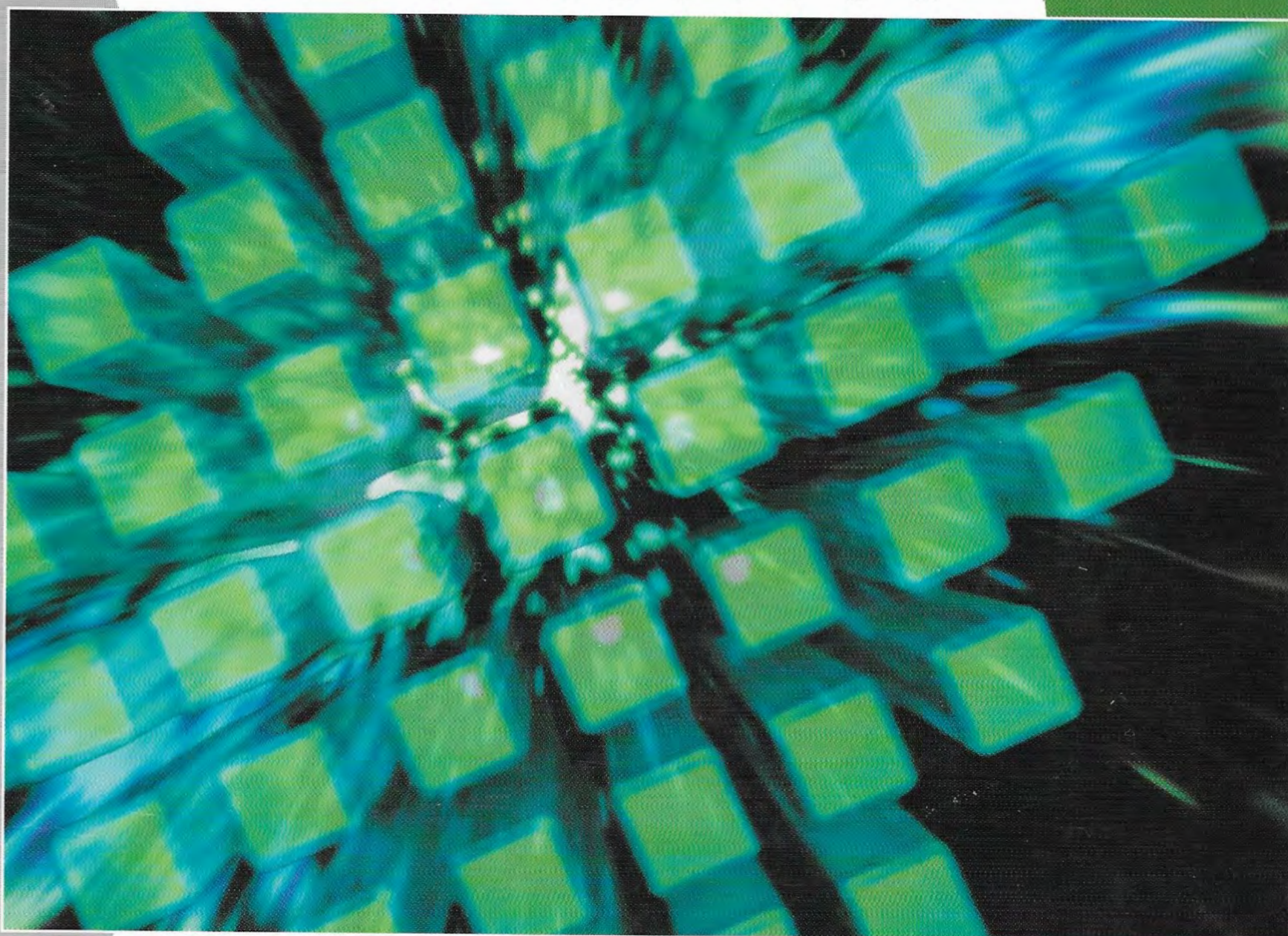


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Manufacturing Processes

for Engineering Materials

F I F T H E D I T I O N



Serope Kalpakjian
Steven R. Schmid

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Manufacturing Processes for Engineering Materials

FIFTH
EDITION

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PEARSON

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Authorized adaptation from the United States edition, entitled *Manufacturing Processes for Engineering Materials, 5th Edition*, ISBN: 9780132272711, by Kalpakjian, Serope; Schmid, Steven, R., published by Pearson Education, Inc., publishing as Prentice Hall, Copyright © 2008

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ISBN 978-81-317-0566-7

First Impression, 2007

Eighteenth Impression, 2015

Nineteenth Impression

This edition is manufactured in India and is authorized for sale only in India, Bangladesh, Bhutan, Pakistan, Nepal, Sri Lanka and the Maldives.

Published by Pearson India Education Services Pvt Ltd, CIN: U72200TN2005PTC057128, formerly known as TutorVista Global Pvt Ltd, licensee of Pearson Education in South Asia.

Head Office: 7th Floor, Knowledge Boulevard, A-8(A), Sector 62, Noida 201 309 U.P., India.
Registered Office: Module G4, Ground Floor, Elnet Software City, TS-140, Block 2 and 9, Rajiv Gandhi Salai, Taramani, Chennai 600 113, Tamil Nadu, India. Fax: 080-30461003,
Phone: 080-30461060, www.pearson.co.in, Email: companysecretary.india@pearson.com

Printed in India by India Binding House..

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die making, because deep cavities are not accessible for grinding. The process offers a distinct advantage over traditional diamond-wheel grinding when processing very hard materials, for which wheel wear can be high. ECG machines are available with numerical controls, thus improving dimensional accuracy and providing repeatability and increased productivity.

EXAMPLE 9.5 Machining time in electrochemical machining vs. drilling

A round hole 12 mm in diameter is being produced in a titanium-alloy block by electrochemical machining. Using a current density of 5 A/mm^2 , estimate the time required for machining a 15-mm-deep hole. Assume that the efficiency is 92%. Compare this time with that required for ordinary drilling.

Solution. Note from Eqs. (9.13) and (9.14) that the feed rate can be expressed by the equation

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

Letting $C = 1.5 \text{ mm}^3/\text{A-min}$ and the feed rate is $f = (1.5)(5)(0.92) = 6.9 \text{ mm/min}$. Since the hole is 15 mm deep,

$$\text{Machining time} = \frac{15}{6.9} = 2.17 \text{ min.}$$

To determine the drilling time, refer to Table 8.12 and note the data for titanium alloys. Selecting the following values for a 10-mm drill—rpm = 325 and feed = 0.15 mm/rev—it can be seen that the feed rate is $(325 \text{ rev/min})(0.15 \text{ mm/rev}) = 48.75 \text{ mm/min}$. Since the hole is 15 mm deep,

$$\text{Drilling time} = \frac{15}{48.75} = 0.030 \text{ min.,}$$

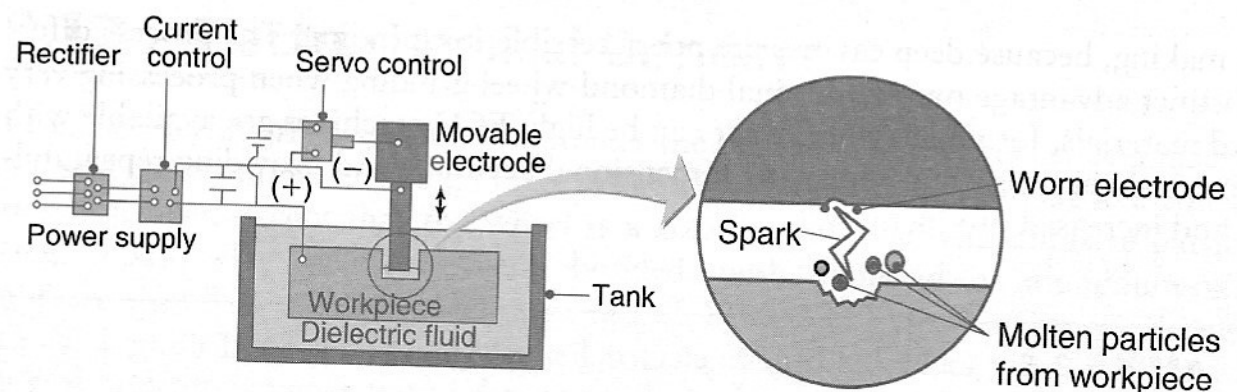
which is about 14% of the time required for ECM.

9.13 | Electrical-Discharge Machining

The principle of *electrical-discharge machining* (EDM), also called *electrodischarge* or *spark-erosion 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. When the point of contact between the two wires is closely examined, it will be noted 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. It has become one of the most important and widely used 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 nonconducting) fluid. When a voltage is applied to the tool, a magnetic field causes suspended particles in the dielectric fluid to concentrate between the electrode and workpiece, 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 tooling material as well. In addition, the dielectric fluid is heated rapidly, causing evaporation of the fluid

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



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 workpiece surface and entrain any molten workpiece material into the dielectric fluid. The capacitor discharge is repeated at rates of between 50 and 500 kHz, with voltages usually ranging between 50 and 380 V and currents from 0.1 to 500 A.

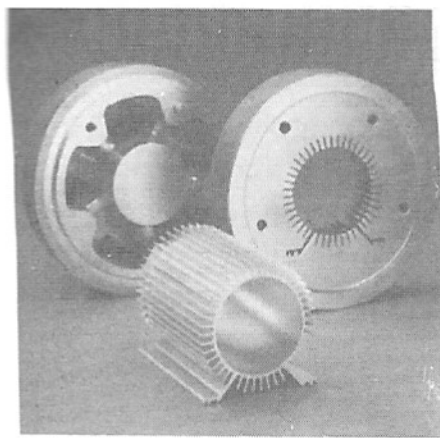
The dielectric fluid (a) acts as an insulator until the potential is sufficiently high, (b) acts as a flushing medium and carries away the debris in the gap, and (c) provides a cooling medium. The gap between the tool and the workpiece (*overcut*) is critical; thus, the downward feed of the tool is controlled by a servo-mechanism, 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} mm³. Since the process does not 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.

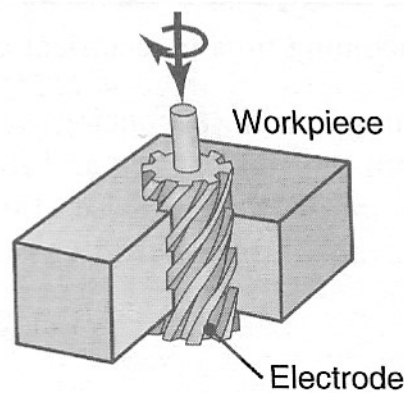
Electrodes for EDM are usually made of graphite, although brass, copper, or copper-tungsten alloy may be used. The tools are shaped by forming, casting, powder metallurgy, or machining. Electrodes as small as 0.1 mm in diameter have been used. Tool wear is an important factor because it adversely affects 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 (Fig. 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).

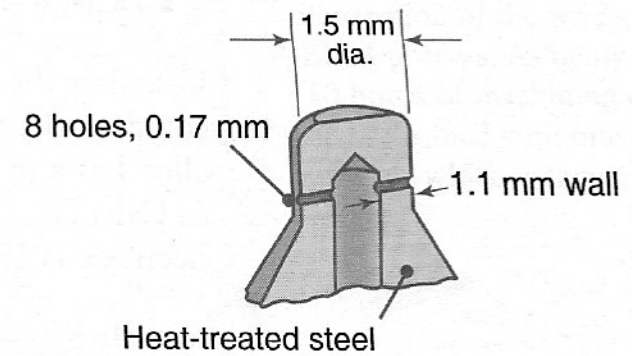
The material removal rate in electrical-discharge machining is basically a function of the current and the melting point of the workpiece material, although other process variables, such as temperature and frequency, also have an effect. The following



(a)



(b)



(c)

FIGURE 9.33 (a) Examples of shapes produced by the electrical-discharge machining process, using shaped electrodes. The two round parts in the rear are a set of dies for extruding the aluminum piece shown in front; see also Section 6.4. (b) A spiral cavity produced using a shaped rotating electrode. (c) Holes in a fuel-injection nozzle produced by electrical-discharge machining. *Source:* (a) Courtesy of AGIE USA Ltd. (b) *American Machinist*.

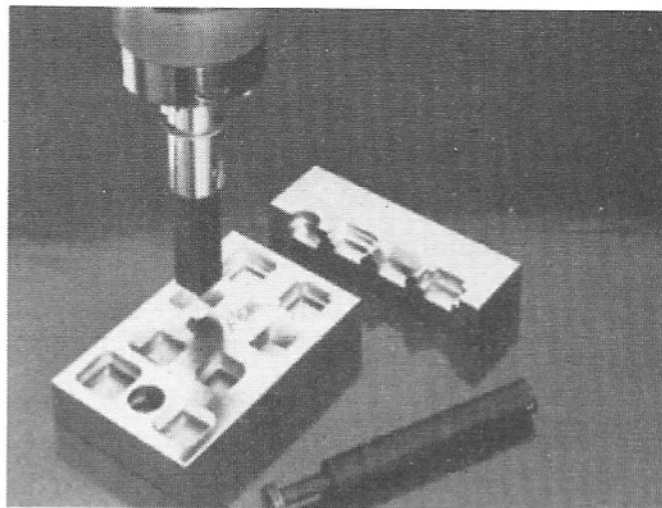


FIGURE 9.34 Stepped cavities produced with a square electrode by EDM. In this operation, the workpiece moves in the two principal horizontal directions, and its motion is synchronized with the downward movement of the electrode to produce these cavities. Also shown is a round electrode capable of producing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

approximate empirical relationship can be used as a guide to estimate the metal removal rate in EDM:

$$\text{MRR} = 4 \times 10^4 I T_w^{-1.23}, \quad (9.18)$$

where MRR is in mm^3/min , I is the current in amperes, and T_w is the melting point of the workpiece in $\text{K} - 273.15 \text{ K}$.

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

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

where W_t is mm^3/min and T_t is the melting point of the electrode material in $\text{K} - 273.15 \text{ K}$. The wear ratio of the workpiece to electrode, R , can be estimated from the expression

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

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

Metal removal rates in EDM usually range from 2 to $400 \text{ mm}^3/\text{min}$. 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 later removed by finishing operations such as grinding. A more recent technique is to use an oscillating electrode, which provides very fine surface finish, requiring significantly less benchwork to improve the luster of cavities.

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 1873.15 K (see Table 3.3) and that the current is 100 A. Calculate the wear rate of the electrode, assuming that the melting point of the electrode is 1373.15 K.

Solution.

1. Using Eq. (9.18),

$$\begin{aligned} \text{MRR} &= (4 \times 10^4)(100)(1873.15 - 273.15)^{-1.23} \\ &= 458 \text{ mm}^3/\text{min}. \end{aligned}$$

The volume of the hole is

$$V = \pi \left[\frac{(12.5)^2}{4} \right] (20) = 2452 \text{ mm}^3.$$

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, the machining time for EDM will be only 1.8 minutes, which is less than the time for ECM.

2. The wear rate of the electrode is calculated using Eq. (9.19). Thus,

$$W_t = (11 \times 10^3)(100)(1373.15 - 273.15)^{-2.38} = 0.064 \text{ mm}^3/\text{min}.$$

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 workpiece surface by repetitive spark discharges between the rotating wheel and the workpiece. The material removal rate can be estimated from the equation

$$\text{MRR} = KI, \quad (9.21)$$

where MRR is in mm^3/min , I = current in amperes, and K = workpiece material factor in $\text{mm}^3/\text{A-min}$; for example, $K = 16$ for steel and 4 for tungsten carbide.

The EDG process can be combined with electrochemical grinding, a process 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 slits 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

An important 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

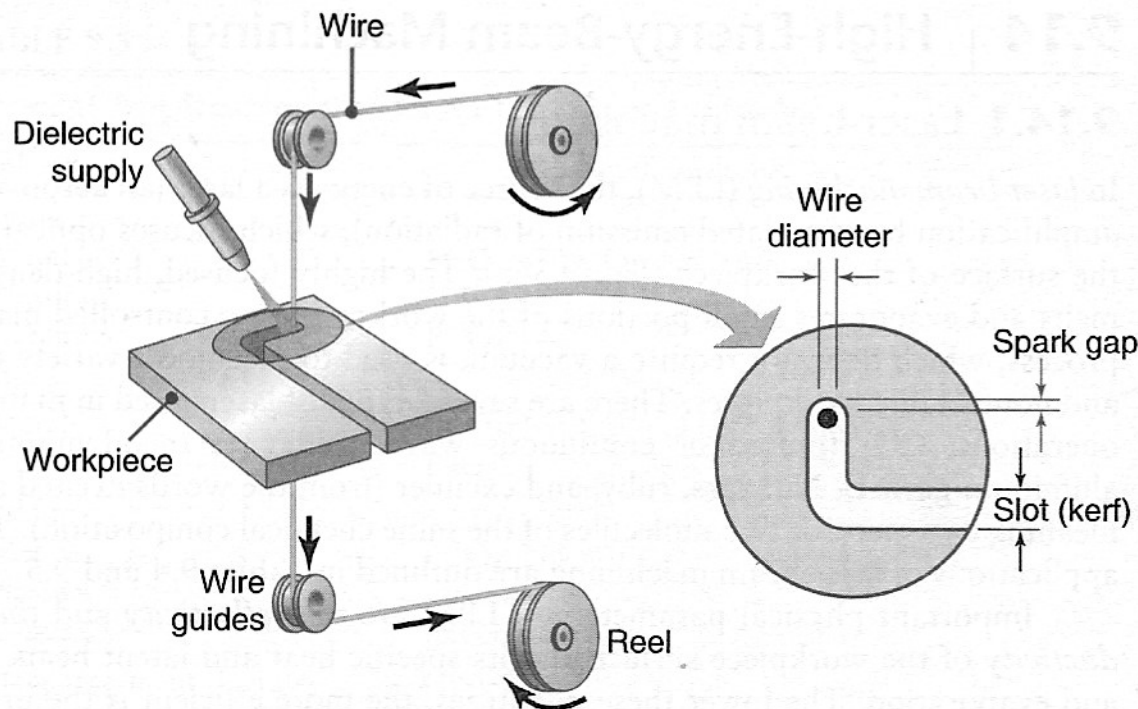


FIGURE 9.35 Schematic illustration of the wire EDM process. As many as 50 hours of machining can be performed with one reel of wire, which is then recycled.

(Section 8.10.5), 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 as 300 mm 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 in diameter, making narrow cuts possible. Zinc- or brass-coated, as well as multicoated, wires are also used. The wire should have sufficient tensile strength and fracture toughness, and high electrical conductivity. The wire is generally used only once, as it is relatively inexpensive, and is then recycled. It travels at a constant velocity in the range of 0.15 to 9 m/min, and a constant gap (*kerf*; Fig. 9.35) 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 mm²/hr for 50-mm thick D2 tool steel, and 45,000 mm²/hr for 150-mm thick aluminum. These material removal rates indicate a linear cutting speed of 18,500/50 = 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

$$\text{MRR} = V_f h b, \quad (9.22)$$

where MRR is in mm³/min; V_f is the feed rate of the wire into the workpiece in mm/min; h is the thickness or height in mm; and the kerf, b (see Fig. 9.35), is denoted as $b = d_w + 2s$, 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 (a) computer controls to control the cutting path of the wire and its angle with respect to the workpiece plane, (b) automatic self-threading features in case of wire breakage, (c) multiheads for cutting two parts at the same time, (d) automatic controls that prevent wire breakage, and (e) 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 *light amplification by stimulated emission of radiation*), which focuses optical energy on the surface of the workpiece (Fig. 9.36a). The highly focused, high-density energy melts and evaporates small 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 workpieces. There are several types of lasers used in manufacturing operations: CO₂ (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

$$t \propto \frac{P}{vd}, \quad (9.23)$$

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 (see Fig. 12.15) that, for 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.

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

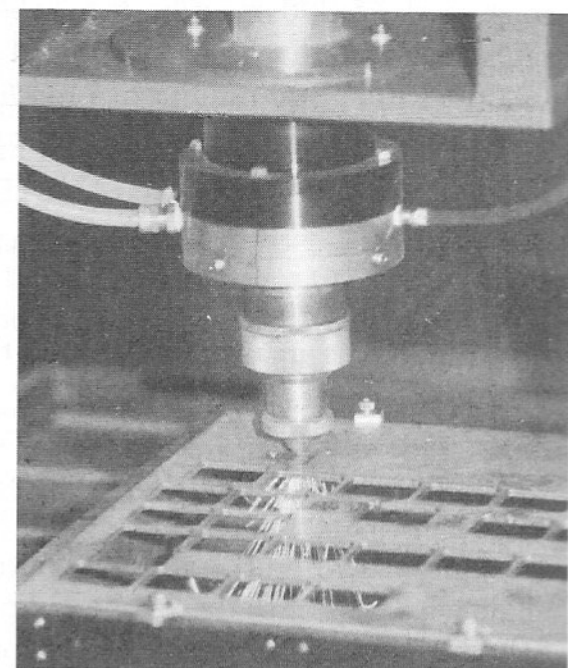
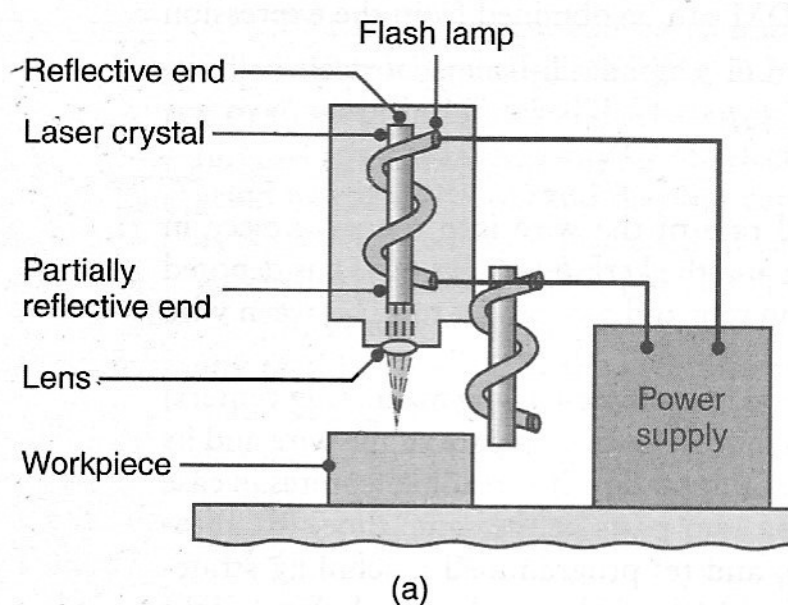


FIGURE 9.36 (a) Schematic illustration of the laser-beam machining process and (b) cutting sheet metal with a laser beam. Source: (b) Courtesy of Rofin-Sinat, Inc.

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.

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

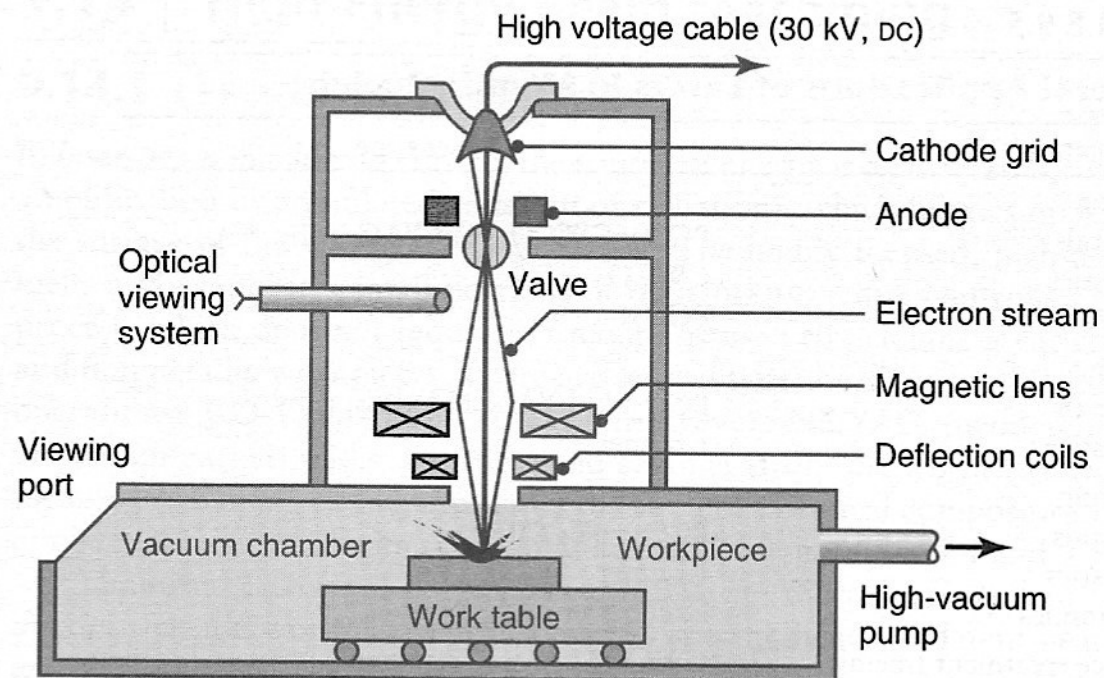
Laser beams are also used for (a) *welding* (see Section 12.5), (b) small-scale *heat treating* of metals and ceramics to modify their surface mechanical and tribological properties (see Section 4.4), and (c) *marking* of parts with letters, numbers, codes, etc. Marking also can be done by devices such as punches, pins, styli, scroll rolls, or stamps by etching. Although the equipment is more expensive than for other methods, marking and engraving with lasers have become increasingly common, due to the accuracy, reproducibility, flexibility, ease of automation, and on-line application in a wide variety of manufacturing operations.

The inherent flexibility of the laser-beam cutting process with fiber-optic-beam delivery, simple fixturing, low setup times, and the availability of multi-kW machines and 2D and 3D computer-controlled systems are attractive features. Thus, laser cutting can compete successfully with cutting of sheet metal using the traditional punching processes, described in Section 7.3, although the two processes can be combined 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 electrons, which strike the surface of the workpiece and generate heat (Fig. 9.37). The applications of this process are similar to those of laser-beam machining, except that EBM requires a vacuum. The 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. 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 12.5 on electron-beam welding.) The interaction of the

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



electron beam with the workpiece surface produces hazardous X-rays; consequently, the equipment should be used only by highly trained personnel.

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 (9673 K, 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 through the use of programmable controls.

A more traditional method is **oxyfuel-gas cutting (OFC)**, using a torch as in welding (Chapter 12). The operation 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.

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, there is considerable concentrated force acting on our hand. This force is a result of 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 next.

1. **Water-jet machining (WJM).** In this process, also called *hydrodynamic machining* (Fig. 9.38a), the force from the jet is utilized in cutting and deburring operations. The water jet acts like a saw and cuts a narrow groove in the material. Although pressures as high as 1400 MPa can be generated, a pressure level of about 400 MPa is typically used for efficient operation. Jet-nozzle diameters usually range between 0.05 and 1 mm. A water-jet cutting machine and typical parts produced are shown in Fig. 9.38.

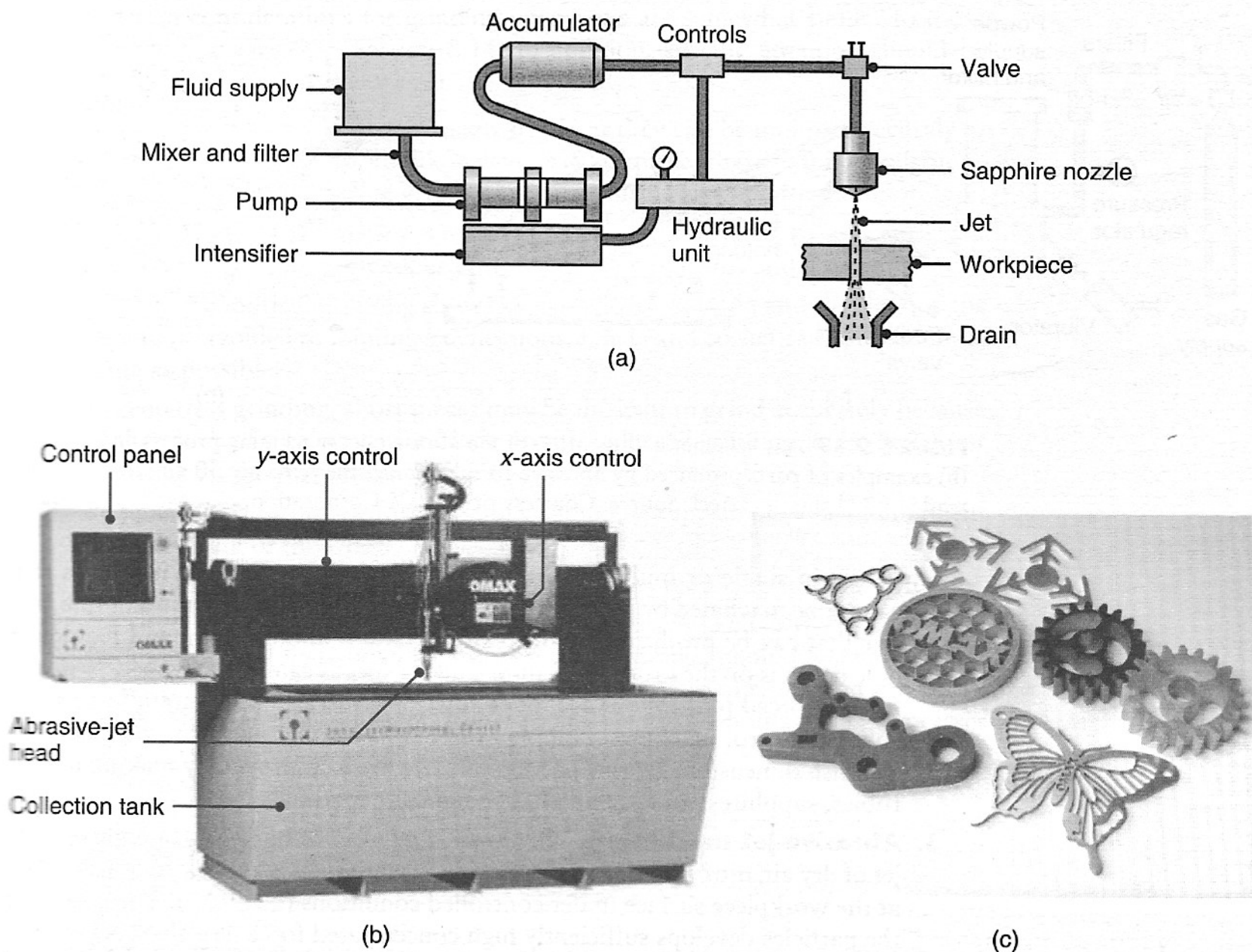


FIGURE 9.38 (a) Schematic illustration of water-jet machining, (b) a computer-controlled water-jet cutting machine, and (c) examples of various nonmetallic parts machined by the water-jet cutting process. *Source:* Courtesy of OMAX Corporation.

A variety of nonmetallic 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 to 25 mm or even higher. Vinyl and foam coverings for some automobile dashboards are, for example, cut using multiple-axis, robot-guided water-jet machining equipment. Because it is an efficient and clean operation compared with other cutting processes, WJM also is used in the food-processing industry for cutting and slicing food products (Table 9.4).

The advantages of this process are that (a) cuts can be started at any location without the need for predrilled holes, (b) no heat is produced, (c) no deflection of the rest of the workpiece takes place (hence the process is suitable for flexible materials), (d) little wetting of the workpiece takes place, (e) the burr produced is minimal, and (f) it is environmentally friendly and safe.

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 composite materials of various thicknesses can

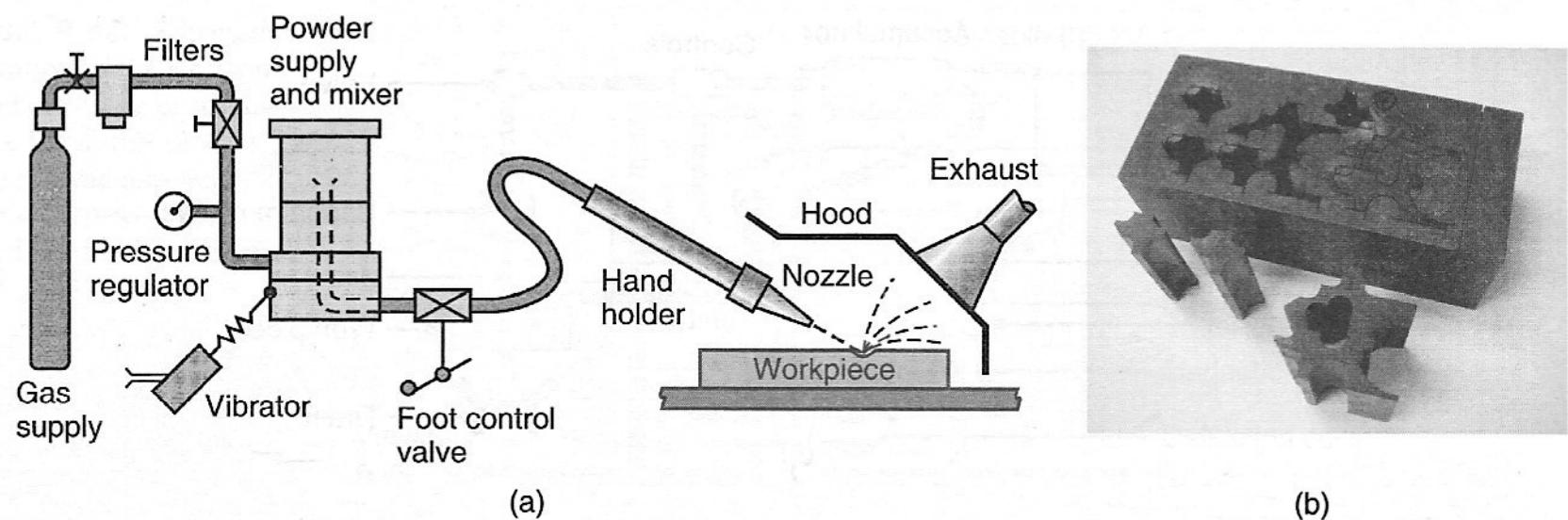


FIGURE 9.39 (a) Schematic illustration of the abrasive-jet machining process and (b) examples of parts produced by abrasive-jet machining; the parts are 50 mm thick and are made of 304 stainless steel. *Source:* Courtesy of OMAX Corporation.

be cut in single or multiple layers, particularly heat-sensitive materials that cannot be machined by processes in which heat is produced. The minimum hole size that can be produced satisfactorily to date is about 3 mm, and maximum hole depth is on the order of 25 mm. Cutting speeds can be as high as 7.5 m/min for reinforced plastics but are 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 it 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 sufficiently high concentrated force (see also Section 9.7) for operations such as (a) cutting small holes, slots, or intricate patterns in very hard or brittle metallic and nonmetallic materials, (b) deburring or removing small flash from parts, (c) trimming and beveling, (d) removing oxides and other surface films, and (e) general cleaning of components with irregular surfaces.

The gas supply pressure is on the order of 850 kPa, and the abrasive-jet velocity can be as high as 300 m/s and is controlled by a valve. The handheld nozzles are usually made of tungsten carbide or sapphire. The abrasive size is in the range of 10–50 μm . Because the flow of the free abrasives tends to round off corners, designs for abrasive-jet machining should avoid sharp corners; holes made in metal parts tend to be tapered. Because of airborne particulates, there is some safety 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 below.

9.16.1 Grinding and abrasive machining processes

Typical grinding operations are performed on workpieces produced to close to their final shape (near-net shape), often through machining operations. They are generally not economical for removing large volumes of material, except in creep-feed grinding,

Hence, design considerations for grinding operations are somewhat similar to those for machining, described in Section 8.14. In addition, specific attention should be given to the following considerations:

1. Parts to be ground should be designed so that they can be mounted securely in suitable fixtures and workholding devices. Workpieces that are thin, straight, or tubular may distort during grinding, thus requiring special attention.
2. If high dimensional accuracy is required, interrupted surfaces, such as holes and keyways, should be avoided, as they can cause vibrations and chatter.
3. Parts for cylindrical grinding should be balanced, and long and slender designs should be avoided to minimize deflections. Fillets and corner radii should be as large as possible.
4. In centerless grinding, short pieces may be difficult to grind accurately because of their lack of support on the blade. In through-feed grinding, only the largest diameter on the parts can be ground.
5. Designs requiring precise form grinding should be kept simple to avoid frequent form dressing of the wheel.
6. Deep and small-diameter holes, and blind holes requiring internal grinding, should be avoided, or they should include a relief (see Fig. 9.40).
7. In order to maintain good dimensional accuracy, designs should preferably allow for all grinding operations to be done without having to reposition the workpiece. (Note that this guideline is also applicable to all manufacturing processes and operations.)

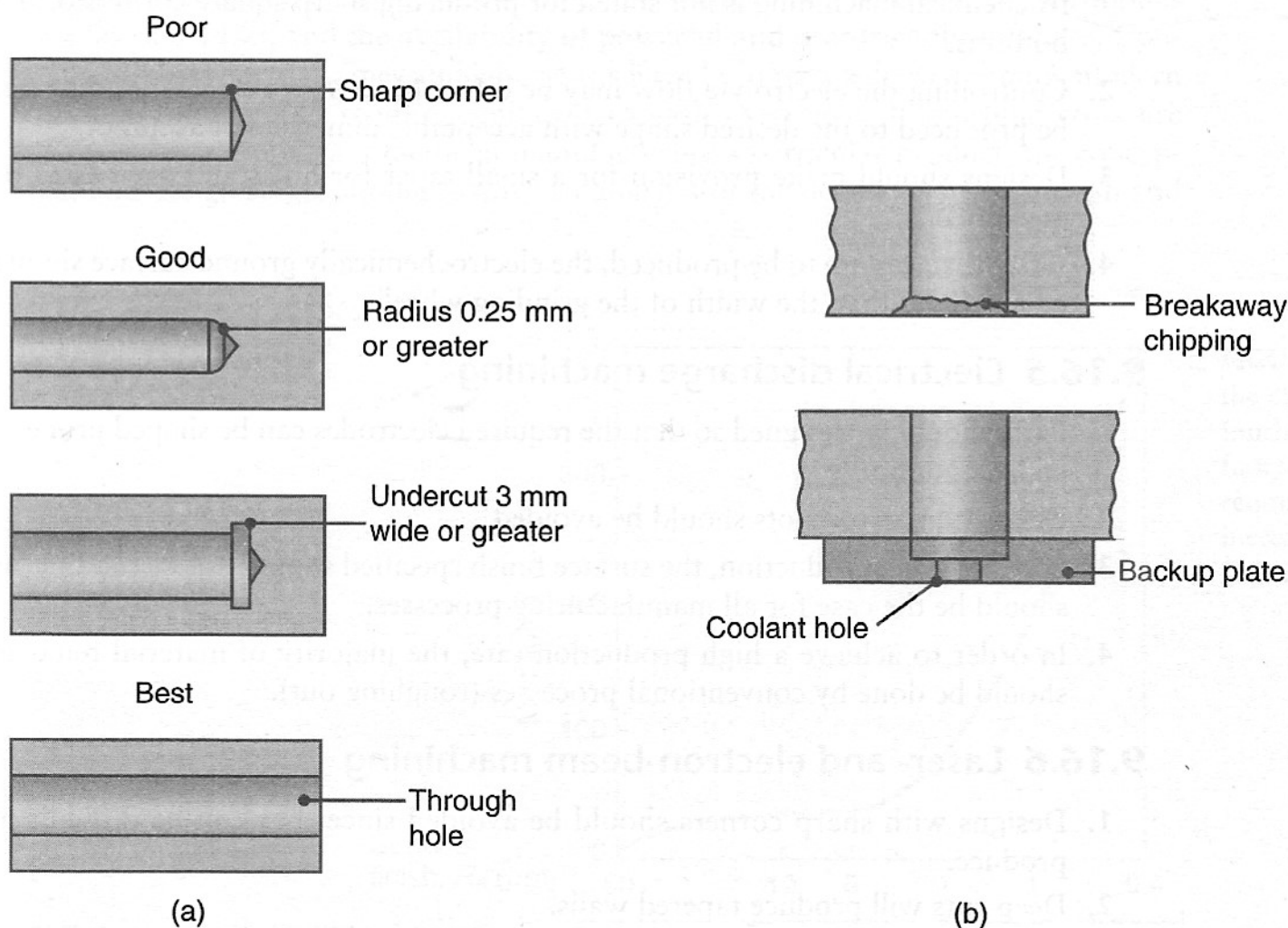


FIGURE 9.40 Design guidelines for internal features, especially as applied to holes. (a) Guidelines for grinding the internal surfaces of holes. These guidelines generally hold for honing as well. (b) The use of a backing plate for producing high-quality through holes by ultrasonic machining. *Source:* After J. Bralla.

9.16.2 Ultrasonic machining

1. Avoid sharp profiles, corners, and radii, because these are eroded by the abrasive slurry.
2. Holes produced will have some taper because of oblique collisions between abrasives and vertical sidewalls.
3. Because of the tendency for chipping of brittle materials at the exit end of holes, the bottom of the parts should have a backup plate (Fig. 9.40b).

9.16.3 Chemical machining

1. Because the etchant attacks all exposed surfaces continuously, designs involving sharp corners, deep and narrow cavities, large tapers, folded seams, or porous workpiece materials should be avoided.
2. Because the etchant attacks the material in both vertical and horizontal directions, *undercuts* may develop (as shown by the areas under the edges of the maskant in Fig. 9.26). Typically, tolerances of $\pm 10\%$ of the material thickness can be maintained in chemical blanking.
3. In order to improve the production rate, the bulk of the workpiece should be preshaped by other processes (such as by machining) prior to chemical machining.

9.16.4 Electrochemical machining and grinding

1. Because of the tendency for the electrolyte to erode away sharp profiles, electrochemical machining is not suited for producing sharp square corners or flat bottoms.
2. Controlling the electrolyte flow may be difficult, so irregular cavities may not be produced to the desired shape with acceptable dimensional accuracy.
3. Designs should make provision for a small taper for holes and cavities to be machined.
4. If flat surfaces are to be produced, the electrochemically ground surface should be narrower than the width of the grinding wheel.

9.16.5 Electrical discharge machining

1. Parts should be designed so that the required electrodes can be shaped properly and economically.
2. Deep and narrow slots should be avoided.
3. For economic production, the surface finish specified should not be too fine, as should be the case for all manufacturing processes.
4. In order to achieve a high production rate, the majority of material removal should be done by conventional processes (roughing out).

9.16.6 Laser- and electron-beam machining

1. Designs with sharp corners should be avoided since they can be difficult to produce.
2. Deep cuts will produce tapered walls.
3. The reflectivity of the workpiece surface is an important consideration in laser-beam machining; dull and unpolished surfaces are preferable.
4. Any adverse effects on the properties of the machined parts caused by high local temperatures and heat-affected zone should be investigated.

5. Because vacuum chambers have limited capacity, part sizes should closely match the size of the vacuum chamber for a high-production rate per cycle for electron-beam machining.
6. If a part requires electron-beam machining on only a small portion of the workpiece, consideration should be given to manufacturing it as several smaller components and assembling them after electron-beam machining.

9.17 Process Economics

This chapter has indicated that the grinding process can be employed both as a finishing operation and for large-scale removal operations. The use of grinding as a finishing operation is often necessary because forming and machining processes alone usually cannot produce parts with the desired dimensional accuracy and surface finish (see, for example, Fig. 9.27). However, because it is an additional operation, grinding can contribute significantly to product cost. Creep-feed grinding, on the other hand, has proven 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 typically are required, and hence the cost increases. Note in Fig. 9.41, for example, 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 advanced computer controls, the increased use of robotics (see Section 14.7), and the availability of powerful and user-friendly software. Consequently, production times and labor costs have been reduced, even though modern machine tools would require significant capital investment. If finishing costs are 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

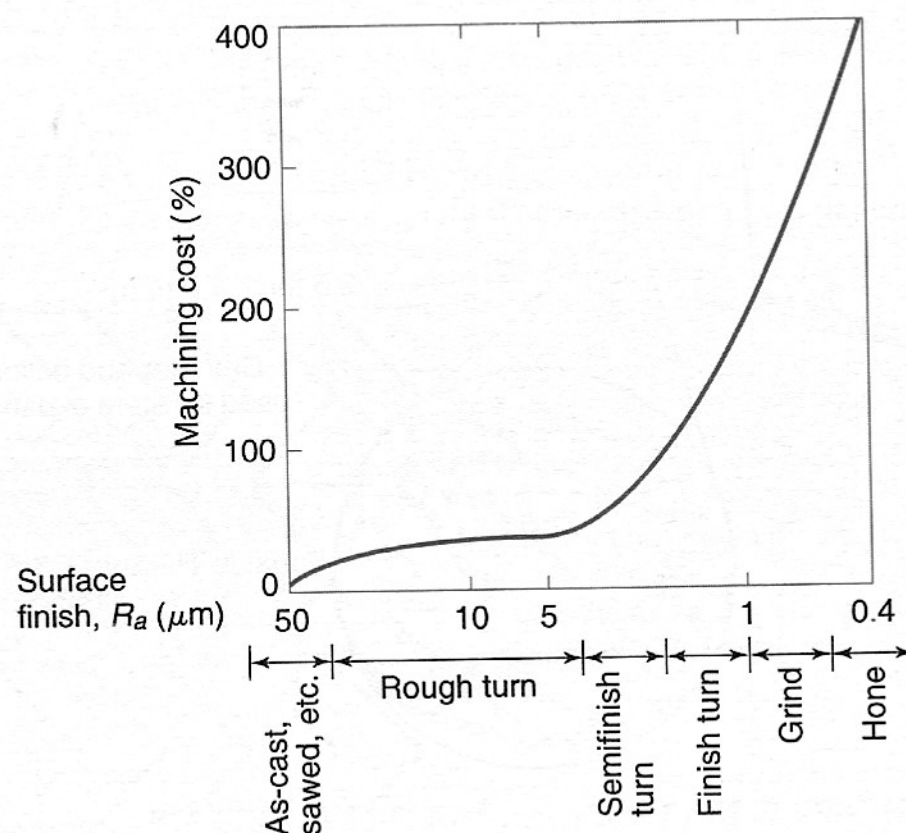


FIGURE 9.41 Increase in the cost of machining and finishing operations as a function of the surface finish required. Note the rapid increase associated with finishing operations.

dimensional accuracy required (see Chapter 1). Furthermore, all processes that precede finishing operations should be analyzed for their capability to produce a more acceptable surface finish and dimensional accuracy (net-shape manufacturing). This task can be accomplished through proper selection of tools and process parameters, as well as the characteristics of the machine tools involved.

The economic production run (see Chapter 16) for a particular machining 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 can be significant.

The rate of material removal, and hence the production rate, can also 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 machine tools such as for electrical and high-energy-beam machining should be justified in terms of the production runs they are able to generate versus the difficulty and cost of manufacturing the same part by other methods.

CASE STUDY | Manufacture of Stents

Heart attacks, strokes, and other cardiovascular diseases claim one life every 33 seconds in the United States alone. 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. 9.42, 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

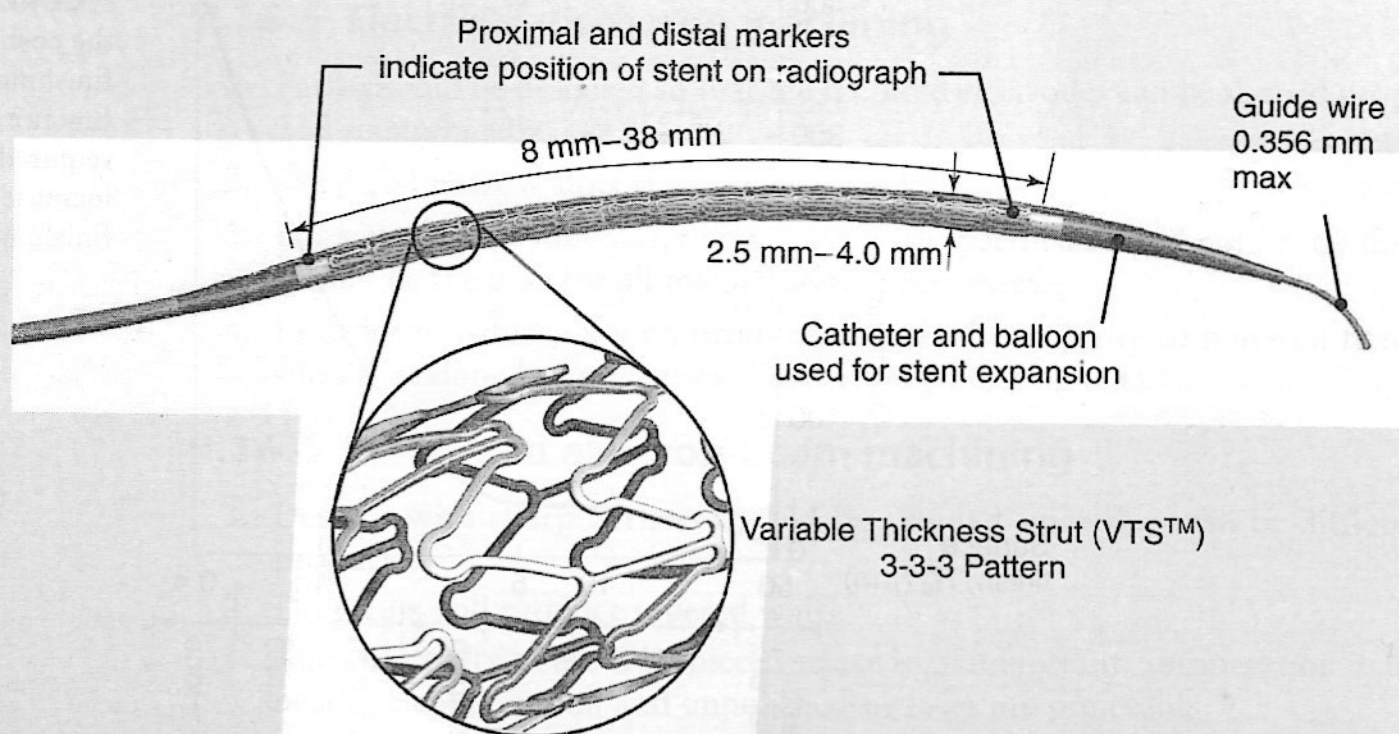


FIGURE 9.42 The Guidant MULTI-LINK TETRA™ coronary stent system.

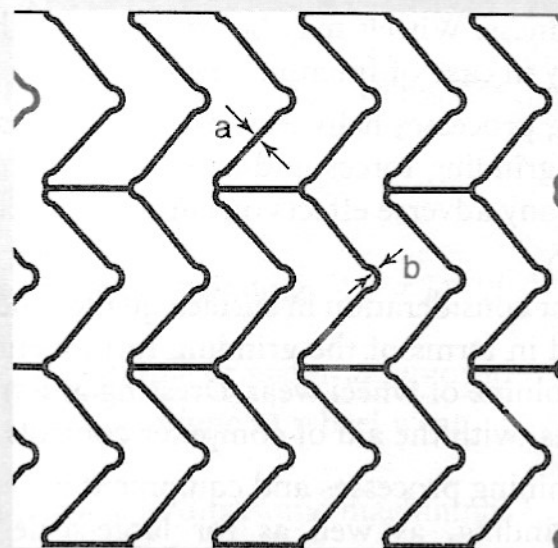
heart disease for which the alternative is usually open-heart bypass surgery, a procedure with greater risk, pain, rehabilitation time, and cost to the patient.

Stent manufacturing is extremely demanding because 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 with the body, because it remains there for the rest 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 9.43, 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. 9.44a). 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. 9.44b. Once the



Notes:
a. 0.12 mm
section thickness to provide
radiopacity
b. 0.091 mm
thickness for flexibility

FIGURE 9.43 Detail of the 3-3-3 MULTI-LINK TETRA™ pattern.

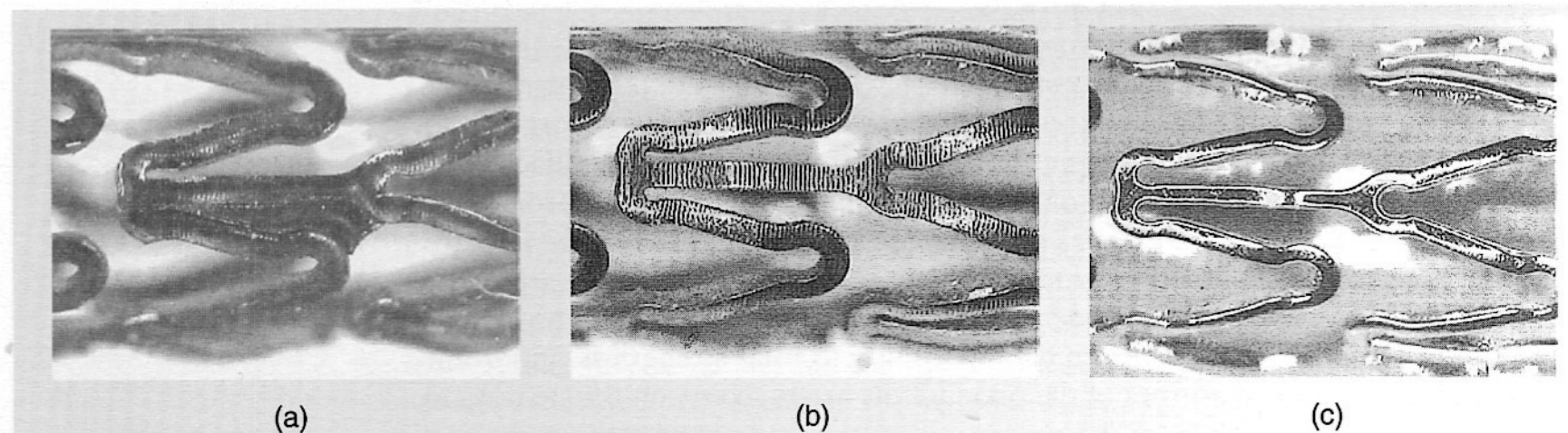


FIGURE 9.44 Evolution of the stent surface. (a) MULTI-LINK TETRA™ after lasing. Note that a metal slug is still attached. (b) After removal of slag. (c) After electropolishing.

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 formation 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. 9.44c) 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 their shape and size. (Section 9.2)
- Grinding wheels typically consist of a combination of abrasive grains and bonding agents. Important characteristics of wheels include the types of abrasive grain and bond, grade, and hardness. Wheels may be reinforced with metallic or fibers to maintain wheel integrity in case of fracture. (Section 9.3)
- The mechanics of grinding processes help 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 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 for improving 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 also can be used. (Section 9.9)
- Advanced machining processes include chemical and electrical means and high-energy beams and are particularly suitable for hard materials and complex part shapes. The effects of these processes on surface integrity must be investigated as they can damage surfaces, 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. (Section 9.15)
- As in all other 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, controls, 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 :

$$\text{surface grinding: } l = \sqrt{Dd}$$

$$\text{external grinding: } l = \sqrt{\frac{Dd}{1 + D/D_w}}$$

$$\text{internal grinding: } l = \sqrt{\frac{Dd}{1 - D/D_w}}$$

$$\text{Undeformed chip thickness, surface grinding: } t = \sqrt{\frac{4v}{VCr}} \sqrt{\frac{d}{D}}$$

$$\text{Relative grain force: } \propto \frac{v}{VC} \sqrt{\frac{d}{D}}$$

$$\text{Temperature rise in surface grinding: } \Delta T \propto D^{1/4} d^{3/4} \left(\frac{V}{v} \right)^{1/2}$$

$$\text{Grinding ratio: } G = \frac{\text{Volume of material removed}}{\text{Volume of wheel wear}}$$

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