Surface Treatments, Coatings, and Cleaning

CHAPTER 34

- Although material and process selection are critical aspects of manufacturing, often the surface properties of a component or a part also determine its performance.
- This chapter describes various surface-modification operations that can be performed on parts, for technical and aesthetic reasons.
- The chapter presents the surface treatment, cleaning, and coating processes that are commonly performed, and includes a discussion of mechanical surface treatments such as shot peening, laser peening, and roller burnishing, for imparting compressive residual stresses onto metal surfaces.
- Coating operations are then examined, including cladding, thermal-spray operations, physical and chemical vapor deposition, ion implantation, and electroplating; the benefits of diamond and diamond-like carbon coatings also are investigated.

34.1 Introduction 985
34.2 Mechanical Surface Treatments 986
34.3 Mechanical Plating and Cladding 987
34.4 Case Hardening and Hard Facing 988
34.5 Thermal Spraying 988
34.6 Vapor Deposition 989
34.7 Ion Implantation and Diffusion Coating 993
34.8 Laser Treatments 993
34.9 Electroplating, Electroless Plating, and Electroforming 994
34.10 Conversion Coatings 998
34.11 Hot Dipping 998
34.12 Porcelain Enameling; Ceramic and Organic Coatings 999
34.13 Diamond Coating and Diamond-like Carbon 1000
34.14 Surface Texturing 1001
34.15 Painting 1001
34.16 Cleaning of Surfaces 1002

EXAMPLES:

34.1 Applications of Laser Surface Engineering 994
34.2 Ceramic Coatings for High-temperature Applications 1000

34.1 Introduction

After a part is manufactured, some of its surfaces may have to be processed further in order to ensure that they have certain properties and characteristics. **Surface treatments** may be necessary in order to

- *Improve resistance to wear, erosion, and indentation*, such as for machine-tool slideways (Figs. 23.2 and 35.1), shafts, rolls, cams, and gears
- *Reduce friction*, such as on sliding surfaces of tools, dies, bearings, and machine ways
- *Reduce adhesion*, such as for electrical contacts
- *Improve resistance to corrosion and oxidation*, on sheet metals for automobile bodies, gas-turbine components, food packaging, and medical devices
- *Improve fatigue resistance*, of bearings and shafts with fillets
- *Rebuild surfaces*, on worn tools, dies, molds, and machine components
- *Modify surface texture*, appearance, dimensional accuracy, and frictional characteristics
- *Impart decorative features*, such as texture or color and texture

Numerous techniques are employed to impart these characteristics to various types of metallic, nonmetallic, and ceramic materials, and include mechanisms that involve (a) plastic deformation of the workpiece surface, (b) chemical reactions, (c) thermal means, (d) deposition, (e) implantation, and (f) organic coatings and paints. Some of these techniques also are used in the manufacture of semiconductor devices, as described in Chapter 28.

The chapter ends with a discussion of the methods used for cleaning manufactured surfaces, before the components are assembled into the completed product and made ready for service. Environmental considerations regarding the fluids used and the waste material from various surface-treatment processes also are included.

34.2 Mechanical Surface Treatments

Several approaches are used to mechanically improve the surface properties of manufactured components; the more common methods are:

Shot Peening. In this process, the workpiece surface is impacted repeatedly with cast steel, glass, or ceramic balls (called *shot*), which make overlapping indentations on the surface. Using shot sizes that range from 0.125 to 5 mm in diameter, this action causes plastic surface deformation, at depths up to 1.25 mm. Because the plastic deformation is not uniform throughout the part's thickness (see also Fig. 2.14c), shot peening causes compressive residual stresses on the surface, thus improving the fatigue life of the component. Unless the process parameters are controlled properly, the deformation can be so severe as to cause damage to the surface. The extent of deformation can be reduced by *gravity peening*, which involves larger shot sizes, but fewer impacts on the workpiece surface.

Shot peening is used extensively on shafts, gears, springs, oil-well drilling equipment, and turbine and compressor blades. Note, however, that if these parts are later subjected to high temperatures (such as gas turbine blades), the residual stress will begin to relax (*thermal relaxation*) and their beneficial effects will be diminished.

Laser Shot Peening. In this process, also called *laser shock peening* (first developed in the mid-1960s but not commercialized until much later), the workpiece surface is subjected to *pulses* (planar laser shocks) from high-power lasers. This peening process produces compressive residual-stress layers that are typically 1 mm deep, with less than 1% of cold working taking place at the surface.

Laser shot peening has been applied successfully and reliably to jet-engine fan blades and to materials such as titanium, nickel alloys, and steels for improved fatigue resistance and some corrosion resistance. Laser intensities are on the order of 100–300 J/cm^2 and have a pulse duration of 10–50 ns. The basic limitation of laser shot peening for industrial, cost-effective applications is the high cost of the high-power lasers (up to 1 kW) that must operate at energy levels of 100 J/pulse.

Water-jet Peening. In this process, a water jet, at pressures as high as 400 MPa, impinges on the workpiece surface, inducing compressive residual stresses, and with surface and subsurface hardening at the same level as in shot peening. The water-jet peening process has been used successfully on steels and aluminum alloys. The control of process variables (such as jet pressure, jet velocity, nozzle design, and its distance from the surface) is important in order to avoid excessive surface roughness or damage.

Ultrasonic Peening. This process uses a hand tool that is vibrated by a piezoelectric transducer, at a frequency of 22 kHz. A variety of heads can be used for different applications.

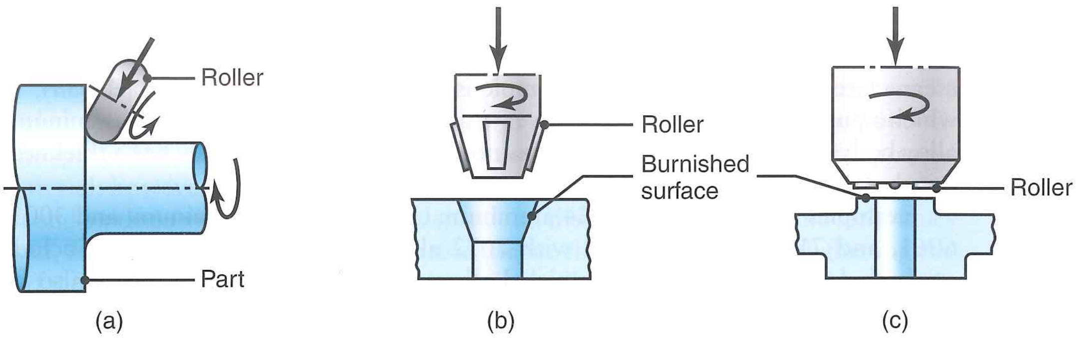


FIGURE 34.1 Burnishing tools and roller burnishing of (a) the fillet of a stepped shaft to induce compressive surface residual stresses for improved fatigue life; (b) a conical surface; and (c) a flat surface.

Roller Burnishing. Also called *surface rolling*, the surface of the component is cold worked by the action of a hard and highly polished roller or set of rollers; the process is used on various flat, cylindrical, or conical surfaces (Fig. 34.1). Roller burnishing improves surface finish by removing scratches, tool marks, and pits, and induces beneficial compressive surface residual stresses. Consequently, corrosion resistance is improved, since corrosive products and residues cannot be entrapped. In a variation of this process, called *low-plasticity burnishing*, the roller travels only once over the surface, inducing minimal plastic deformation.

The internal cylindrical surfaces of holes also can be burnished by a process called **ballizing** or **ball burnishing**. In this operation, a smooth ball (slightly larger than the bore diameter) is pushed through the length of the hole.

Typically used on hydraulic-system components, seals, valves, spindles, and fillets on shafts, roller burnishing improves mechanical properties as well as surface finish. It can be used either by itself or in combination with other finishing processes (such as grinding, honing, and lapping) in which case, the finishing operation is performed after burnishing the part, in order to produce a smooth surface. The equipment can be mounted on various CNC machine tools, for improved productivity and consistency of performance. All types of soft or hard metals can be roller burnished.

Explosive Hardening. In this process, the surfaces are subjected to high pressures through the placement and detonation of a layer of an explosive sheet, placed directly on the workpiece surface. The contact pressures developed can be as high as 35 GPa, lasting about 2–3 μs. Significant increases in surface hardness can be achieved, with very little change (less than 5%) in the shape of the component. Railroad rail surfaces, for example, are explosively hardened.

34.3 Mechanical Plating and Cladding

Mechanical Plating. In *mechanical plating* (also called *mechanical coating*, *impact plating*, or *peen plating*), fine metal particles are compacted over the workpiece surfaces by glass, ceramic, or porcelain beads, that are propelled by rotary means (such as tumbling). This process, which is basically one of cold-welding particles onto a surface, is typically used for hardened-steel parts, such as for automobiles, with plating thickness usually less than 25 μm.

Cladding. In this process, also called *clad bonding*, metals are bonded with a thin layer of corrosion-resistant metal through the application of pressure by rolls or other means (see Fig. 31.1). A typical example is the cladding of aluminum (*Alclad*), in which a pure or corrosion-resistant layer of aluminum alloy is clad over an aluminum-alloy body (core). The cladding layer is anodic to the core and usually has a thickness less than 10% of the total thickness.

Examples of cladding are 2024 aluminum clad with 1230 aluminum, and 3003, 6061, and 7178 aluminum clad with 7072 aluminum; other applications include steels clad with stainless-steel or nickel alloys. The cladding material may also be applied using dies (as in cladding steel wire with copper) or with explosives. Multiple-layer cladding is also utilized in special applications.

Laser cladding involves fusion of a wire or powder material over a substrate. It has been applied successfully to metals and ceramics, especially for enhanced friction and wear behavior of the components.

34.4 Case Hardening and Hard Facing

Surfaces also may be hardened by thermal means in order to improve their frictional and wear properties, as well as their resistance to indentation, erosion, abrasion, and corrosion. The most common methods are:

Case Hardening. Traditional methods of case hardening (*carburizing, carbonitriding, cyaniding, nitriding, flame hardening*, and *induction hardening*) are described in Section 4.10 and summarized in Table 4.1. In addition to common heat sources (such as gas and electricity), an electron beam or laser beam also can be used as a heat source, for both metals and ceramics. Case hardening, as well as some of the other surface-treatment processes described in this chapter, induces residual stresses on surfaces, such as, for example, by the formation of martensite, which causes compressive residual stresses.

Hard Facing. In this process, a relatively thick layer, edge, or point of wear-resistant hard metal is deposited on the workpiece surface by fusion-welding techniques (Chapter 30). Several layers, known as *weld overlay*, can be deposited to repair worn parts. Hard facing enhances the wear resistance of the materials, hence it is used in the manufacture of tools, dies, and various industrial components.

Spark Hardening. Hard coatings of tungsten, chromium, or molybdenum carbides can be deposited by an electric arc, in a process called *spark hardening*, *electric spark hardening*,œ*electrospark deposition*. The deposited layer is typically 250 μm thick. Hard-facing alloys can be used as electrodes, rods, wires, or powder in spark hardening. Typical applications are for valve seats, oil-well drilling tools, and dies for hot metalworking.

34.5 Thermal Spraying

Thermal spraying is a series of processes in which coatings of various metals, alloys, carbides, ceramics, and polymers are applied to metal surfaces by a spray gun, with a stream heated by an oxyfuel flame, an electric arc, or a plasma arc. The earliest applications of thermal spraying, in the 1910s, involved metals, hence the term **metallizing**, which also has been used. The surfaces to be sprayed are first cleaned of oil and dirt, and then roughened by, for example, grit blasting, to improve their bond strength (see Section 26.8). The coating material can be in the form of wire, rod, or powder, and when the droplets or particles impact the workpiece, they solidify and bond to the surface.

Particle velocities typically range from a low of about 150 to 1000 m/s, but can be higher for special applications. Temperatures are in the range of 3000° to 8000°C. The sprayed coating is hard and wear resistant, with a layered structure of deposited material; however, the coating can have a porosity as high as 20%, due to entrapped air and oxide particles. Bond strength depends on the particular process and techniques used, and is mostly mechanical in nature (hence the importance of roughening the surface prior to spraying), but can also be metallurgical. Bond strength generally ranges from 7 to 80 MPa, depending on the particular process used.

Typical applications of thermal spraying include aircraft engine components (such as those used in rebuilding worn parts), structures, storage tanks, tank cars, rocket motor nozzles, and components that require resistance to wear and corrosion. In an automobile, thermal spraying is often applied to crankshafts, valves, fuel-injection nozzles, piston rings, and engine blocks. The process also is used in the gas and petrochemical industries, for the repair of worn parts, and to restore dimensional accuracy to parts that may have not been machined or formed properly.

The source of energy in thermal-spraying processes is of two types: chemical combustion and electrical.

1. Combustion Spraying
    - **Thermal wire spraying** (Fig. 34.2a): The oxyfuel flame melts the wire and deposits it on the surface. The bond is of medium strength, and the process is relatively inexpensive.
    - **Thermal metal powder spraying** (Fig. 34.2b): This process is similar to thermal wire spraying, but uses a metal powder instead of wire.
    - **Detonation gun:** Controlled and repeated explosions take place by means of an oxyfuel–gas mixture. The detonation gun has a performance similar to that of plasma.
    - **High-velocity oxyfuel–gas spraying** (HVOF): This process has characteristics that are similar to that of the detonation gun, but is less expensive.
2. Electrical Spraying
    - **Twin-wire arc:** An arc is formed between two consumable wire electrodes; the resulting bond has good strength, and the process is the least expensive.
    - **Plasma:** Conventional, high-energy, or vacuum (Fig. 34.2c) plasma produces temperatures on the order of 8300°C, and results in good bond strength with very low oxide content. **Low-pressure plasma spray** (LPPS) and **vacuum plasma spray** both produce coatings with high bond strength and with very low levels of porosity and surface oxides.

Cold Spraying. The particles to be sprayed are at a lower temperature and are not melted; thus, oxidation is minimal. The spray jet in cold spraying is narrow and highly focused; it has very high impact velocities, thereby improving the bond strength of the particles on the surface.

34.6 Vapor Deposition

Vapor deposition is a process in which the substrate (workpiece surface) is subjected to chemical reactions by gases that contain chemical compounds of the material to be deposited. The coating thickness is usually a few microns, which is much less than

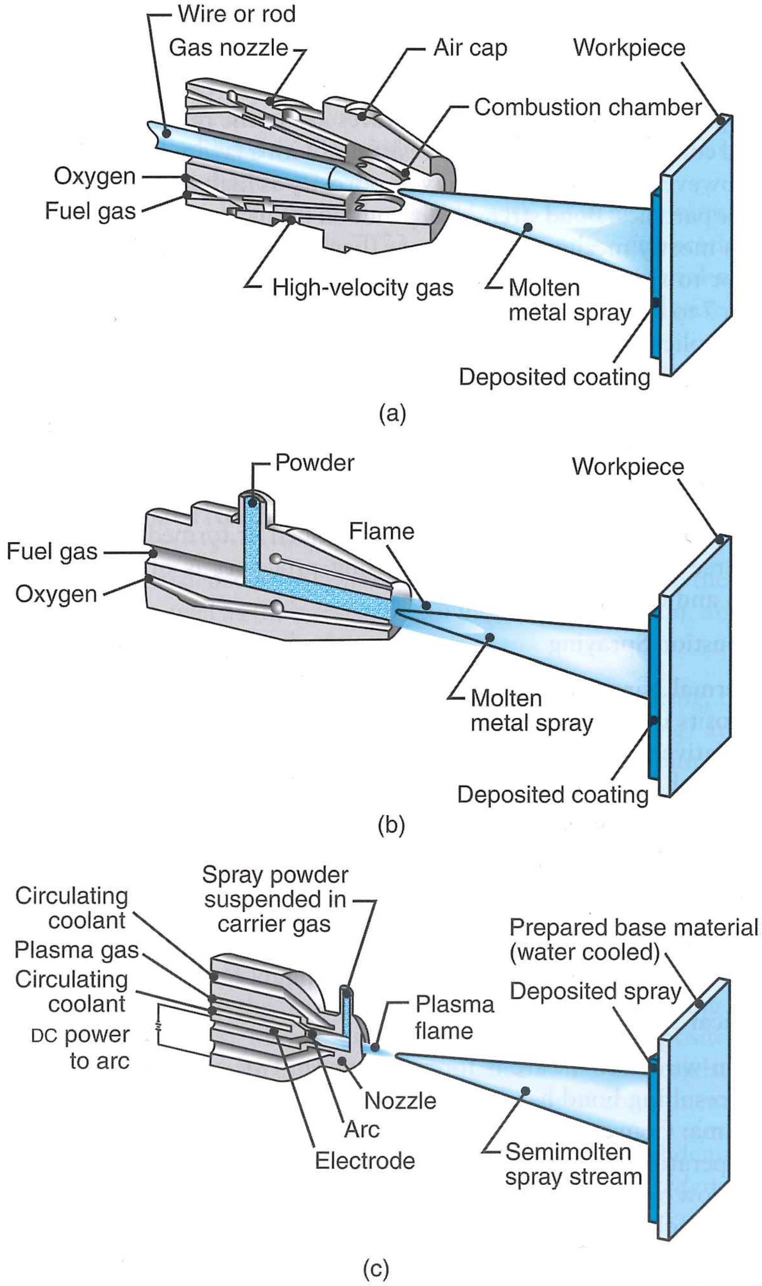


FIGURE 34.2 Schematic illustrations of thermal-spray operations: (a) thermal wire spray, (b) thermal metal-powder spray, and (c) plasma spray.

the thicknesses that result from the techniques described in Sections 34.2 and 34.3. The substrate may be metal, plastic, glass, or paper, and the deposited material may consist of metals, alloys, carbides, nitrides, borides, ceramics, or oxides. Control of the coating composition, thickness, and porosity is important. Typical applications for vapor deposition are coating of cutting tools, drills, reamers, milling cutters, punches, dies, and wear surfaces.

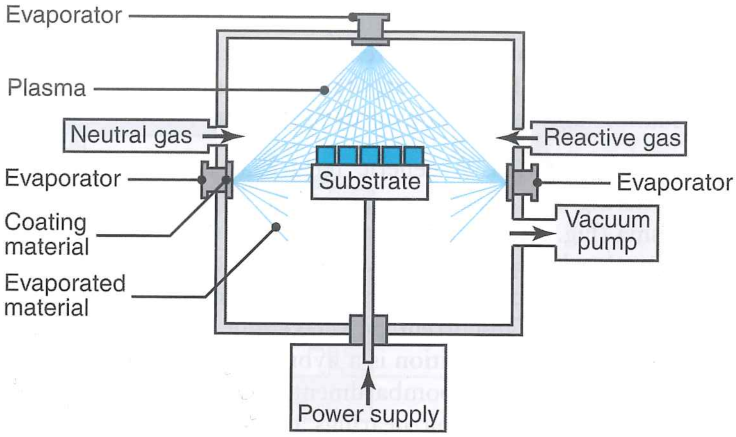


FIGURE 34.3 Schematic illustration of the physical-vapor-deposition process; note that there are three arc evaporators and the parts to be coated are placed on a tray inside the chamber.

There are two major vapor-deposition processes: physical vapor deposition and chemical vapor deposition.

34.6.1 Physical Vapor Deposition

The three basic types of *physical vapor deposition* (PVD) processes are (a) vacuum deposition or arc evaporation; (b) sputtering; and (c) ion plating. These processes are carried out in a high vacuum and at temperatures in the range from 200° to 500°C. In PVD, the particles to be deposited are carried physically to the workpiece, rather than by chemical reactions, as in chemical vapor deposition.

Vacuum Deposition. In vacuum deposition or evaporation, the metal is evaporated at a high temperature in a vacuum and is deposited on the substrate, which usually is at room temperature or slightly higher, for improved bonding. Coatings of uniform thickness can be deposited, even on complex shapes. In **arc deposition** (PV/ARC), the coating material (cathode) is evaporated by several arc evaporators (Fig. 34.3), using highly localized electric arcs. The arcs produce a highly reactive plasma, which consists of the ionized vapor of the coating material; the vapor condenses on the substrate (anode) and coats it. Applications of this process are both functional (oxidation-resistant coatings for high-temperature applications, electronics, and optics) and decorative (hardware, appliances, and jewelry). **Pulsed-laser** and **electron-beam deposition** are more recent, related processes in which the energy beams heat the target into a vapor.

Sputtering. In *sputtering*, an electric field ionizes an inert gas (usually argon); the positive ions then bombard the coating material (cathode) and cause sputtering (ejection) of its atoms. The atoms condense on the workpiece, which is heated to improve bonding (Fig. 34.4). In **reactive sputtering**, the inert gas is replaced by a reactive gas (such as oxygen), in which case the atoms are oxidized and the oxides are deposited. Carbides and nitrides also are deposited by

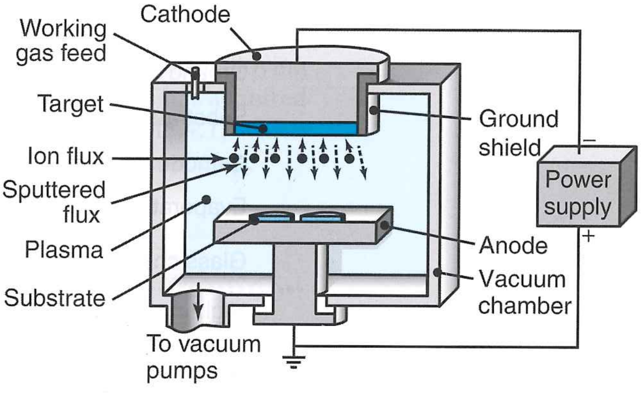


FIGURE 34.4 Schematic illustration of the sputtering process.

reactive sputtering. Alternatively, very thin polymer coatings can be deposited on metal and polymeric substrates, with a reactive gas, causing polymerization of the plasma. **Radio-frequency** (RF) **sputtering** is used for nonconductive materials, such as electrical insulators and semiconductor devices.

Ion Plating. *Ion plating* is a generic term that describes various combined processes of sputtering and vacuum evaporation. An electric field causes a glow, generating a plasma (Fig. 34.5); the vaporized atoms are ionized only partially. **Ion-beam-enhanced (assisted) deposition** is capable of producing thin films, as coatings for semiconductor, tribological, and optical applications. Bulky parts can be coated in large chambers, using high-current power supplies of 15 kW and voltages of 100,000 DC. **Dual ion-beam deposition** is a hybrid coating technique that combines PVD with simultaneous ion-beam bombardment, resulting in good adhesion on metals, ceramics, and polymers. Ceramic bearings and dental instruments are examples of its applications.

34.6.2 Chemical Vapor Deposition

Chemical vapor deposition (CVD) is a *thermochemical* process (Fig. 34.6). In a typical application, such as coating cutting tools with titanium nitride (TiN; Section 22.5), the tools are placed on a graphite tray and heated to 950°–1050°C, at atmospheric pressure and in an inert atmosphere. Titanium tetrachloride (a gas), hydrogen, and nitrogen are then introduced into the chamber. The chemical reactions form titanium nitride on the tool surfaces, with hydrogen chloride produced and exhausted from the reaction chamber. Because of its toxicity, however, this exhaust gas must be carefully cleaned, using exhaust scrubbers before being vented to the atmosphere. For a coating of titanium carbide, methane is substituted for the other gases.

Deposited CVD coatings usually are thicker than those obtained with PVD. A typical cycle is long, consisting of (a) three hours of heating, (b) four hours of coating, and (c) six to eight hours of cooling to room temperature. The thickness of the coating depends on the flow rates of the gases used, time, and temperature.

CVD is a very versatile process. Almost any material can be coated and any material can serve as a substrate, although bond strength will vary. This process

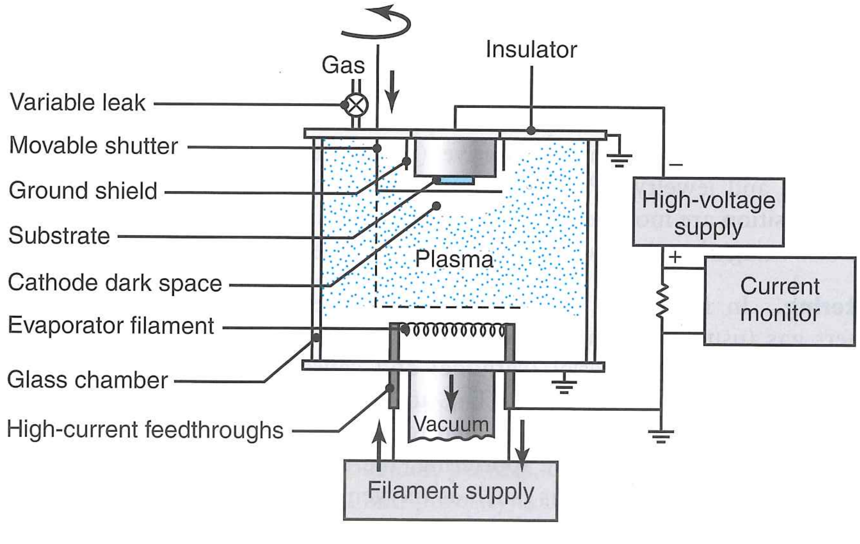


FIGURE 34.5 Schematic illustration of an ion-plating apparatus.

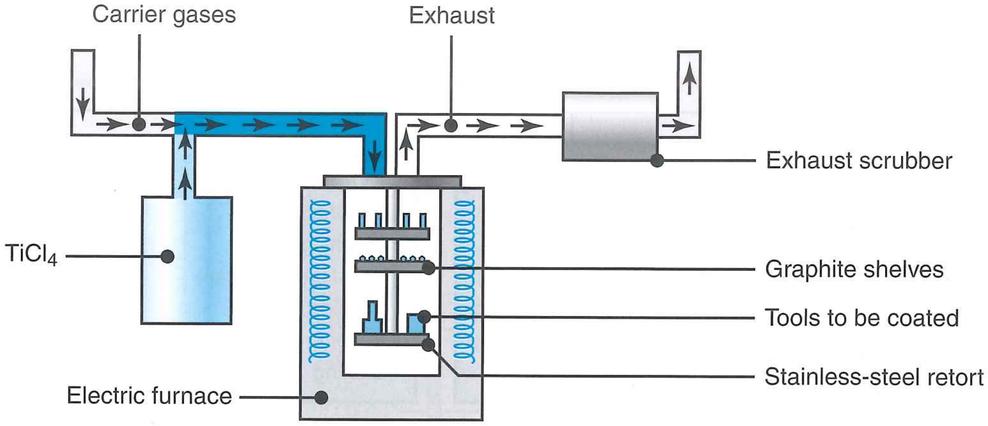


FIGURE 34.6 Schematic illustration of the chemical-vapor-deposition process; note that parts and tools to be coated are placed on trays inside the chamber.

is also used to produce diamond coatings without binders, unlike polycrystalline diamond films which use 1 to 10% binder materials. The **medium-temperature CVD** (MTCVD) technique results in a higher resistance to crack propagation than CVD.

34.7 Ion Implantation and Diffusion Coating

In *ion implantation*, ions (charged atoms) are introduced into the surface of the workpiece. The ions are accelerated in a vacuum, to such an extent that they penetrate the substrate to a depth of a few microns. Ion implantation (not to be confused with ion plating, Section 34.6.1) modifies surface properties, by increasing surface hardness and improving resistance to friction, wear, and corrosion. The process can be controlled accurately, and the surface can be masked to prevent ion implantation in unwanted locations.

Ion implantation is particularly effective on such materials as aluminum, titanium, stainless steels, tool and die steels, carbides, and chromium coatings. The process is typically used on cutting and forming tools, dies and molds, and metal prostheses, such as artificial hips and knees. When used in specific applications, such as semiconductors (Section 28.3), ion implantation is called **doping**, that is, alloying with small amounts of various elements.

Diffusion Coating. This is a process in which an alloying element is diffused into the surface of the substrate (usually steel), altering its surface properties. The alloying elements can be supplied in solid, liquid, or gaseous states. The process has acquired different names, depending on the diffused element, as shown in Table 4.1, which lists various diffusion processes, such as *carburizing*, *nitriding*, and *boronizing*.

34.8 Laser Treatments

As described in various chapters of this book, lasers are having increasingly wider use in manufacturing processes (e.g., laser machining, forming, joining, rapid prototyping, and metrology) and surface engineering (laser peening, alloying, surface treatments, and texturing). Powerful, efficient, reliable, and less expensive lasers are now available for a variety of cost-effective surface treatments, as outlined in Fig. 34.7.

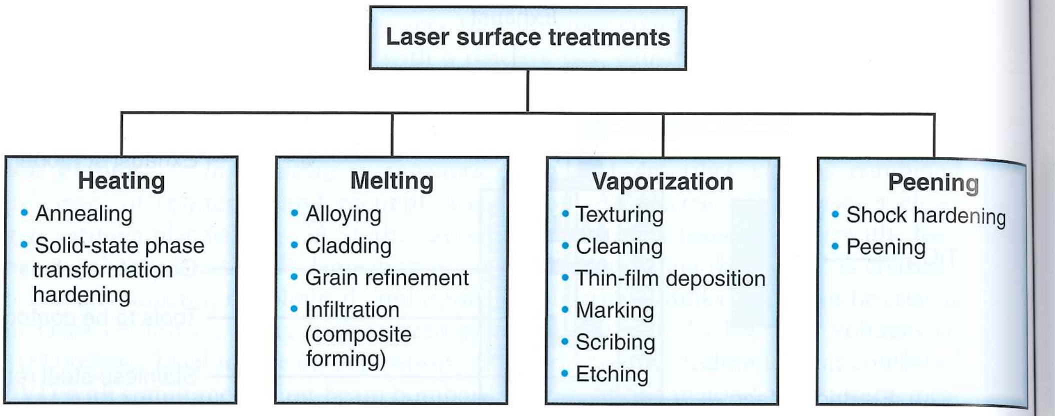


FIGURE 34.7 An outline of laser surface-engineering processes. *Source:* Based on N.B. Dahotre.

EXAMPLE 34.1 Applications of Laser Surface Engineering

Several applications of lasers in engineering practice are given in this example. The most commonly used lasers are Nd:YAG and CO_2; excimer lasers are generally used for surface texturing (see also Table 27.2).

1. *Localized surface hardening*
   - Cast irons: diesel-engine cylinder liners, automobile steering assemblies, and camshafts
   - Carbon steels: gears and electromechanical parts
2. *Surface alloying*
   - Alloy steels: bearing components
   - Stainless steels: diesel-engine valves and seat inserts
   - Tool and die steels: dies for forming and die casting
3. *Cladding*
   - Alloy steels: automotive valves and valve seats
   - Superalloys: turbine blades
4. *Ceramic coating*
   - Aluminum-silicon alloys: automotive-engine bore
5. *Surface texturing*
   - Metals, plastics, ceramics, and wood: all types of products

34.9 Electroplating, Electroless Plating, and Electroforming

Plating imparts resistance to wear, resistance to corrosion, high electrical conductivity, better appearance, and reflectivity.

Electroplating. In *electroplating*, the workpiece (cathode) is plated with a different metal (anode), which is transferred through a water-based electrolytic solution (Fig. 34.8). Although the plating process involves a number of reactions, the process consists basically of the following sequence:

1. The metal ions from the anode are discharged by means of the potential energy from the external source of electricity, or are delivered in the form of metal salts.

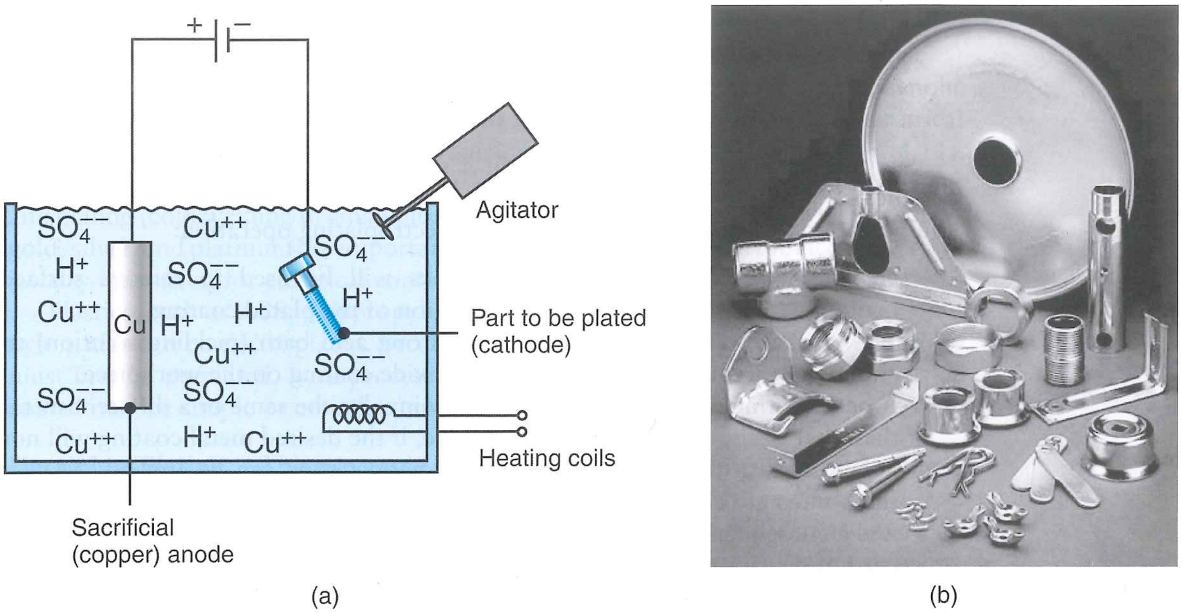


FIGURE 34.8 (a) Schematic illustration of the electroplating process. (b) Examples of electroplated parts. *Source:* Courtesy of BFG Manufacturing Service.

2. The metal ions are dissolved into the solution.
3. The metal ions are deposited on the cathode.

The volume of the plated metal can be calculated from the equation

$$\text{Volume} = cIt, \tag{34.1}$$

where I is the current, in amperes, t is time, and c is a constant that depends on the plate metal, the electrolyte, and the efficiency of the system; typically, it is in the range of 0.03–0.1 mm^3/amp-s. It can be noted that for the same volume of material deposited, the deposited thickness is inversely proportional to the surface area. The deposition rate is typically on the order of 75 μm/h, thus electroplating is a slow process. Thin plated layers are typically on the order of 1 μm; for thick layers, the plating can be as much as 500 μm.

The *plating solutions* are either strong acids or cyanide solutions. As the metal is plated from the solution, it has to be periodically replenished. This is accomplished through two principal methods: (a) salts of metals are occasionally added to the solution or (b) a *sacrificial anode*, of the metal to be plated, is used in the electroplating tank and dissolves at the same rate that the metal is deposited.

There are three basic methods of electroplating:

1. **Rack plating:** The parts to be plated are placed in a rack, which is then conveyed through a series of process tanks.
2. **Barrel plating:** Small parts are placed inside a permeable barrel, made mostly of wire mesh, which is then placed inside the processing tank(s). This operation is commonly performed with small parts, such as bolts, nuts, gears, and fittings. Electrolytic fluid can freely penetrate through the barrel and provide the metal for plating, and electrical contact is provided through the barrel and through contact with other parts.

3. **Brush processing:** the electrolytic fluid is pumped through a handheld brush with metal bristles. The workpiece can be very large, and the process is suitable for field repair or plating, and it can be used to apply coatings on large equipment without disassembling them.

Simple electroplating can be done in a single-process bath or tank, but more commonly, a sequence of operations is involved in a plating line. The following equipment and processes may be part of an electroplating operation:

- Chemical cleaning and degreasing tanks will be used to remove surface contaminants and enhance surface adhesion of the plated coating.
- The workpieces may be exposed to a strong acid bath (pickling solution) to eliminate or reduce the thickness of the oxide coating on the workpiece.
- A base coating may be applied. This may involve the same or a different metal than that of the final surface; for example, if the desired metal coating will not adhere well to the substrate, an intermediate coating can be applied. Also, if thick films are required, a plating tank can be used to quickly develop a film and a subsequent tank, with brightener additives in the electrolytic solution, is used to develop the final surface finish.
- A separate tank performs final electroplating.
- Rinse tanks will be used throughout the sequence.

Rinse tanks are essential for several reasons. Some plating is performed with cyanide salts, delivering the required metal ions. If any residue acid (such as that from a pickling tank) is conveyed to the cyanide-solution tank, poisonous hydrogen-cyanide gas is evolved. This is a significant safety concern, thus environmental controls are essential in plating facilities. Also, plating solution residue will contain some metal ions, and it is often desirable to recover those ions by capturing them in a rinse tank.

The rate of coating deposition depends on the local current density, which is not necessarily uniform on a part. Workpieces with complex shapes may require a modified geometry because of varying plating thicknesses, as can be seen in Fig. 34.9.

Common plating metals are chromium, nickel (for corrosion protection), cadmium, copper (corrosion resistance and electrical conductivity), and tin and zinc (corrosion protection, especially for sheet steel). **Chromium plating** is done by first plating the metal with copper, then with nickel, and finally with chromium. **Hard chromium plating** is done directly on the base metal, and results in a surface hardness of up to 70 HRC (see Fig. 2.14) and a thickness of about 0.05 mm or

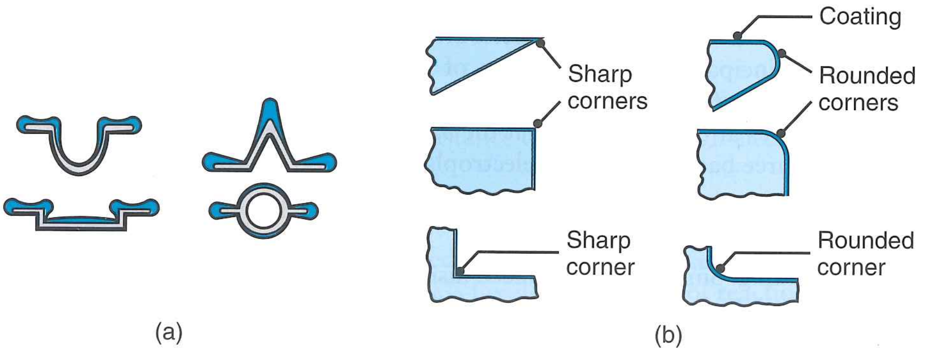


FIGURE 34.9 (a) Schematic illustration of nonuniform coatings (exaggerated) in electroplated parts. (b) Design guidelines for electroplating; note that sharp external and internal corners should be avoided for uniform plating thickness.

higher. This method is used to improve the resistance to wear and corrosion of tools, valve stems, hydraulic shafts, and diesel- and aircraft-engine cylinder liners.

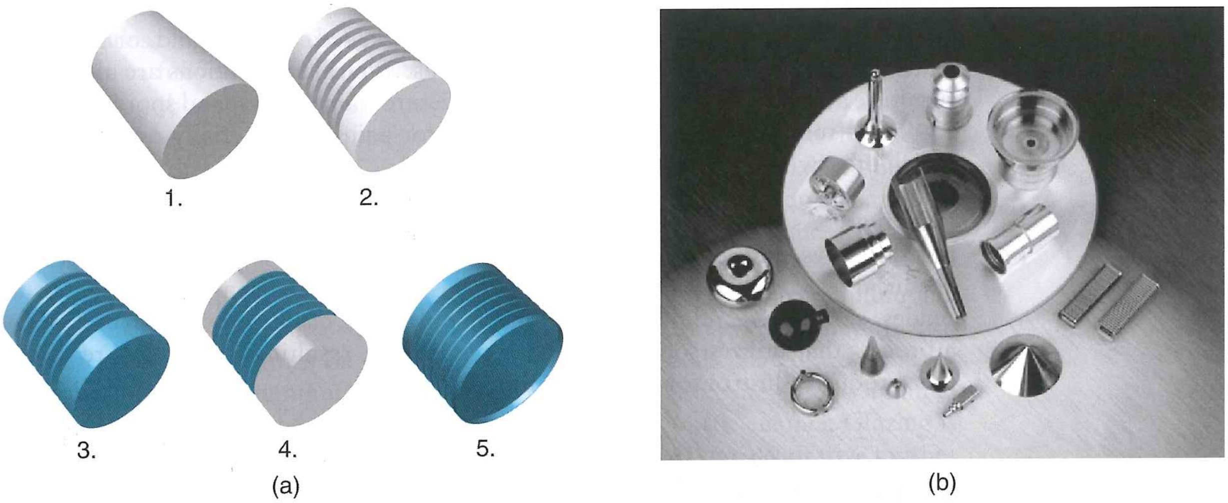
Examples of electroplating include copper-plating aluminum wire and phenolic boards for printed circuits, chrome-plating hardware, tin-plating copper electrical terminals (for ease of soldering), galvanizing sheet metal (see also Section 34.11), and plating components such as metalworking dies that require resistance to wear and galling (cold welding of small pieces from the workpiece surface). Metals such as gold, silver, and platinum are important electroplating materials in the electronics and jewelry industries, for electrical contact and for decorative purposes, respectively.

Plastics, such as ABS, polypropylene, polysulfone, polycarbonate, polyester, and nylon, also can be electroplated. Because they are not electrically conductive, plastics must first be preplated, by a process such as electroless nickel plating. Parts to be coated may be simple or complex, and size is not a limitation.

Electroless Plating. This process is carried out by a chemical reaction and without using an external source of electricity. The most common application utilizes nickel as the plating material, although copper also is used. In *electroless nickel plating*, nickel chloride (a metallic salt) is reduced (with sodium hypophosphite as the reducing agent) to nickel metal, which is then deposited on the workpiece. The hardness of nickel plating ranges between 425 and 575 HV; the plating can subsequently be heat treated to 1000 HV. The coating has excellent wear and corrosion resistance.

Cavities, recesses, and the inner surfaces of tubes can be plated successfully. Electroless plating also can be used with nonconductive materials, such as plastics and ceramics. The process is more expensive than electroplating, but unlike electroplating, the coating thickness of electroless plating is always uniform.

Electroforming. A variation of electroplating, *electroforming* is a metal-fabricating process. Metal is electrodeposited on a *mandrel* (also called a *mold* or a *matrix*), which is then removed with an appropriate solvent; the coating itself thus becomes the product (Fig. 34.10). Both simple and complex shapes can be produced by



(a)

(b)

FIGURE 34.10 (a) Typical sequence in electroforming: (1) A mandrel is selected with the correct nominal size. (2) The desired geometry (in this case, that of a bellows) is machined into the mandrel. (3) The desired metal is electroplated onto the mandrel. (4) The plated material is trimmed, if necessary. (5) The mandrel is dissolved through chemical machining. (b) A collection of electroformed parts. *Source:* Courtesy of Servometer®—PMG LLC, Cedar Grove, NJ.

electroforming, with wall thicknesses as small as 0.025 mm. Parts may weigh from a few grams to as much as 270 kg.

Mandrels are made from a variety of materials, including (a) metallic, such as zinc or aluminum; (b) nonmetallic, which can be made electrically conductive with the appropriate coatings; and (c) low-melting alloys, wax, or plastics, all of which can be melted away or dissolved with suitable chemicals. Mandrels should be physically removable from the electroformed part without damaging it.

The electroforming process is particularly suitable for low production quantities or intricate parts (such as molds, dies, waveguides, nozzles, and bellows) made of nickel, copper, gold, and silver. The process is also suitable for aerospace, electronics, and electro-optics applications.

34.10 Conversion Coatings

Conversion coating, also called *chemical-reaction priming*, is the process of producing a coating that forms on metal surfaces as a result of chemical or electrochemical reactions. Oxides that naturally form on their surfaces (see Section 33.2) represent a form of conversion coating. Various metals (particularly steel, aluminum, and zinc) can be conversion coated.

Phosphates, chromates, and *oxalates* are used to produce conversion coatings, for such purposes as providing corrosion protection, prepainting, and decorative finishing. An important application is the conversion coating of workpieces to serve as lubricant carriers in cold-forming operations, particularly zinc-phosphate and oxalate coatings (see Section 33.7.6). The two common methods of coating are *immersion* and *spraying*.

Anodizing. This is an oxidation process (*anodic oxidation*) in which the workpiece surfaces are converted to a hard and porous oxide layer, that provides corrosion resistance and a decorative finish. The workpiece is the anode in an electrolytic cell immersed in an acid bath, which results in chemical adsorption of oxygen from the bath. Organic dyes of various colors (usually black, red, bronze, gold, or gray) can be used to produce stable, durable surface films. Typical applications are aluminum furniture and utensils, architectural shapes, picture frames, keys, and sporting goods. Anodized surfaces also serve as a good base for painting, especially on aluminum, which otherwise is difficult to paint.

Coloring. As the name implies, *coloring* involves processes that alter the color of metals, alloys, and ceramics. This change is caused by the conversion of surfaces (by chemical, electrochemical, or thermal processes) into such chemical compounds as oxides, chromates, and phosphates. An example is the *blackening* of iron and steels, a process that utilizes solutions of hot caustic soda, resulting in chemical reactions that produce a lustrous, black oxide film on surfaces.

34.11 Hot Dipping

In *hot dipping*, the workpiece (usually steel or iron) is dipped into a bath of molten metal, such as (a) zinc, for galvanized-steel sheet and plumbing supplies; (b) tin, for tinplate and tin cans for food containers; (c) aluminum, for aluminizing; and (d) *terne*, an alloy of lead with 10–20% tin. Hot-dipped coatings on discrete parts provide long-term corrosion resistance to galvanized pipes, plumbing supplies, and many other products.

A typical continuous *hot-dipped galvanizing line* for sheet steel is shown in Fig. 34.11. The rolled sheet is first cleaned electrolytically and scrubbed by brushing. The sheet is then annealed in a continuous furnace with controlled atmosphere and temperature, and dipped in molten zinc at about 450°C.

The thickness of the zinc coating is controlled by a wiping action from a stream of air or steam, called an *air knife* (also used in wave soldering; see Fig. 32.7b). Proper draining for the removal of excess coating materials is important for product quality. The service life depends on the thickness of the zinc coating and the environment to which the galvanized steel is exposed. Various **precoated sheet steels** are used extensively in automobile bodies.

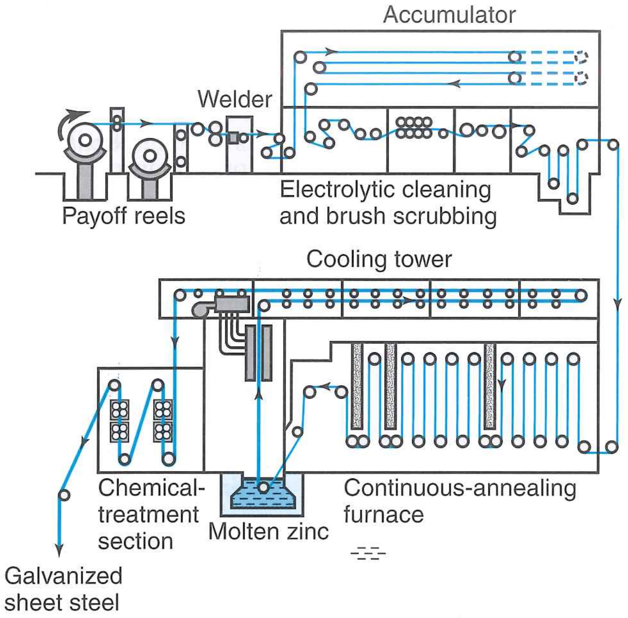


FIGURE 34.11 Flow line for the continuous hot-dipped galvanizing of sheet steel; the welder (upper left) is used to weld the ends of coils to maintain continuous material flow. *Source:* Courtesy of American Iron and Steel Institute.

34.12 Porcelain Enameling; Ceramic and Organic Coatings

Metals can be coated with a variety of glassy (*vitreous*) coatings to provide corrosion and electrical resistance, and for protection at elevated temperatures. These coatings usually are classified as **porcelain enamels**, and generally include enamels and ceramics. The root of the word "porcelain" is *porcellana*, in Italian meaning "marine shell." Note that the word *enamel* also is used as a term for glossy paints, indicating a smooth, hard coating.

Enamels. Porcelain enamels are glassy inorganic coatings that consist of various metal oxides, and are available in various colors and transparencies. *Enameling* (which was a fully developed art by the Middle Ages) involves fusing the coating material to the substrate, at temperatures of 425° to 1000°C to liquefy the oxides. The coating may be applied by dipping, spraying, or electrodeposition, and thicknesses are usually in the range of 0.05–0.6 mm. The viscosity of the material can be controlled using binders, so that the coating adheres to vertical surfaces during application. Depending on their composition, enamels have varying resistances to alkali, acids, detergents, cleansers, and water.

Typical applications for porcelain enameling are household appliances, plumbing fixtures, chemical-processing equipment, signs, cookware, and jewelry; they are also used as protective coatings on jet-engine components. Metals coated are typically steels, cast iron, and aluminum. For chemical resistance, glasses are used as a lining, where the thickness of the glass is much greater than that of the enamel. **Glazing** is the application of glassy coatings onto ceramic wares to give them decorative finishes and to make them impervious to moisture.

Ceramic Coatings. Ceramics, such as aluminum oxide and zirconium oxide, are applied to a substrate at room temperature by means of binders, then fired in a furnace to fuse the coating material. Usually applied using thermal-spraying techniques, these coatings act as thermal barriers for turbine blades, diesel-engine components, hot-extrusion dies, and nozzles for rocket motors, to extend the life of these components. They also are used for electrical-resistance applications to withstand repeated arcing.

Organic Coatings. Metal surfaces can be coated or precoated with a variety of organic coatings, films, and laminates, in order to improve appearance and corrosion resistance. Coatings are applied to the coil stock on continuous lines (see Fig. 13.10), with thicknesses generally in the range of 0.0025–0.2 mm. Organic coatings have a wide range of properties, such as flexibility, durability, hardness, resistance to abrasion and chemicals, color, texture, and gloss. Coated sheet metals are subsequently shaped into various products, such as cabinets, appliance housings, paneling, shelving, residential-building siding, gutters, and metal furniture.

Critical applications of organic coatings involve, for example, the protection of naval aircraft, which are subjected to high humidity, rain, seawater, pollutants, aviation fuel, deicing fluids, and battery acid, as well as being impacted by particles such as dust, gravel, stones, and deicing salts. For aluminum structures, organic coatings consist typically of an epoxy primer and a polyurethane topcoat.

EXAMPLE 34.2 Ceramic Coatings for High-temperature Applications

Table 34.1 shows various ceramic coatings and their typical applications at elevated temperatures. These coatings may be applied either singly or in layers, each layer having its own special properties, as is done in multiple-layer coated cutting tools (see Fig. 22.8).

TABLE 34.1

Ceramic Coatings Used for High-temperature Applications

Property	Type of ceramic	Applications
Wear resistance	Chromium oxide, aluminum oxide, aluminum titania	Pumps, turbine shafts, seals, and compressor rods for the petroleum industry; plastics extruder barrels; extrusion dies
Thermal insulation	Zirconium oxide (yttria stabilized), zirconium oxide (calcia stabilized), magnesium zirconate	Fan blades, compressor blades, and seals for gas turbines; valves, pistons, and combustion heads for automotive engines
Electrical insulation	Magnesium aluminate, aluminum oxide	Induction coils, brazing fixtures, general electrical applications

34.13 Diamond Coating and Diamond-like Carbon

The properties of *diamond* that are relevant to manufacturing engineering were described in Section 8.7. Important advances have been made in *diamond coating* of metals, glass, ceramics, and plastics, using various techniques such as chemical vapor deposition, plasma-assisted vapor deposition, and ion-beam-enhanced deposition.

Examples of diamond-coated products are scratchproof windows, such as those used in aircraft and military vehicles for protection in sandstorms; cutting tools, such as inserts, drills, and end mills; wear faces of micrometers and calipers; surgical knives; razors; electronic and infrared heat seekers and sensors; light-emitting diodes; speakers for stereo systems; turbine blades; and fuel-injection nozzles.

Techniques also have been developed to produce **freestanding diamond films**, on the order of 1 mm thick and up to 125 mm in diameter. These films include smooth, optically clear diamond film, which is then laser cut to desired shapes, and brazed onto workpieces.

Studies also are continuing concerning growing of diamond films on crystalline-copper substrate, by implantation of carbon ions. An important application is in making computer chips (Chapter 28). Diamond can be doped to form p- and n-type ends on semiconductors to make transistors, and its high thermal conductivity allows the closer packing of chips than would be possible with silicon or gallium-arsenide chips, significantly increasing the speed of computers. Diamond is also an attractive material for MEMS devices (Chapter 29), because of its favorable friction and wear characteristics.

Diamond-like Carbon. *Diamond-like carbon* (DLC) coatings, a few nanometers in thickness, are produced by a low-temperature, ion-beam-assisted deposition process. The structure of DLC is between that of diamond and graphite (Section 8.6). Less expensive than diamond films but with similar properties (such as low friction, high hardness, and chemical inertness, as well as having a smooth surface), DLC has applications in such areas as tools and dies, engine components, gears, bearings, MEMS devices, and microscale probes. As a coating on cutting tools, DLC has a hardness of about 5000 HV, as compared with about twice that for diamond.

34.14 Surface Texturing

Recall that each manufacturing process produces a certain surface texture, finish, and appearance. However, manufactured surfaces can be modified further by secondary operations for functional, optical, or aesthetic reasons.

Called *surface texturing*, the secondary operations generally consist of the following techniques:

- **Etching**, using chemicals or sputtering techniques
- **Electric arcs**
- **Lasers**, using excimer lasers with pulsed beams
- **Atomic oxygen**, reacting with surfaces to produce a fine, cone-like surface texture

The possible beneficial as well as adverse effects of these additional processes on material properties, and the performance of the textured parts are important considerations. Usually, the performance is related to appearance or tribological issues. A rough surface, for example, can help entrain a lubricant and reduce friction, but it can also increase friction in unlubricated contacts.

34.15 Painting

Because of its decorative and functional properties, such as environmental protection, low cost, relative ease of application, and the range of available colors, *paint* has been widely used for thousands of years, as a surface coating and decoration. Paints are generally classified as

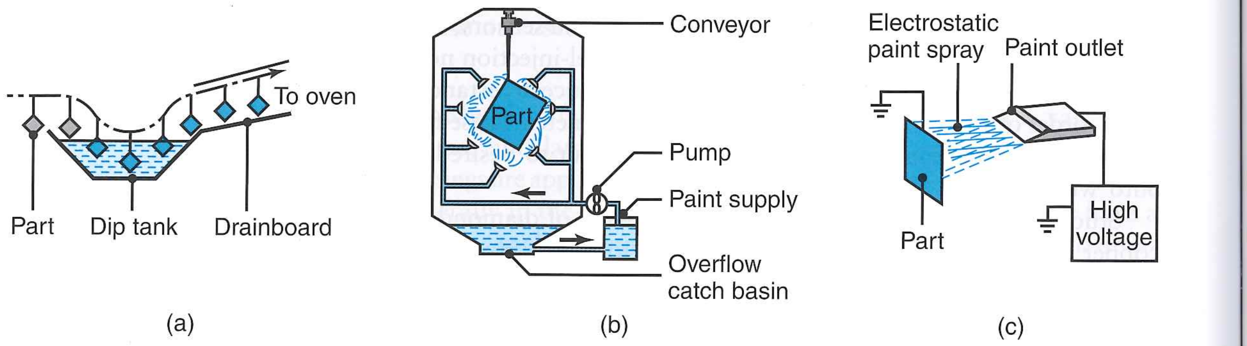


FIGURE 34.12 Methods of paint application: (a) dip coating, (b) flow coating, and (c) electrostatic spraying (used particularly for automotive bodies).

- **Enamels,** producing a smooth coat with a glossy or semiglossy appearance
- **Lacquers,** forming an adherent film by evaporation of a solvent
- **Water-based paints,** applied easily, but have a porous surface and absorb water, making them more difficult to clean

Paints are now available with good resistance to abrasion, high temperatures, and fading. Their selection depends on specific requirements, such as resistance to mechanical actions (abrasion, marring, impact, and flexing) and to chemical reactions (acids, solvents, detergents, alkali, fuels, staining, and general environmental attack).

Common methods of applying paint are dipping, brushing, rolling, and spraying (Fig. 34.12). In **electrocoating** or **electrostatic spraying,** paint particles are charged *electrostatically* and are attracted to surfaces to be painted, producing a uniformly adherent coating. Unlike paint losses in conventional spraying, which may be as much as 70% of the paint, the loss can be as little as 10% in electrostatic spraying. However, deep recesses and corners can be difficult to coat with this method. The use of *robotic controls* for guiding the spray nozzles is now in common practice (Section 37.6.3).

34.16 Cleaning of Surfaces

The importance of surfaces in manufacturing, and the effects of deposited or adsorbed layers of various contaminants on surface characteristics, have been stressed throughout many chapters. The word **clean** or *degree of cleanliness* of a surface is somewhat difficult to define; two common and simple tests are:

1. Observing whether water continuously and uniformly coats the surface, known as the *waterbreak* test; if water collects as individual droplets, the surface is not clean. (This phenomenon can easily be observed by wetting dinner plates that have been washed to different degrees of cleanliness.)
2. Wiping the surface with a clean white cloth and observing any residues on the cloth.

A clean surface can have both beneficial and detrimental effects. Although a surface that is not clean may reduce the tendency for adhesion in sliding (and thus reduce friction), cleanliness generally is essential for a more effective application of coatings, painting, adhesive bonding, brazing, and soldering, as well as for the reliable functioning of moving parts in machinery, assembly operations, and for food and beverage containers.

Cleaning involves the removal of solid, semisolid, or liquid contaminants from a surface, and is an important part of manufacturing operations and the economics of production. In manufacturing operations, the type of cleaning process required depends on the type of *metalworking-fluid residues* and *contaminants* to be removed. Water-based fluids, for example, are easier and less expensive to remove than oil-based fluids. Contaminants (also called *soils*) may consist of rust, scale, chips, various metallic and nonmetallic debris, metalworking fluids, solid lubricants, pigments, polishing and lapping compounds, and general environmental elements.

Basically, there are three types of cleaning methods:

Mechanical Cleaning. This operation consists of physically disturbing the contaminants, often with wire or fiber brushing, abrasive blasting, tumbling, or steam jets. Many of these processes are particularly effective in removing rust, scale, and other solid contaminants from surfaces. *Ultrasonic cleaning* is also in this category.

Electrolytic Cleaning. A charge is applied to the part to be cleaned, in an aqueous (often alkaline) cleaning solution; the charge results in bubbles of hydrogen or oxygen (depending on polarity) being released at the surface; the bubbles are abrasive and aid in the removal of contaminants.

Chemical Cleaning. Chemical cleaning usually involves the removal of oil and grease from surfaces; this operation consists of one or more of the following processes:

- **Solution:** The soil dissolves in the cleaning solution
- **Saponification:** A chemical reaction converts animal or vegetable oils into a soap that is soluble in water
- **Emulsification:** The cleaning solution reacts with the soil or lubricant deposits and forms an emulsion; the soil and the emulsifier then become suspended in the emulsion
- **Dispersion:** The concentration of soil on the surface is decreased by surface-active elements in the cleaning solution
- **Aggregation:** Lubricants are removed from the surface by various agents in the cleanser, and are collected as large dirt particles

Cleaning Fluids. Common cleaning fluids, used in conjunction with electrochemical processes for more effective cleaning, include:

- **Alkaline solutions:** A complex combination of water-soluble chemicals, alkaline solutions are the least expensive and most widely used cleaning fluids in manufacturing operations. Small parts may be cleaned in rotating drums or barrels. Most parts are cleaned on continuous conveyors by spraying them with the solution and rinsing them with water.
- **Emulsions:** Emulsions generally consist of kerosene and oil-in-water and various types of emulsifiers.
- **Solvents:** Petroleum solvents, chlorinated hydrocarbons, and mineral–spirits solvents generally are used for short runs. Fire and toxicity are major hazards.
- **Hot vapors:** Chlorinated solvents can be used to remove oil, grease, and wax. The solvent is first boiled in a container and then condensed and collected for reuse. This hot-vapor process, also known as **vapor degreasing**, is simple and

the cleaned parts are dry. The solvents are never diluted or made less effective by the dissolution of oil, since the oil does not evaporate.

- **Acids, salts, and mixtures of organic compounds:** These are effective in cleaning parts that are covered with heavy paste or oily deposits and rust.

Design Guidelines for Cleaning. Cleaning discrete parts with complex shapes can be difficult. Some basic design guidelines include (a) avoiding deep, blind holes; (b) making several smaller components instead of one large component, which may be difficult to clean; and (c) providing appropriate drain holes in the parts to be cleaned.

The *treatment* and *disposal* of cleaning fluids, as well as of various fluids and waste materials from the processes described in this chapter, are among the most important considerations for environmentally safe manufacturing operations. (See also Section I.4.)

SUMMARY

- Surface treatments are an important aspect of all manufacturing operations. They are used to impart specific mechanical, chemical, and physical properties, such as appearance, and corrosion, friction, wear, and fatigue resistance.
- The processes used include mechanical working and surface treatments, such as heat treatment, deposition, and plating. Surface coatings include enamels, nonmetallic materials, and paints.
- Clean surfaces can be important in the further processing, such as coating, painting, and welding, and in the use of the product. Cleaning can have a significant economic impact on manufacturing operations.

KEY TERMS

Anodizing
Ballizing
Blackening
Case hardening
Chemical cleaning
Chemical vapor deposition
Cladding
Cleaning fluids
Coloring
Conversion coating
Diamond coating
Diamond-like carbon
Diffusion coating
Electroforming
Electroless plating
Electroplating
Enamel
Explosive hardening
Freestanding diamond film
Glazing
Hard chromium plating
Hard facing
Hot dipping
Ion implantation
Ion plating
Laser peening
Mechanical plating
Metallizing
Painting
Physical vapor deposition
Porcelain enamel
Roller burnishing
Shot peening
Spraying
Sputtering
Surface texturing
Thermal spraying
Vacuum evaporation
Vapor deposition
Waterbreak test
Water-jet peening

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REVIEW QUESTIONS

34.1 Explain why surface treatments may be necessary for various parts made by one or more processes.

34.2 What is shot peening? Why is it performed?

34.3 What are the advantages of roller burnishing?

34.4 Explain the difference between case hardening and hard facing.

34.5 Describe the principles of physical and chemical vapor deposition. What applications do these processes have?

34.6 Review Fig. 34.2 and describe the principles behind thermal spray.

34.7 What is electroplating? Why can it be hazardous?

34.8 What is the principle of electroforming? What are its advantages?

34.9 Explain the difference between electroplating and electroless plating.

34.10 How is hot dipping performed?

34.11 What is an air knife? How does it function?

34.12 Describe the common painting systems presently in use in industry.

34.13 What is a conversion coating? Why is it so called?

34.14 Describe the difference between thermal spraying and plasma spraying.

34.15 What is cladding, and why is it performed?

34.16 How are diamond coatings produced?

QUALITATIVE PROBLEMS

34.17 Describe how roller-burnishing processes induce compressive residual stresses on the surfaces of parts.

34.18 Explain why some parts may be coated with ceramics. Give some examples.

34.19 List and briefly describe five surface treatment techniques that use lasers.

34.20 Give examples of part designs that are suitable for hot-dip galvanizing.

34.21 Comment on your observations regarding Fig. 34.9.

34.22 It is well known that coatings may be removed or depleted during the service life of components, particularly at elevated temperatures. Describe the factors involved in the strength and durability of coatings.

34.23 Make a list of the coating processes described in this chapter, and classify them in relative terms as "thick" or "thin."

34.24 Sort the coating processes described in this chapter according to (a) maximum thickness generally achieved and (b) typical coating time.

34.25 Why is galvanizing important for automotive-body sheet metals?

34.26 Explain the principles involved in various techniques for applying paints.

QUANTITATIVE PROBLEMS

34.27 Taking a simple example, such as the parts shown in Fig. 34.1, estimate the force required for roller burnishing. (*Hint:* See Sections 2.6 and 14.4.)

34.28 Estimate the plating thickness in electroplating a 20-mm solid-metal ball using a current of 10 A and a plating time of 1.5 h. Assume that $c = 0.08$ in Eq. (34.1).

SYNTHESIS, DESIGN, AND PROJECTS

34.29 Which surface treatments are functional, and which are decorative? Are there any treatments that serve both functions? Explain.

34.30 An artificial implant has a porous surface area where it is expected that the bone will attach and grow into the