.

Electrodes for EDM are usually made of graphite, although brass, copper, or copper–tungsten alloy may be used. The tools are shaped by forming, casting, powder metallurgy, or machining. Electrodes as small as 0.1 mm (0.005 in.) in diameter have been used. *Tool wear* is an important factor, since it affects dimensional accuracy and the shape produced. Tool wear can be minimized by reversing the polarity and using copper tools, a process called **no-wear EDM**.

Electrical-discharge machining has numerous applications, such as producing die cavities for large automotive-body components (die-sinking machining centers); narrow slots; turbine blades; various intricate shapes (Figs. 9.33a and b); and small-diameter deep holes (Fig. 9.33c), using tungsten wire as the electrode. Stepped cavities can be produced by controlling the relative movements of the workpiece in relation to the electrode (Fig. 9.34).

The material removal rate in electrical-discharge machining is basically a function of the current and the melting point of the workpiece material, although other process variables also have an effect. The following approximate empirical relationship can be used as a guide to estimate the metal removal rate in EDM:

$$\text{MRR} = 4 \times 10^4 I T_w^{-1.23}. \tag{9.18}$$

In this equation, MRR is in mm^3/min, I is the current in amperes, and T_w is the melting point of the workpiece in °C.

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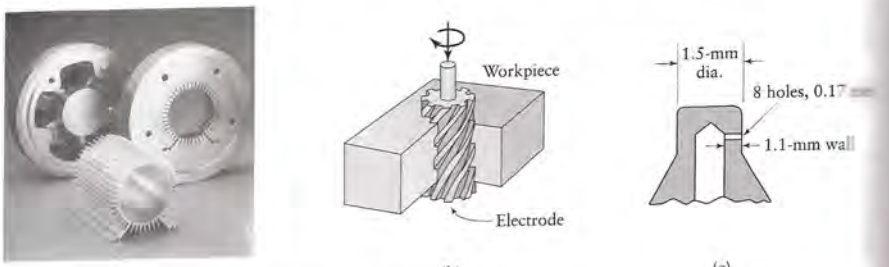

(a) (b) (c)

FIGURE 9.33 (a) Examples of cavities produced by the electrical-discharge-machining process, using shaped electrodes. The two round parts (rear) are the set of dies for extruding the aluminum piece shown in front. *Source*: Courtesy of AGIE USA Ltd. (b) A spiral cavity produced by a rotating electrode. *Source*: *American Machinist*. (c) Holes in a fuel-injection nozzle made by electrical-discharge machining. Material: Heat-treated steel.

FIGURE 9.34 Stepped cavities produced with a square electrode by EDM. The workpiece moves in the two principal horizontal directions, and its motion is synchronized with the downward movement of the electrode to produce various cavities. Also shown is a round electrode capable of producing round or elliptical cavities. *Source*: Courtesy of AGIE USA Ltd.

The wear rate of the electrode, W_t, can be estimated from the empirical equation

$$W_t = 1.1 \times 10^{11} I T_t^{-2.38} \qquad (9.19)$$

where W_t is mm^3/min and T_t is the melting point of the electrode material in °C. The wear ratio of the workpiece to electrode, R, can be estimated from the expression

$$R = 2.25\, T_r^{-2.38} \qquad (9.20)$$

where T_r is the ratio of workpiece to electrode melting points. In practice, the value of R varies over a wide range, between 0.2 and 100. (Note that in abrasive processing, grinding ratios also are in the same range; see Section 9.5.2.)

Metal removal rates usually range from 2 to 400 mm^3/min. High rates produce a very rough finish, with a molten and resolidified (recast) structure with poor surface integrity and low fatigue properties; thus, finishing cuts are made at low metal removal rates, or the recast layer is removed later by finishing operations. A more recent technique is to use an oscillating electrode, which provides very fine surface finish, requiring significantly less benchwork to improve lustrous cavities.

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EXAMPLE 9.6 Machining time in electrical-discharge machining vs. drilling

Calculate the machining time for producing the hole in Example 9.5 by EDM, and compare the time with that for drilling and for ECM. Assume that the titanium alloy has a melting point of 1600°C (see Table 3.2) and that the current is 100 A. Also calculate the wear rate of the electrode, assuming that the melting point of the electrode is 1100°C.

Solution. Using Eq. (9.18), we find that

$$\text{MRR} = (4 \times 10^4)(100)(1600^{-1.23}) = 458\ \text{mm}^3/\text{min}.$$

The volume of the hole is

$$V = \pi\left[\frac{(12.5)^2}{4}\right](20) = 2454\ \text{mm}^3.$$

Hence, the machining time for EDM is 2454/458 = 5.4 min; this time is 2.35 times that for ECM and 11.3 times that for drilling. Note, however, that if the current is increased to 300 A, then the machining time for EDM will only be 1.8 minutes, which is less than the time for ECM. The wear rate of the electrode is calculated using Eq. (9.19). Thus,

$$W_t = (11 \times 10^3)(100)(1100^{-2.38}) = 0.064\ \text{mm}^3/\text{min}.$$

9.13.1 Electrical-discharge grinding

The grinding wheel in *electrical-discharge grinding* (EDG) is made of graphite or brass and contains no abrasives. Material is removed from the surface of the workpiece by repetitive spark discharges between the rotating wheel and the workpiece. The material removal rate can be estimated from the equation

$$\text{MRR} = KI, \tag{9.21}$$

where MRR is in mm³/min, I = current in amperes, and K = workpiece material factor in mm³/A-min; for example, K = 16 for steel and 4 for tungsten carbide.

The EDG process can be combined with electrochemical grinding; the process is then called **electrochemical-discharge grinding** (ECDG). Material is removed by chemical action, with the electrical discharges from the graphite wheel breaking up the oxide film, which is washed away by the electrolyte flow. The process is used primarily for grinding carbide tools and dies, but can also be used for grinding fragile parts, such as surgical needles, thin-walled tubes, and honeycomb structures. The ECDG process is faster than EDG, but power consumption for ECDG is higher.

In **sawing** with EDM, a setup similar to a band or circular saw (but without any teeth) is used with the same electrical circuit as in EDM. Narrow cuts can be made at high rates of metal removal. Because the cutting forces are negligible, the process can be used on slender components.

9.13.2 Wire EDM

A variation of EDM is *wire* EDM (Fig. 9.35), or *electrical-discharge wire cutting*. In this process, which is similar to contour cutting with a band saw (Section 8.9.5), a slowly moving wire travels along a prescribed path, cutting the workpiece, with the discharge sparks acting like cutting teeth. This process is used to cut plates as thick

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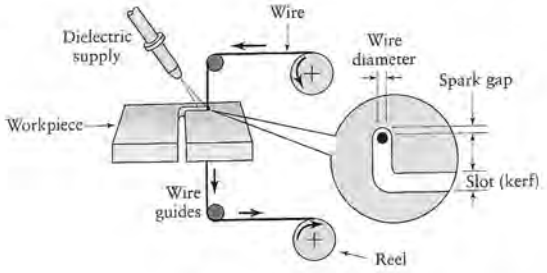

FIGURE 9.35 Schematic illustration of the wire EDM process. As much as 50 hours of machining can be performed with one reel of wire, which is then discarded or recycled.

as 300 mm (12 in.) and for making punches, tools, and dies from hard metals; it can also cut intricate components for the electronics industry (Table 9.4).

The wire is usually made of brass, copper, or tungsten and is typically about 0.25 mm (0.01 in.) in diameter, making narrow cuts possible; zinc- or brass-coated and multicoated wires are also used. The wire should have sufficient tensile strength and fracture toughness, as well as high electrical conductivity and capacity to flush away the debris produced during cutting. The wire is generally used only once, as it is relatively inexpensive. It travels at a constant velocity in the range of 0.15 to 9 m/min (6 to 360 in./min), and a constant gap (*kerf*) is maintained during the cut. The cutting speed is generally given in terms of the cross-sectional area cut per unit time; some typical examples are 18,000 mm^2/hr (28 in^2/hr) for 50-mm-thick (2-in-thick) D2 tool steel and 45,000 mm^2/hr (70 in^2/hr) for 150-mm-thick (6-in-thick) aluminum. These removal rates indicate a linear cutting speed of 18,000/50 = 360 mm/hr = 6 mm/min and 45,000/150 = 300 mm/hr = 5 mm/min, respectively.

The material removal rate for wire EDM can be obtained from the expression

$$\text{MRR} = V_f hb, \qquad (9.2)$$

where MRR is in mm^3/min; V_f = feed rate of the wire into the workpiece in mm/min; h = workpiece thickness or height in mm; and the kerf (see Fig. 9.35) is denoted by $b = d_w + 2s$, where d_w = wire diameter in mm and s = gap, in mm, between wire and workpiece during machining.

Modern wire-EDM machines (**multiaxis EDM wire-cutting machining centers**) are equipped with (1) computer controls to control the cutting path of the wire, (2) automatic self-threading features in case of wire breakage, (3) multiheads for cutting two parts at the same time, (4) controls that prevent wire breakage, and (5) programmed machining strategies. Two-axis computer-controlled machines can produce cylindrical shapes in a manner similar to that of a turning operation or cylindrical grinding.

9.14 High-Energy-Beam Machining

9.14.1 Laser-beam machining

In *laser-beam machining* (LBM), the source of energy is a laser (an acronym for *L*ight *A*mplification by *S*timulated *E*mission of *R*adiation), which focuses optical energy on the surface of the workpiece (Fig. 9.36a). The highly focused, high-density energy melts and evaporates portions of the workpiece in a controlled manner. This process, which does not require a vacuum, is used to machine a variety of metallic and nonmetallic materials. There are several types of lasers used in manufacturing operations.

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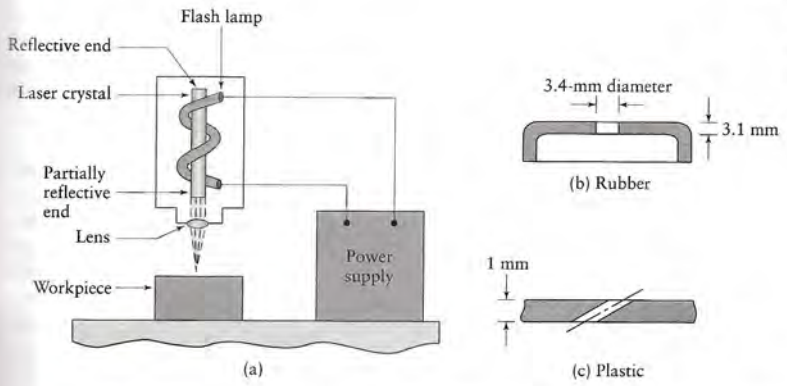

FIGURE 9.36
(a) Schematic illustration of the laser-beam-machining process. (b) and (c) Examples of holes produced in nonmetallic parts by LBM.

CO_2 (pulsed or continuous wave), Nd:YAG (neodymium: yttrium–aluminum–garnet), Nd:glass, ruby, and excimer (from the words *excited* and *dimer*, meaning two mers, or two molecules of the same chemical composition). The typical applications of laser-beam machining are outlined in Tables 9.4 and 9.5.

Important physical parameters in LBM are the *reflectivity* and *thermal conductivity* of the workpiece surface and its specific heat and latent heats of melting and evaporation; the lower these quantities, the more efficient is the process. The cutting depth t may be expressed as

$$t \propto \frac{P}{vd}, \tag{9.23}$$

where P is the power input, v is the cutting speed, and D is the laser-beam spot diameter. The surface produced by LBM is usually rough and has a heat-affected zone that, in critical applications, may have to be removed or heat treated. Kerf width is an important consideration, as it is in other cutting processes such as sawing, wire EDM, and electron-beam machining.

TABLE 9.5

General Applications of Lasers in Manufacturing

Application	Laser Type
Cutting	
Metals	PCO_2; $CWCO_2$; Nd:YAG; ruby
Plastics	$CWCO_2$
Ceramics	PCO_2
Drilling	
Metals	PCO_2; Nd:YAG; Nd:glass; ruby
Plastics	Excimer
Marking	
Metals	PCO_2; Nd:YAG
Plastics	Excimer
Ceramics	Excimer
Surface treatment (metals)	$CWCO_2$
Welding (metals)	PCO_2; $CWCO_2$; Nd:YAG; Nd:glass; ruby

Note: P = pulsed; CW = continuous wave.

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Laser beams may be used in combination with a gas stream, such as oxygen, nitro or argon (*laser-beam torch*), for cutting thin sheet materials. High-pressure inert-g assisted (e.g., nitrogen) laser cutting is used for stainless steel and aluminum; it leaves oxide-free edge that can improve weldability. Gas streams also have the important funct of blowing away molten and vaporized material from the workpiece surface.

Laser-beam machining is used widely in cutting and drilling metals, nonmet and composite materials (Figs. 9.36b and c). The abrasive nature of composite ma terials and the cleanliness of the operation have made laser-beam machining attractive alternative to traditional machining methods. Holes as small as 0.005 (0.0002 in.), with hole depth-to-diameter ratios of 50 to 1, have been produced in ious materials, although a more practical minimum is 0.025 mm (0.001 in.). Extre caution should be exercised with lasers, as even low-power lasers can cause dam to the retina of the eye if proper precautions are not observed.

Laser-beam machining is being used increasingly in the electronics and aut motive industries. Bleeder holes for fuel-pump covers and lubrication holes in tra mission hubs, for example, are being drilled; the cooling holes in the first-stage va of the Boeing 747 jet engines are also produced by lasers. Significant cost savi have been achieved by laser-beam machining, such that it now competes w electrical-discharge machining in this respect.

Laser beams are also used for (1) *welding* (see Section 12.4), (2) small-scale *heat treating* of metals and ceramics to modify their surface mechanical and tribologi properties (see Section 4.4), and (3) *marking* of parts with letters, numbers, codes, Marking can be done by processes such as with ink; with mechanical devices such punches, pins, styli, scroll rolls, or stamps; by etching; and with lasers. Although t equipment is more expensive than for other methods, marking and engraving w lasers has become increasingly common, due to the process' accuracy, reproducib ty, flexibility, ease of automation, and on-line application in manufacturing.

The inherent flexibility of the laser-beam cutting process with fiber-optic-be delivery, simple fixturing, low setup times, the availability of multi-kW machines 2D and 3D computer-controlled systems are attractive features; thus, laser cutt can compete successfully with cutting of sheet metal using the traditional punch processes described in Section 7.3. There are now efforts to combine the two proce es for improved overall efficiency.

9.14.2 Electron-beam machining and plasma-arc cutting

The source of energy in *electron-beam machining* (EBM) is high-velocity electro which strike the surface of the workpiece and generate heat (Fig. 9.37). The appli tions of this process are similar to those of laser-beam machining, except that EB

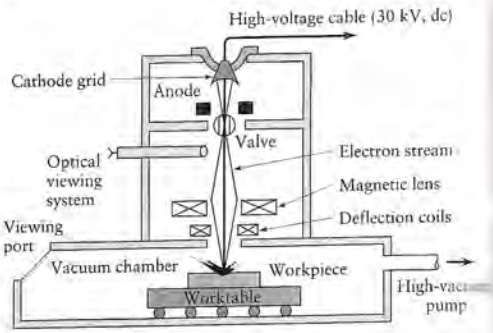

FIGURE 9.37 Schematic illustration of the electron-beam-machining process. Unlike LBM, this process requires a vacuum, and hence workpiece size is limited.

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requires a vacuum. These machines use voltages in the range of 50–200 kV to accelerate the electrons to speeds of 50% to 80% of the speed of light. The interaction of the electron beam with the workpiece surface produces hazardous X rays; consequently, the equipment should be used only by highly trained personnel. Electron-beam machining is used for very accurate cutting of a wide variety of metals. Surface finish is better and kerf width is narrower than that for other thermal-cutting processes. (See also the discussion in Section 12.4 on electron-beam welding.)

In **plasma-arc cutting** (PAC), *plasma beams* (ionized gas) are used for rapid cutting of nonferrous and stainless-steel plates. The temperatures generated are very high (9400°C, or 17,000°F, in the torch for oxygen as a plasma gas); consequently, the process is fast, kerf width is small, and the surface finish is good. Material removal rates are much higher than in the EDM and LBM processes, and parts can be machined with good reproducibility. Plasma-arc cutting is highly automated today, through the use of programmable controls.

A more traditional method is **oxyfuel-gas cutting** (OFC), using a torch as in welding. It is particularly useful for cutting steels, cast irons, and cast steels. Cutting occurs mainly by oxidation and burning of the steel, with some melting taking place as well. Kerf widths are usually in the range of 1.5–10 mm (0.06–0.4 in.).

9.15 Water-Jet, Abrasive Water-Jet, and Abrasive-Jet Machining

We know that when we put our hand across a jet of water or air, we feel a considerable concentrated force acting on our hand. This force results from the momentum change of the stream and, in fact, is the principle on which the operation of water or gas turbines is based. This principle is also used in water-jet, abrasive water-jet, and abrasive-jet machining, described as follows:

1. **Water-jet machining** (WJM). In water-jet machining, also called *hydrodynamic machining* (Fig. 9.38a), the force from the jet is used in cutting and deburring operations. The water jet acts like a saw and cuts a narrow groove

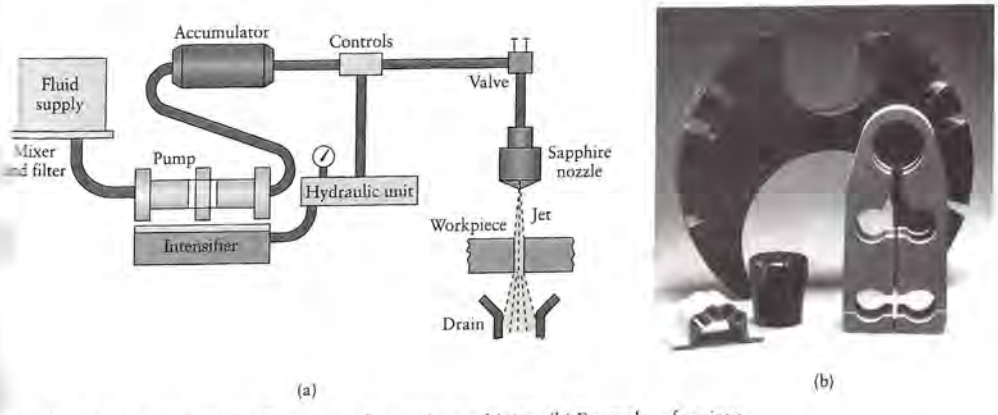

FIGURE 9.38 (a) Schematic illustration of water-jet machining. (b) Examples of various nonmetallic parts cut by a water-jet machine. *Source*: Jet Edge.

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in the material. Although pressures as high as 1400 MPa (200 ksi) can be generated, a pressure level of about 400 MPa (60 ksi) is generally used for efficient operation. Jet-nozzle diameters usually range between 0.05 mm and 1 mm (0.002 in. and 0.040 in.).

A variety of materials can be cut with this technique, including plastics, fabrics, rubber, wood products, paper, leather, insulating materials, brick, and composite materials (Fig. 9.38b). Thicknesses range up to 25 mm (1 in.) and higher. Vinyl and foam coverings for some automobile dashboards, for example, are cut using multiple-axis, robot-guided water-jet machining equipment. Because it is an efficient and clean operation compared with other cutting processes, WJM is also used in the food-processing industry for cutting and slicing food products (Table 9.4).

The advantages of this process are that cuts can be started at any location without the need for predrilled holes; no heat is produced; no deflection of the rest of the workpiece takes place (hence the process is suitable for flexible materials); little wetting of the workpiece takes place; and the burr produced is minimal. It is also an environmentally safe manufacturing process.

2. **Abrasive water-jet machining.** In *abrasive water-jet machining* (AWJM), the water jet contains abrasive particles such as silicon carbide or aluminum oxide, thus increasing the material removal rate over that of water-jet machining. Metallic, nonmetallic, and advanced composite materials of various thicknesses can be cut in single or multiplelayers, particularly heat-sensitive materials that cannot be machined by processes in which heat is produced. Cutting speeds are as high as 7.5 m/min (2.5 ft/min) for reinforced plastics, but much lower for metals. With multiple-axis and robotic-control machines, complex three-dimensional parts can be machined to finish dimensions by this process. Nozzle life is improved by making the nozzle from rubies, sapphires, and carbide-base composite materials.

3. **Abrasive-Jet Machining.** In *abrasive-jet machining* (AJM), a high-velocity jet of dry air, nitrogen, or carbon dioxide containing abrasive particles is aimed at the workpiece surface under controlled conditions (Fig. 9.39). The impact of the particles develops sufficient concentrated force (see also Section 9.7) to perform operations such as (1) cutting small holes, slots, or intricate patterns in very hard or brittle metallic and nonmetallic materials; (2) deburring or removing small flash from parts; (3) trimming and beveling; (4) removing oxides and other surface films; and (5) general cleaning of components with irregular surfaces.

The gas supply pressure is on the order of 850 kPa (125 psi), and the abrasive-jet velocity can be as high as 300 m/s (100 ft/s) and is controlled by a valve. The handheld nozzles are usually made of tungsten carbide or sapphire.

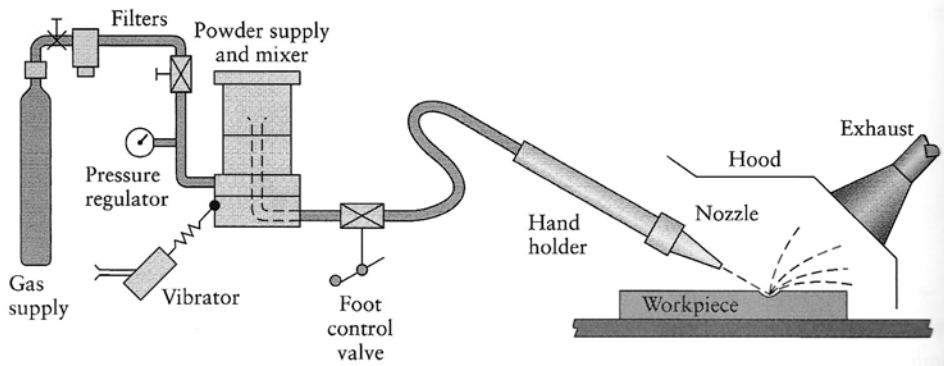

FIGURE 9.39 Schematic illustration of the abrasive-jet-machining process.

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The abrasive size is in the range of 10–50 μm (400–2000 μin.). Because the flow of the free abrasives tends to round off corners, designs for abrasive-jet machining should avoid sharp corners; also, holes made in metal parts tend to be tapered. Because of airborne particulates, there is some hazard involved in using this process.

9.16 Design Considerations

The important design considerations for the processes and operations described in this chapter are outlined as follows:

1. **Abrasive processes.** Parts to be ground should be designed so that they can be held securely in workholding devices without causing part distortion. For high dimensional accuracy, interrupted surface features should be avoided, as they could cause vibration and chatter. In cylindrical grinding, parts should be balanced, and long, slender designs should be avoided to minimize deflections. Fillets and corner radii should be as large as possible, or relief should be provided for by prior machining. Designs requiring accurate form grinding should be kept as simple as possible to avoid frequent wheel dressing. Deep and small holes, and blind holes requiring internal grinding, should be avoided, or they should include a relief. In ultrasonic machining, sharp profiles should be avoided, and the bottom of brittle parts should be supported to avoid chipping; some taper should be expected for holes made by this process.
2. **Chemical, electrochemical, and electrical processes.** In chemical machining, sharp corners and deep and narrow cavities should be avoided; undercuts may occur under the edges of the maskant; the bulk of the workpiece should preferably be preshaped by other processes to reduce machining time; and size changes in artwork due to humidity and temperature can affect dimensional accuracy. In electrochemical machining, sharp corners or flat bottoms should be avoided; designs should make provision for a small taper for holes and cavities; and irregular cavities may not be produced to the desired dimensions. In electrical-discharge machining, the bulk of the workpiece should preferably be preshaped by other processes to reduce machining time; deep slots and narrow openings should be avoided; and, for economic production, the surface finish specified should not be too fine.
3. **High-energy-beam processes.** Any adverse effects of the processes on surface finish and integrity should be considered. In laser-beam machining, dull and unpolished workpiece surfaces are preferable, and designs should avoid deep cuts or very sharp profiles. In electron-beam machining, part size and shape are limited by the size of the vacuum chamber, and if a part requires machining on only a small portion, consideration should be given to making the part in a number of small components.

9.17 Process Economics

This chapter has shown that grinding may be used both as a finishing operation and for large-scale removal operations (as in creep-feed grinding). The use of grinding as a finishing operation is often necessary, because forming and machining processes

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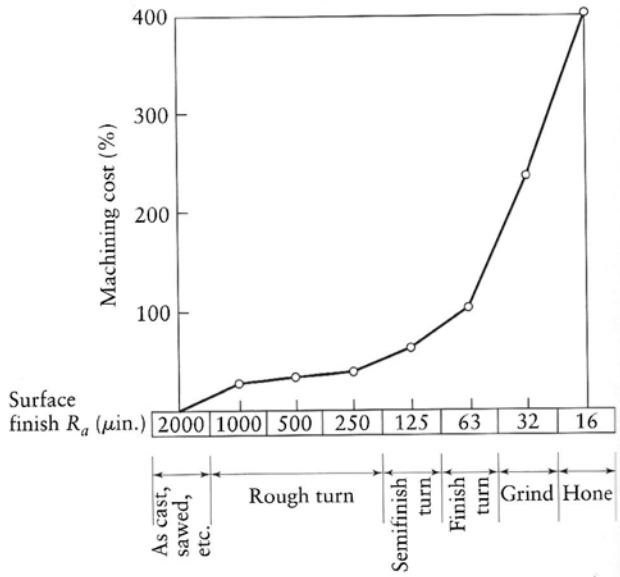

FIGURE 9.40 Increase in the cost of machining and finishing a part as a function of the surface finish required.

alone usually cannot produce parts with the desired dimensional accuracy and surface finish. However, because it is an additional operation, grinding contributes significantly to product cost. Creep-feed grinding, on the other hand, has proved to be an economical alternative to machining operations such as milling, even though wheel wear is high.

All finishing operations contribute to product cost. On the basis of the discussion thus far, it can be seen that as the surface finish improves, more operations are required, and hence the cost increases. Note in Fig. 9.40 how rapidly cost increases as surface finish is improved by processes such as grinding and honing.

Much progress has been made in automating the equipment involved in finishing operations, including computer controls. Consequently, labor costs and production times have been reduced, even though such machinery may require significant capital investment. If finishing is likely to be an important factor in manufacturing a particular product, the conceptual and design stages should involve an analysis of the degree of surface finish and dimensional accuracy required. Furthermore, all processes that precede finishing operations should be analyzed for their capability to produce a more acceptable surface finish and dimensional accuracy. This can be accomplished through proper selection of tools and process parameters and the characteristics of the machine tools involved.

The economic production run for a particular process depends on the cost of tooling and equipment, the material removal rate, operating costs, and the level of operator skill required, as well as the cost of secondary and finishing operations that may be necessary. In chemical machining, the costs of reagents, maskants, and disposal, together with the cost of cleaning the parts, are important factors; in electrical-discharge machining, the cost of electrodes and the need to replace them periodically are significant. The rate of material removal, and hence the production rate, can vary significantly in these processes. The cost of tooling and equipment also varies significantly, as does the operator skill required. If possible, the high capital investment for machines such as for electrical and high-energy-beam machining should be justified in terms of the production runs they are able to generate and the lack of feasibility of manufacturing the same part by other means.

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CASE STUDY | Manufacture of Stents

Heart attacks, strokes, and other cardiovascular diseases claim one life every 33 seconds in the United States alone.[1] These illnesses are attributed mostly to coronary artery disease, which is the gradual buildup of fat (cholesterol) within the artery wall causing the coronary arteries to become narrowed or blocked. This condition reduces the blood flow to the heart muscle and eventually leads to a heart attack, stroke, or other cardiovascular diseases. One of the most popular methods today for keeping blocked arteries open is to implant a stent into the artery. The MULTI-LINK TETRA™, shown in Fig. 9.41, consists of a tiny mesh tube that is expanded using a balloon dilatation catheter and implanted into a blocked or partially blocked coronary artery. A stent serves as a scaffolding or mechanical brace to keep the artery open. A stent offers the patient a minimally invasive method for treating coronary heart disease for which the alternative is usually open-heart bypass surgery, a procedure with greater risk, pain, rehabilitation time, and cost to the patient.

Stent manufacturing is extremely demanding for which the accuracy and precision of its design are paramount for proper performance. The manufacture of the stent must allow satisfaction of all of the design constraints and provide an extremely reliable device; thus, strict quality control procedures must be in place throughout the manufacturing process. When designing a stent there are many material-selection factors to consider, such as radial strength, corrosion resistance, endurance limit, flexibility, and biocompatibility. Radial strength is important because the stent must withstand the pressure the artery exerts on the stent upon expansion. Because the stent is implantable in the body it must be corrosion resistant; it must also be able to withstand the stress undulations caused by heartbeats, and consequently, the material must also have high resistance to fatigue. In addition, the stent must have the appropriate wall thickness in order to be flexible enough to negotiate through the tortuous anatomy of the heart. Above all, the material must be biocompatible to the body, because it remains there for the rest

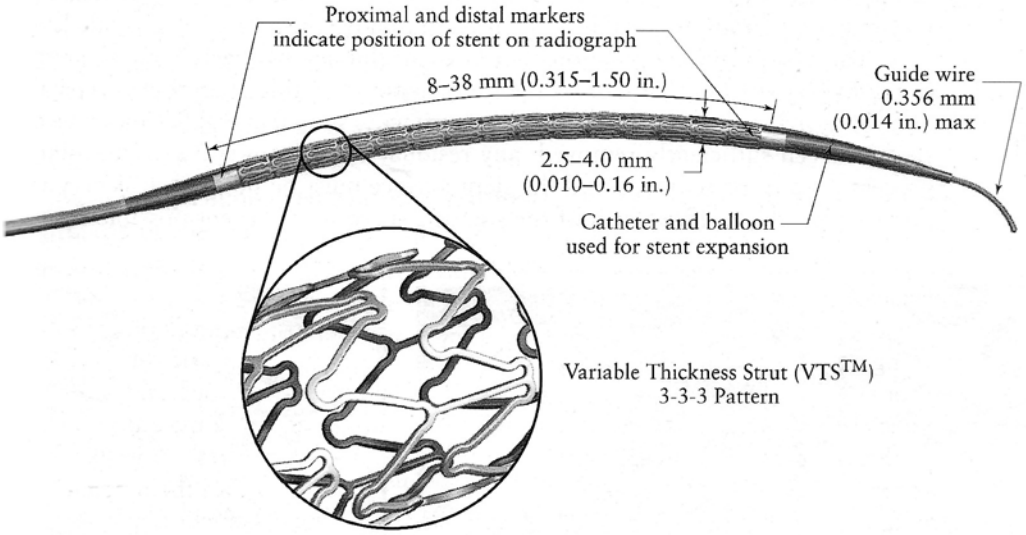

FIGURE 9.41 The Guidant MULTI-LINK TETRA™ coronary stent system.

[1] 2002 Heart and Stroke Statistical Update, American Heart Association, p. 4

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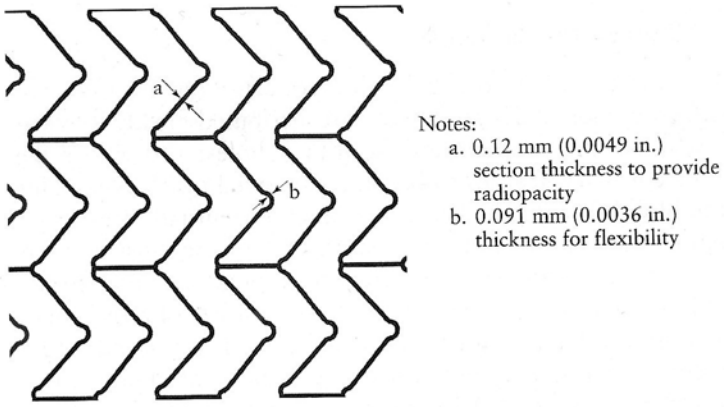


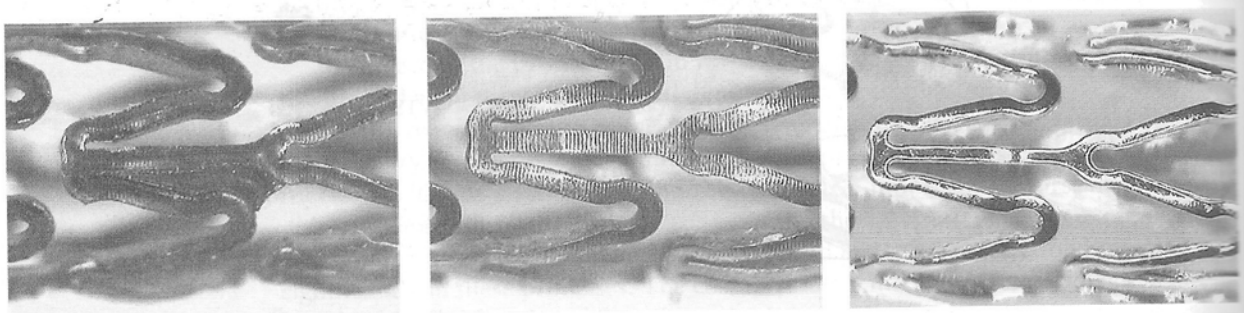
FIGURE 9.42 Detail of the 3-3-3 MULTI-LINK TETRA™ pattern.

of the patient's life. A standard material for stents, one that satisfies all of these requirements, is 316L stainless steel (Section 3.10.2).

The pattern of a stent also affects its performance. A finite-element analysis of the stent's design is first performed to determine how the stent will perform under the stresses induced from the beating heart. The strut pattern, tube thickness, and strut-leg width all affect the performance of the stent. Many different patterns are possible, such as the MULTI-LINK TETRA™ stent, which is shown in Figure 9.42 including some of the critical dimensions.

A stent starts out as a drawn stainless-steel tube with outer diameter that matches the final stent dimension, and a wall thickness selected to provide proper strength when expanded. The drawn tube is then laser machined (Section 9.14.1) to achieve the desired pattern (Fig. 9.43a). This method has proven to be very effective because of the small, intricate pattern of the stent and the tight dimensional tolerances that it must have. As the laser cuts the pattern of the stent, it leaves small metal slugs that need to be removed, therefore, it is very important that the laser cut all the way through the tube wall. A thick oxide layer or slag inevitably develops on the stainless steel due to the thermal and chemical attack from the air; in addition, weld splatter, burrs, and other surface defects result from laser machining. Finishing operations are therefore required to remove the splatter and oxide layer.

The first finishing operation after laser machining involves chemical etching to remove as much of the slag on the stent as possible; this operation is typically done in an acid solution, and the resulting surface is shown in Fig. 9.43b. Once the slag has been sufficiently removed, any residual burrs from the laser machining process need to be removed and the stent surface must be finished. It is very important that the surface finish of the stent be smooth to prevent possible forma-



(a) (b) (c)

FIGURE 9.43 Evolution of the stent surface. (a) MULTI-LINK TETRA™ after lasing. Note that a metal slug is still attached. (b) After removal of slag. (c) After electropolishing.

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tion of clots (thrombi) on the stent. To remove the sharp points, the stent is electropolished (Section 9.8) by passing an electrical current through an electrochemical solution, to ensure proper surface finish (Fig. 9.43c) that is both shiny and smooth. The stent is then placed onto a balloon catheter assembly, and sterilized and packaged for delivery to the surgeon.

Source: Courtesy of K. L. Graham, Guidant Corporation.

SUMMARY

- Abrasive machining and advanced machining processes are often necessary and economical when workpiece hardness is high, the materials are brittle or flexible, part shapes are complex, and surface finish and dimensional tolerance requirements are high. (Section 9.1)
- Conventional abrasives consist basically of aluminum oxide and silicon carbide, and superabrasives consist of cubic boron nitride and diamond. Friability of abrasive grains is an important factor, as are shape and size of the grains. (Section 9.2)
- Grinding wheels consist of a combination of abrasive grains and bonding agents. Important characteristics of wheels include abrasive-grain and bond types, grade, and hardness. Wheels may be reinforced to maintain wheel integrity. (Section 9.3)
- The mechanics of grinding processes are studied in order to establish quantitative relationships regarding chip dimensions, grinding forces and energy requirements, temperature rise, residual stresses, and any adverse effects on surface integrity of ground components. (Section 9.4)
- Wheel wear is an important consideration in ground surface quality and product integrity. Wear is usually monitored in terms of the grinding ratio, defined as the ratio of material removed to the volume of wheel wear. Dressing and truing of wheels are done by various techniques, with the aid of computer controls. (Section 9.5)
- A variety of abrasive machining processes and equipment is available for surface, external, and internal grinding, as well as for large-scale material removal processes. The proper selection of abrasives, process variables, and grinding fluids is important for obtaining the desired surface finish and dimensional accuracy and for avoiding damage such as burning, heat checking, harmful residual stresses, and chatter. (Section 9.6)
- Ultrasonic machining removes material by microchipping and is best suited for hard and brittle materials. (Section 9.7)
- Several finishing operations are available to improve surface finish. Because finishing processes can contribute significantly to product cost, proper selection and implementation of finishing operations are important. (Section 9.8)
- Deburring may be necessary for certain finished components. Commonly used deburring methods include vibratory and barrel finishing and shot blasting, although thermal-energy processes and other methods can also be used. (Section 9.9)
- Advanced machining processes involve chemical and electrical means and high-energy beams; they are particularly suitable for hard materials and complex shapes. The effects of these processes on surface integrity must be investigated, as they can damage surfaces considerably, thus reducing fatigue life. (Sections 9.10–9.14)
- Water-jet, abrasive water-jet, and abrasive-jet machining processes can be used effectively for cutting as well as deburring operations. Because they do not use hard tooling, they have inherent flexibility of operation. (Sections 9.15)

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- As in all manufacturing processes, certain design guidelines should be followed for effective use of advanced machining processes. (Section 9.16)
- The processes described in this chapter have unique capabilities; however, because they involve different types of machinery, process variables, and cycle times, the competitive aspects of each process with respect to a particular product must be studied individually. (Section 9.17)

SUMMARY OF EQUATIONS

Undeformed chip length, ℓ:

Surface grinding, $\ell = \sqrt{Dd}$

External grinding, $\ell = \sqrt{\dfrac{Dd}{1 + D/D_w}}$

Internal grinding, $\ell = \sqrt{\dfrac{Dd}{1 - D/D_w}}$

Undeformed-chip thickness, surface grinding, $t = \sqrt{\dfrac{4v}{VCr}\sqrt{\dfrac{d}{D}}}$

Relative grain force $\propto \dfrac{v}{VC}\sqrt{\dfrac{d}{D}}$

Temperature rise in surface grinding, $\Delta T \propto \dfrac{d}{t} \propto d^{3/4}\sqrt{\dfrac{VC}{v}\sqrt{D}}$

Grinding ratio, $G = \dfrac{\text{volume of material removed}}{\text{volume of wheel wear}}$

Average force of particle in ultrasonic machining, where $F_{ave} = \dfrac{2mv}{t_o}$ where $t_o = \dfrac{5r}{c_o}\left(\dfrac{c_o}{v}\right)^{1/5}$

Material removal rate in

electrochemical machining, MRR $= CI\eta$

electrochemical grinding, MRR $= \dfrac{GI}{\rho F}$

electrical-discharge machining, MRR $= 4 \times 10^4 IT_w^{-1.23}$

electrical-discharge grinding, MRR $= KI$

wire EDM, MRR $= V_f hb$, where $b = d_w + 2s$

Penetration rate in electrochemical grinding, $V_s = \left[\dfrac{G}{dF}\right]\left[\dfrac{E}{gK_p}\right]K$

Wear rate of electrode in electrical-discharge machining, $W_t = 1.1 \times 10^{11} IT_t^{-2.38}$

Laser-beam cutting time, $t = \dfrac{P}{vd}$

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