9

Modern Manufacturing Techniques

In Chaps. 6 to 8 of this book, several primary manufacturing processes were presented for the fabrication of metal, plastic, and ceramic parts. The casting, molding, powder processing, metal forming, and conventional machining techniques described in these chapters dominated the manufacturing industry until the mid-1900s. Their total dominance, however, has been reduced with the introduction of numerous new commercial (non-traditional) manufacturing techniques since the 1950s, ranging from ultrasonic machining of metal dies to the nanoscale fabrication of optoelectronic components using a variety of lasers.

The first such processes were developed in response to the common drawbacks of traditional material removal techniques discussed in Chap. 8, for faster and more accurate machining of modern engineering materials. These nontraditional machining processes (introduced mainly in the late 1940s) were originally targeted for the production of complex geometry as well as microdetailed aerospace parts. Today the emphasis remains on reduced scale manufacturing (micro and nano level) with extensive use of lasers for noncontact, toolless fabrication of parts for all industries: household, automotive, aerospace, and electronics.

Modern manufacturing techniques have often been classified according to the principal type of energy utilized to remove or add material—mechanical, electrical, thermal, and chemical.

Mechanical processes: Ultrasonic machining and abrasive jet machining are the two primary (nontraditional) mechanical processes. Material is removed through erosion, where hard particles (in a liquid slurry) are forced into contact with the workpiece at very high speeds.

Electrochemical processes: Electrochemical machining is the primary representative of this group. It uses electrolysis to remove material from a conductive workpiece submerged in an electrolyte bath; particles depart from the anodic workpiece surface toward a cathodic tool and get swept away by the high-speed flowing electrolyte liquid.

Thermal processes: Electrical discharge machining, electron beam machining, and laser beam machining are the three primary thermal energy–based processes. Metal removal in electrical discharge machining is achieved through high-frequency sparks hitting the surface of a workpiece submerged in a dielectric liquid bath. In electron beam machining, a high-speed stream of electrons impinge on a very small focused spot on the surface of the workpiece and, as in electrical discharge machining, vaporize the material (this is preferably carried out in a vacuum chamber). Laser beam machining is utilized for the cutting of thick-walled parts as well as micromachining of very thin walled plates through fusion. Lasers are also commonly used in additive processes, lithography-based or sintering-based, for the solidification of liquids and powders. Naturally, the types of lasers used in these applications are quite varied.

Chemical processes: Chemical machining, also known as etching, refers to the removal of material from metal surfaces through purely chemical reactions. It can favorably be used in etching shallow depths (or holes) in metals such as aluminum, titanium, and copper, which are vulnerable to erosion by certain chemicals (most notably hydrochloric, nitric, and sulphuric acids). Due to difficulties in focusing on small areas, most chemical processes use chemical-resistant masks to protect surfaces from unwanted etching.

All above-mentioned modern material removal or material additive processes are characterized by the following common features: higher power consumption and lower material removal (or additive) rates than traditional fabrication processes, but yielding better surface finish and integrity (i.e., less residual stress and fewer microcracks). A large number of these processes also are capable of fabricating features with dimensions several orders of magnitude less than those obtainable by traditional processes.

In this chapter, we will first review several (nontraditional) processes that belong to the class of material removal techniques in two separate sections: nonlaser versus laser-based fabrication. Subsequently, we will discuss several modern material additive techniques commonly used in the rapid fabrication of layered physical prototypes.

9.1 NONLASER MACHINING

In this section, we will introduce the following nontraditional machining processes: ultrasonic machining, electrochemical machining, electrical discharge machining, and chemical machining. The first three methods utilize machining tools while the last process does not.

9.1.1 Ultrasonic Machining

Ultrasonic machining (USM) is an indirect abrasive process, in which hard, brittle particles contained in a slurry are accelerated toward the surface of the workpiece by a machining tool oscillating at a frequency up to 100 kHz. Through repeated abrasions (material removal), the tool machines a cavity of a cross section identical to its own (Fig. 1). The gap maintained between the tool and the workpiece is typically less than 100 μm.

The literature reports on a British patent issued in 1942 to L. Balamurth as the first design of a USM device. The period for the introduction of the first commercial machines was 1953–1954. Currently, modern USM machines can be used for the fabrication of complex cavity profiles through axial vibration and displacement (Fig. 2a), as well as two-dimensional profiles through a relative planar movement of the workpiece with respect to the machining tool (as in milling) (Fig. 2b).

USM is used primarily for the machining of brittle materials (dielectric or conductive): boron carbide, ceramics, germanium, glass, titanium carbides, ruby, and tool-grade steels. The machining tool must be highly wear resistant, as are low-carbon steels. The abrasives used in the slurry are the same as those used in most grinding wheels: boron carbide, silicon carbide, and aluminum oxide, or when affordable, diamond and cubic boron nitride. Abrasives (25–60 μm in diameter) are normally mixed with a water-based fluid (up to 40% by solid volume) to form the slurry, which may also act as a coolant, in addition to removing the chipped workpiece particles from the interface zone.

Various investigations have shown that higher material removal rates (up to 6 mm/min) can be achieved with (1) increased grain size (up to an optimal diameter) and concentration of abrasives in the slurry, and (2) increased amplitude and frequency of the oscillations of the tool. Increased material removal rates naturally result in increased tool wear rates. Furthermore, harder workpiece materials cause larger tool wear (tungsten

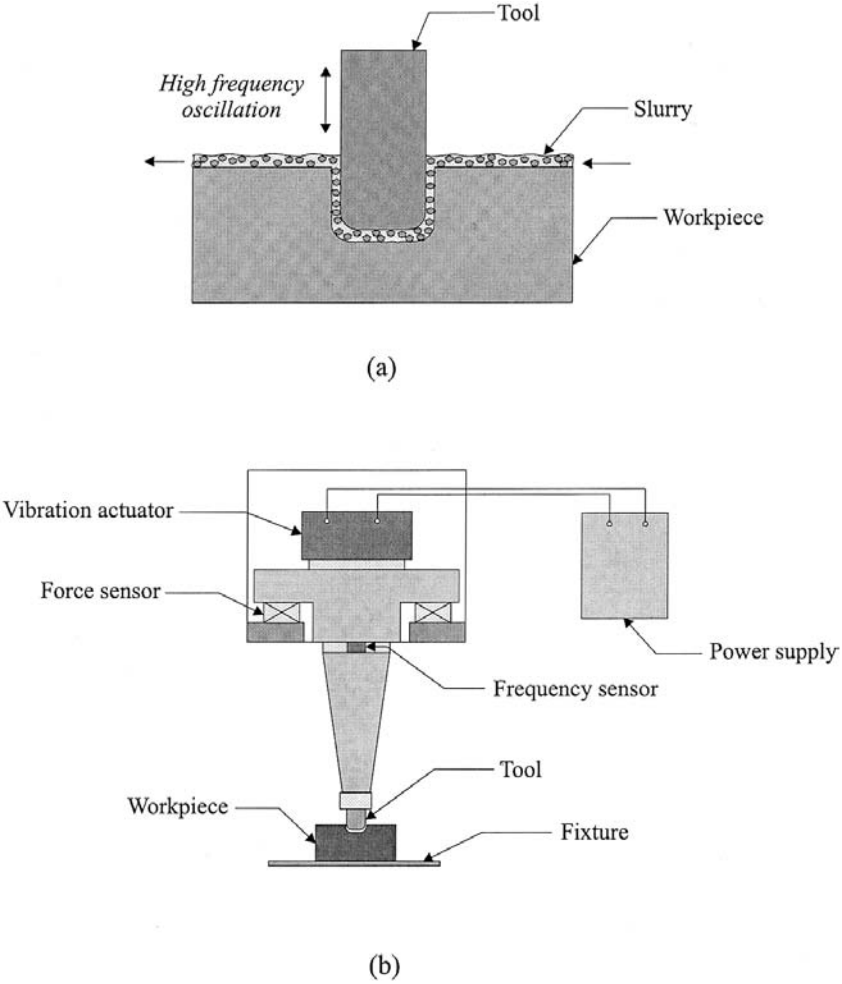


FIGURE 1 Ultrasonic machining (a) process and (b) device.

carbide versus glass). Surface finish in USM can be an order of magnitude better than that achievable through milling.

USM competes with traditional processes based on its strength of machining hard and brittle materials as well as on the workpiece geometry complexity. For example, via USM, we can fabricate holes (many at a time) of diameters as small as 0.1 mm. For such accurate holes, USM can be carried out in two steps, a rough cut and then a finer cut. Another typical

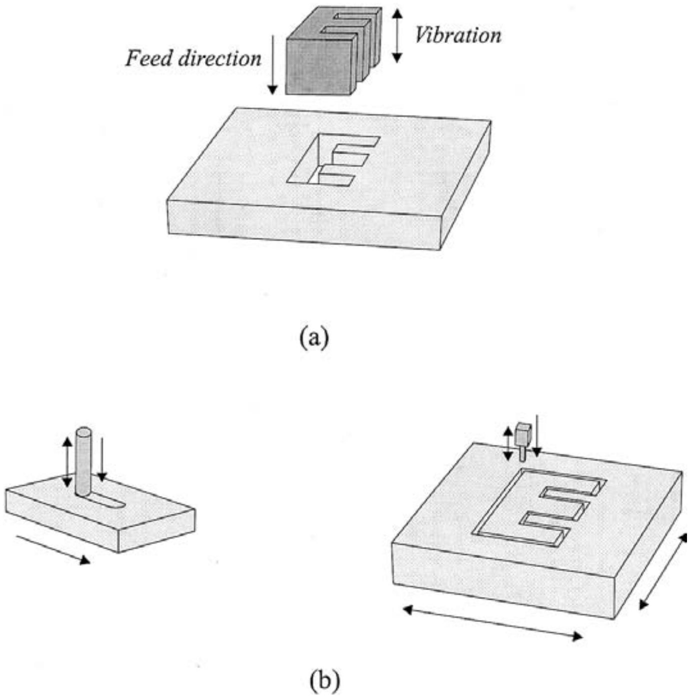


FIGURE 2 (a) Axial and (b) planar USM.

application of USM is the machining of dies of complex geometry to be used in metal forming.

Ultrasonic machine tools resemble small milling machines and drill presses in size and in operation. The major components of such machines are the vibration generator and the slurry storage and pumping unit (Fig. 1b). Those that provide planar motion for the workpiece have appropriate motion controllers as well. There also are some horizontal versions of ultrasonic machines.

9.1.2 Electrochemical Machining

Electrochemical machining (ECM) is a metal removal process based on the principle of reverse electroplating. Since Faraday's work in the early 1800s, it has been known that if two conductive materials are placed in a (conductive) electrolyte bath and energized with a direct current, particles travel from the surface of the anodic material toward the surface of the cathodic material. In ECM, the workpiece is made the anodic (positive) source and a machining tool is made the cathodic (negative) sink (Fig. 3). However, unlike in electroplating, a strong current of electrolyte fluid carries away the deplated material before it has a chance to reach the machining tool. The final shape of the workpiece is determined by the shape of the tool.

Although electroplating can be traced back to the discoveries of M. Faraday (1791–1867), application of ECM to metal removal was first reported in the British patent granted to W. Gussett in 1929. The commercialization of this process is credited to the U.S. company, Anocut

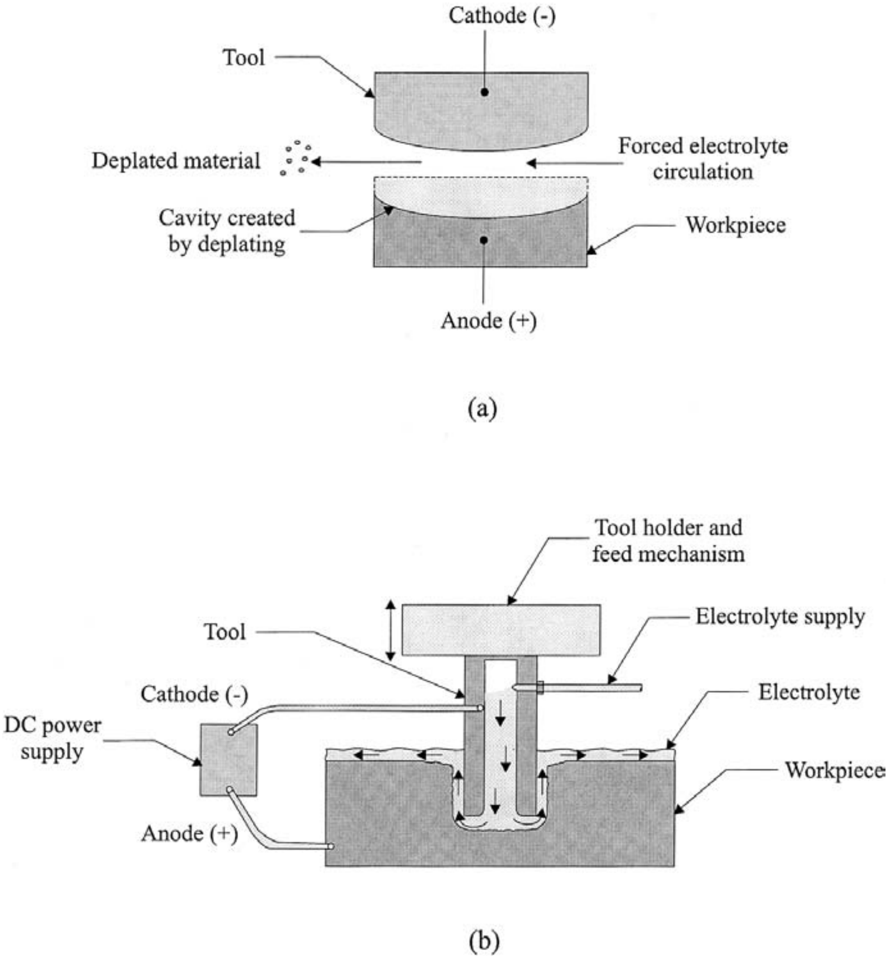


FIGURE 3 Electrochemical machining (a) process and (b) device.

Engineering, in the early part of the 1960s. Today ECM is one of the most widely utilized processes for the fabrication of complex geometry parts. Since ECM involves no mechanical process, but only an electrochemical one, the hardness of the workpiece is of no consequence.

All conductive materials are candidates for ECM, though it would be advantageous to use this costly process for the hardest materials with complex geometries. Also, since there exists no direct or indirect contact between the machining tool and the workpiece, the tool material could be copper, bronze, brass or steel, or any other material with resistance to chemical corrosion. It should be noted that, in certain applications, such as hole drilling, the side surfaces of the tool must be insulated to prevent undesirable removal of material from its surface (Fig. 4). Thus, in such cases, only the tip of the tool is utilized for deplating. The electrolyte must have an excellent conductivity and be nontoxic. The most commonly used electrolytes are sodium chloride and sodium nitrate.

The material removal rate in ECM (the highest of the nontraditional processes) is a direct function of the electrical power, the conductivity of the electrolyte, and the actual gap, maintained between the tool and the workpiece during the feed operation (a few mm/min). The larger the gap, the slower the removal rate will be, though short-circuiting is a danger when the tool and the workpiece come into contact

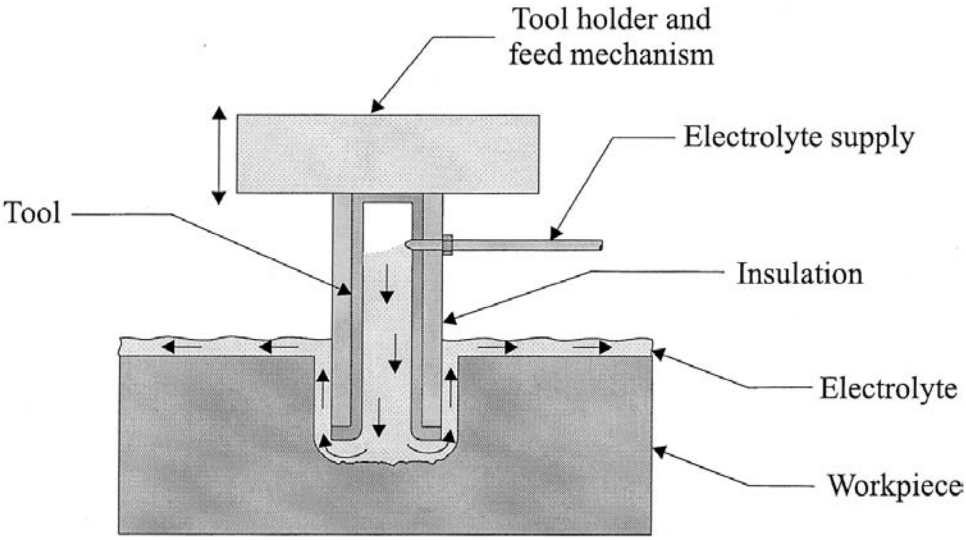


FIGURE 4 Insulation for ECM.

or are in very close proximity. Thus gap control is an important process parameter in ECM. The surface quality in ECM is worse than in ultrasonic machining but still much better than in milling.

ECM is a very versatile process that can be used for profiling and contouring, multiple hole drilling, broaching, deburring, sawing, and most importantly the fabrication of forging die cavities (die sinking) at rates of 10 times those achievable by electrical discharge machining. One must notice that owing to the nature of deplating, sharp corners are not machineable by ECM.

ECM machines exist in very large sizes, as well as in sizes of typical milling machines. They exist in horizontal and vertical configurations. ECM machines utilize 5 to 20 volts DC for deplating, though at current levels of up to 40,000 amps. Most modern ECM machines employ numerical control (NC)–based processors for the control of the workpiece motion with respect to the tool, as well as to regulate all other functions, such as the flow of the electrolyte.

9.1.3 Electrical Discharge Machining

Electrical discharge machining (EDM) is a metal removal process based on the principle of spark-assisted erosion. As in ECM, the workpiece and the shaped tool are energized with opposite polarity, 50 to 380 volts DC and up to 1,500 amps, in a bath of dielectric fluid. As the cutting tool (the electrode) is brought to the vicinity of the workpiece, electrical discharge, in the form of a spark, hits the surface of the workpiece and removes a very small amount of material. The frequency of discharge is controlled; it is typically between 10 and 500 kHz. This is a thermal process; the region of the spark reaches very high temperatures, above the melting point of the metal workpiece (Fig. 5).

The history of the modern EDM process can be traced to the independent work of two groups: B. R. Lazarenko and N. I. Lazarenko in Russia (in the former USSR) and H. L. Stark, H. V. Harding, and I. Beaver. Today EDM is one of the most widely used nontraditional metal cutting processes. It exists commercially in the form of EDM die sinking machines, wire cutting machines (EDWC) and grinding (EDG). In die sinking (Fig. 6a), a shaped electrode (cutting tool) is used to make complex geometry cavities or cutouts in metal workpieces. The workpiece can be of any hardness since there is no mechanical action–based cutting. As expected, the material removal rate is a direct function of the discharge energy and the melting temperature of the workpiece material. In wire-EDM (EDWC) (Fig. 6b), a small diameter (e.g., copper or tungsten) wire travels slowly along a prescribed contour and cuts the entire thickness of the

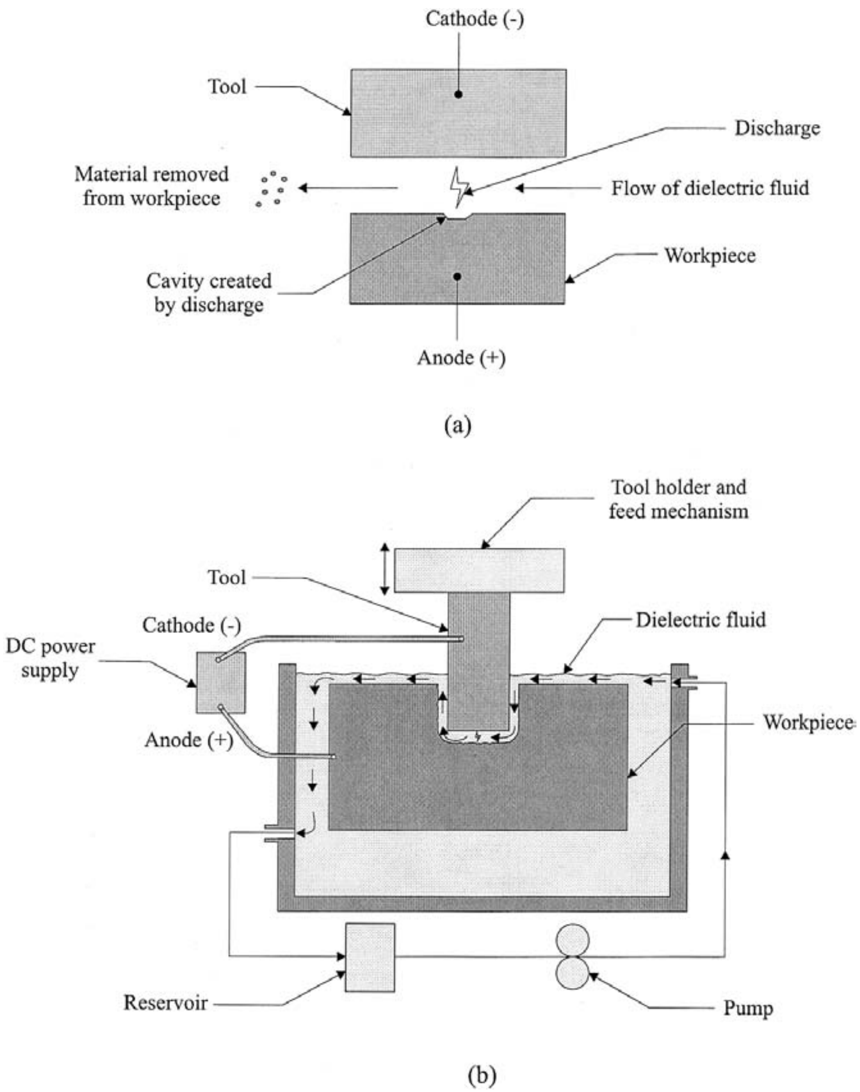
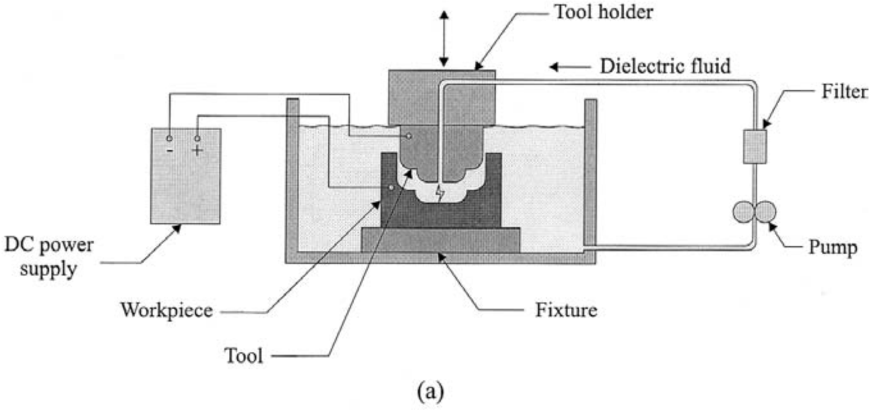


FIGURE 5 Electrical discharge machining (a) process and (b) device.



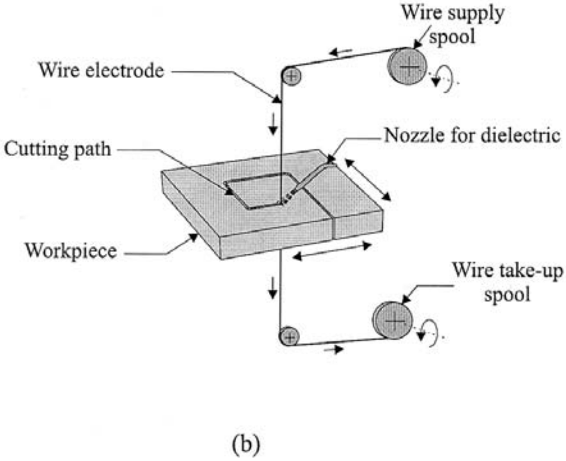


FIGURE 6 EDM (a) die sinking and (b) wire cutting.

workpiece (as in sawing) using the principle of spark erosion. This process can cut workpiece thicknesses of up to 300 mm with a wire of 0.16 to 0.3 mm. The lower the workpiece thickness, the faster is the feed rate.

A primary disadvantage of EDM is tool wear. Thus it is common to utilize several identical geometry cutting tools during the machining of one profile. These tools can be fabricated from the following materials using a variety of casting/powder processing/machining techniques: graphite, copper, brass, tungsten, steel, aluminum, molybdenum, nickel, etc. The principal tool wear mechanism is the same as the spark erosion mechanism that removes particles from the workpiece surface. The dielectric fluid (hydrocarbon oils, kerosene, and deionized water) is an insulator between the tool and the workpiece, a coolant, and a flushing medium for the removal of the chips.

Despite the above serious disadvantage, EDM can yield part geometries not achievable by other nontraditional processes, primarily because it can be configured into multiaxis cutting machine tools (small to very large). As in milling, the rotation of the cutting tool can be synchronized with a planar (*X*–*Y*) motion of the workpiece table to obtain a variety of profiles, including internal threads, teeth, etc. The surface finish achievable in EDM is comparable to ECM or slightly worse. Thus it can be utilized in the fabrication of both tools and dies (e.g., stamping/extrusion/molding dies) and individual parts.

9.1.4 Chemical Machining

The use of chemical etchants in the removal of material from metal parts' surfaces is commonly referred to as chemical machining (CHM). This process is based on the controlled removal of metal particles from a part's surface through targeted etching using acids and alkaline solutions.

The first generic step to all chemical machining processes is the creation of a mask on the surface of the workpiece that is resistant to the etchant used (the terms resist and maskant are interchangeably used to describe the thin film placed on the surface of the part). The next step is etching—material removal from the unprotected sections of the workpiece (Fig. 7).

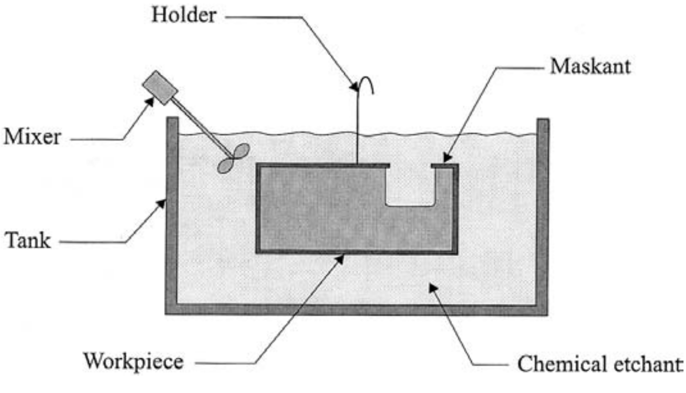


FIGURE 7 Chemical machining.

Chemicals have been used for many centuries in the engraving of decorative items and jewellery, as well as in printing and photography since the 17th century. The widespread use of etching in the manufacturing industry can be traced back only to the early 1940s, when airplane manufacturers started to use chemicals in removing material from airplane structural elements, primarily, for weight reduction. Today the electronics industry is probably the largest user of this technology in the fabrication of printed-circuit boards (PCBs) and integrated-circuit (IC) devices. Therefore in this section we will first review CHM for the fabrication of (relatively) large metal parts and then discuss photolithography for microscale manufacturing.

Chemical Milling and Blanking

In chemical milling, shallow cavities are etched on the surface of a metal workpiece—most commonly on large aerospace structures. In chemical blanking, through holes are blanked in thin plates by etching the unprotected locations (circular profiles) on the part from above and under.

Prior to the individual discussion of both above-mentioned processes, it would be beneficial to review the common set of issues:

Workpiece material: All metals are candidates for CHM. The most common ones include aluminum alloys, magnesium alloys, copper alloys, titanium alloys and steel alloys.

Maskants: Maskants and resists are commonly classified according to the technique utilized in their application and removal. Cut and peel maskants—very common in CHM milling—are applied via dipping or spray coating and removed by cutting (manually or by a laser) and peeling Photoresists—common in CHM blanking and electronics manufacturing—are applied via dipping, spray coating, or roll coating and removed via washing; screen resists are applied via screening (i.e., through a metal mesh placed on the part, which acts as a "negative") and thus there is no need to remove resists from areas to be etched. Naturally, although maskants come in a large variety, they must be utilized according to the material at hand and the etching method to be used: polymers/neoprene for aluminum alloys, polyethylene for nickel, neoprene for brass, and so on.

Etchants: The selection of an etchant depends on the workpiece material, maskant material, depth of etch, and surface finish required. Common etchants include sodium hydroxide (NaOH) for aluminum, sulphuric acid (H_2SO_4) for magnesium, and hydrofluoric acid (HF) for titanium. Material removal rates (i.e., etch rates) using these etchants can vary between 0.01 mm/min and 0.05 mm/min.

Chemical milling (Fig. 8) starts with the preparation of the workpiece surface: removal of residual stresses from the surface (e.g., through shot peening) and cleaning/degreasing. Maskant is applied next. Global

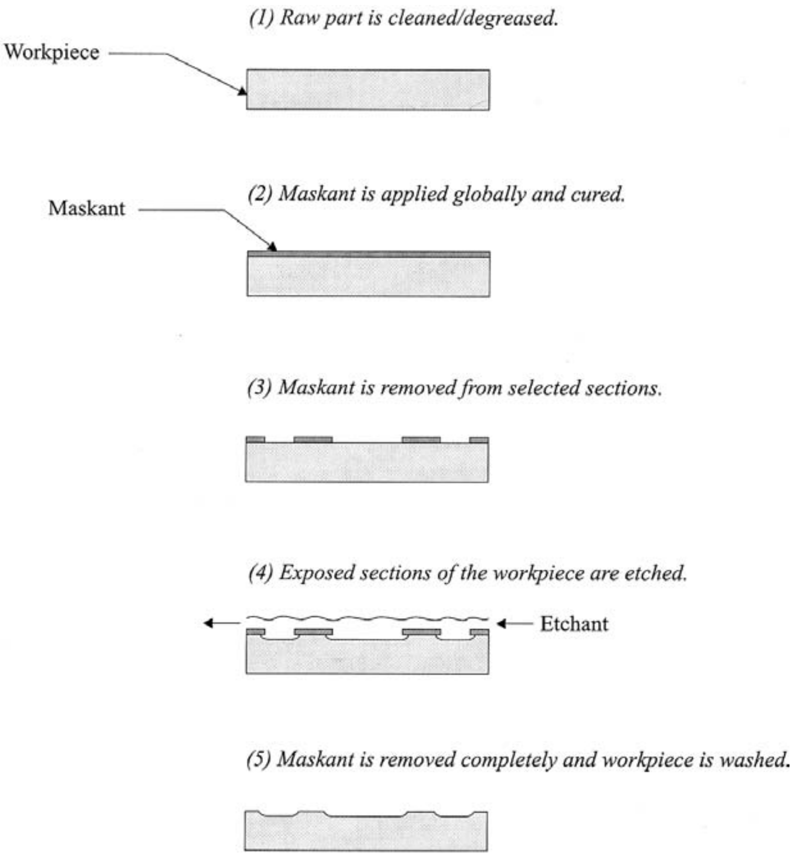


FIGURE 8 Chemical milling.

application and curing of the masking material is followed by the removal of necessary maskant sections (demasking). Exposed workpiece sections are etched using a flow of etchant. The last step is the removal of maskant from all unetched areas and the washing of the workpiece.

Chemical blanking follows the same process of chemical machining, except, in this case the etchant attacks the exposed metal surfaces of the thin workpiece (less than 0.75 mm) to fabricate simple through holes or complex cutout profiles (Fig. 9).

Chemical milling/blanking can be effectively utilized for the machining of airplane wing skins, helicopter vent screens, instrument panels, flat springs, artwork and so on. Although the equipment utilized is generally simple and easy to maintain, one must not underestimate the safety and

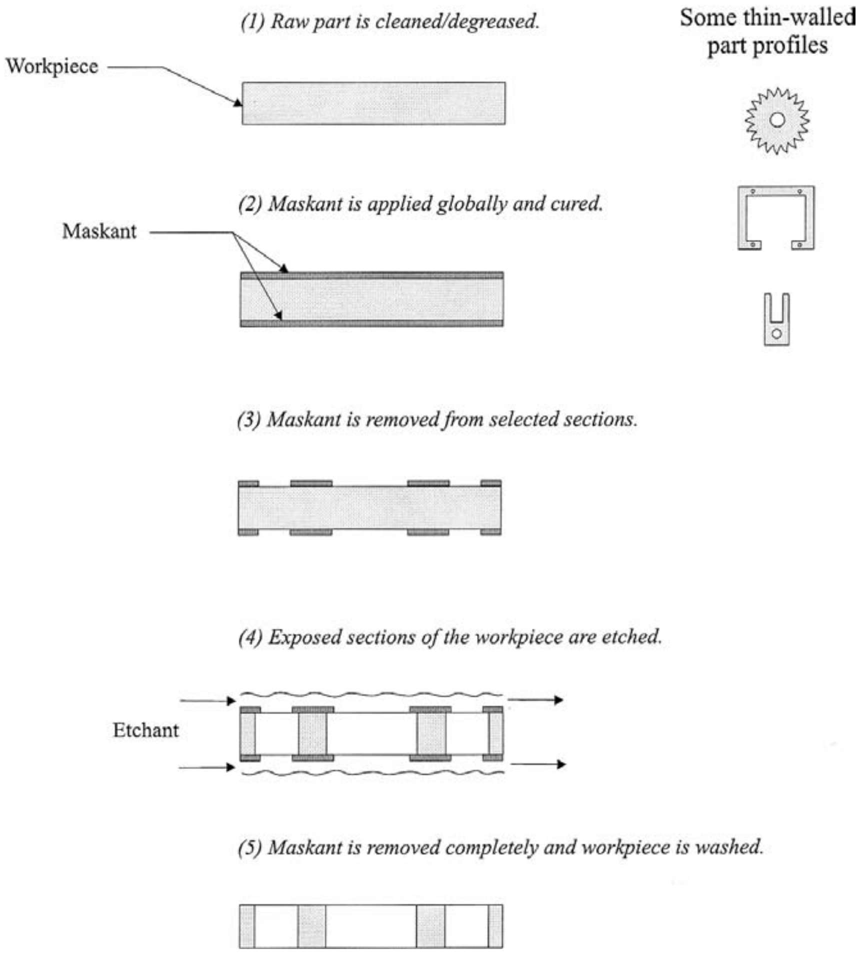


FIGURE 9 Chemical blanking.

environmental precautions necessary when dealing with highly toxic chemicals (maskants and etchants).

Microlithography

Lithography refers to transferring a pattern contained in a photomask into a photoresist polymer film through its curing and then utilizing this resist mask to replicate the desired pattern in an underlying thin conductor film. Microlithography refers to the lithographic process for the manufacturing of microscale patterns, normally in silicon-based wafers used in the fabrication of IC devices.

Although photochemical processes have been in existence for many decades, microlithography owes its start to the invention of the monolithic IC by J. Kilby and R. Noyce in 1960. Since that time, exponential increases in device densities on modern ICs necessitated corresponding innovative mass production techniques for microscale patterns. These techniques have included photolithography, x-ray lithography, electron beam lithography, and ion beam lithography.

The oldest *photolithographic technique* (prior to the 1970s) utilized a (chrome on glass) mask, pressed into contact with a photoresist-coated wafer, and flood exposure of the complete wafer with ultraviolet (UV) light for the curing of the (photopolymer) resist. A more robust technique, developed in 1973, projection lithography, uses optical imaging to reflect directly the photo mask onto the maskant/resist. This technology can yield features of 0.2 to 1.5 μm, only limited by the wavelength of the UV light source (200–450 nm).

X-ray lithography, in existence since the mid-1970s, can yield feature resolutions better than photolithography through the use of x-ray light sources in combination with suitable (polymer) resists. However, since no material is totally transparent to x-rays, mask fabrication is one of major disadvantages of this technique (Fig. 10). Furthermore, it is difficult to collimate or focus x-rays. Thus, owing to excellent resolution improvements in photolithography in the late 1990s, x-ray lithography may never become a commercial success.

Electron beam lithography has evolved from a basic technology utilized in scanning electron microscopy in the 1960s, to become a competing technique to photolithography in the early 1970s. Owing to their extremely short wavelengths (0.01 nm), electron irradiations can be utilized for high-resolution fabrication of IC devices (or the photomasks). However, such high resolutions (below 100 nm and frequently as low as a few nanometers) come with a very high price tag. Thus this technology is often called e-beam nanolithography, and it is primarily targeted for the fabrication of prototype ICs or nanoscale devices.

Ion beam lithography, researched in the late-1970s, offers the promise of better resolution than e-beam lithography, since ions scatter much less than electrons. However, this technology is dependent on the development of high-brightness energy sources, suitable lenses, and stable masks before it can become a commercially viable technique.

In lithography, as in other chemical machining techniques described in this section, the formation of a resist mask on the thin film conductor substrate is followed by an etching operation. The accurate transfer of the

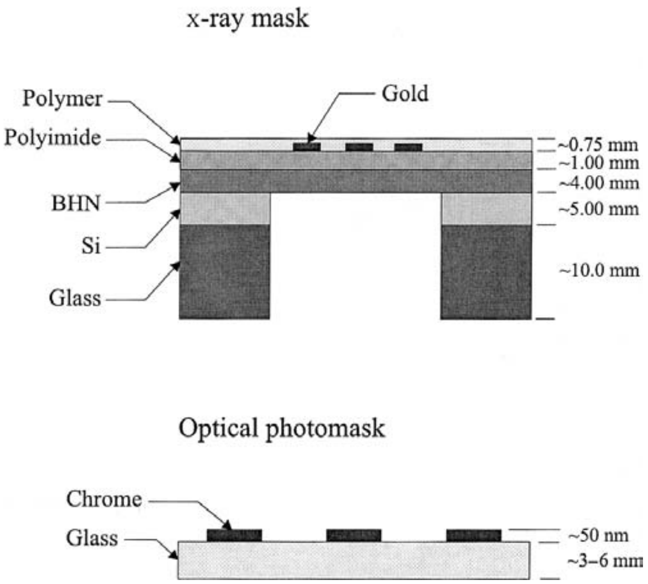


FIGURE 10 X-ray versus optolithography masks.

desired pattern onto the substrate (e.g., silicon, aluminum, silicon nitride) requires vertical side walls, smooth line edges, and no residues, accomplished at a rate that can be tolerated by the masking resist layer. The etching must be highly directional with no lateral etching (Fig. 11). This objective can be achieved via dry glow discharge, high-ion-density plasma etching. (A plasma is a partially ionized gas that includes electrons, ions, and a variety of neutral species—it can achieve metal removal rates of up to 1 μm per min.) Wet etching is undesirable, since it may cause the photoresist to lose adhesion and cause dimensional accuracy problems. Furthermore, dry etching lends itself to automation better than wet processes. Typically, chlorocarbon and fluorocarbon gases (e.g., CCl_4, CF_4) are used for etching metal films.

As a final step in microlithography, the resist layers are removed using O_2 plasmas; then there is a final cleaning process.

9.2 LASER BEAM MACHINING

Laser beam machining is a thermal material removal process that utilizes a high-energy coherent light beam to melt and vaporize particles on the surfaces of metallic and nonmetallic workpieces (Fig. 12). The term LASER is an acronym—light amplification by stimulated emission of radiation. As

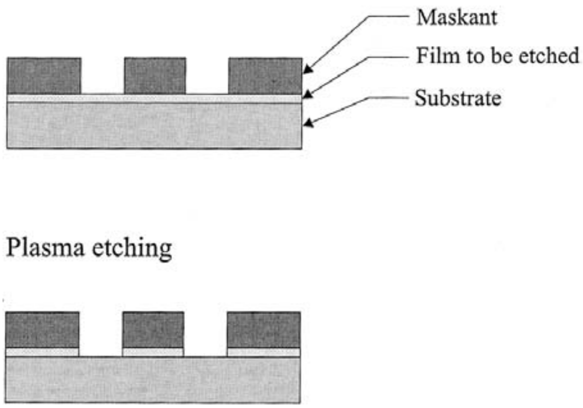


FIGURE 11 Directional plasma etching.

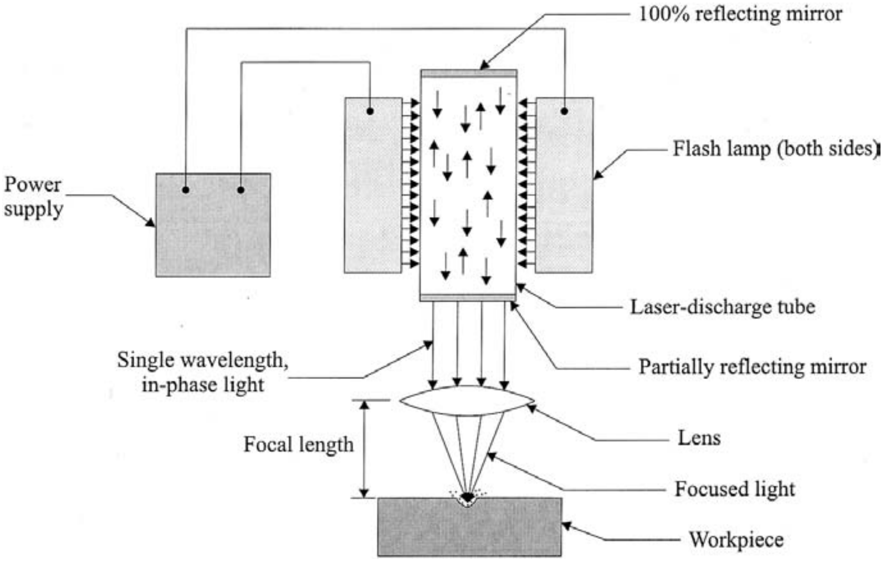


FIGURE 12 Laser beam machining.

the name implies, a laser converts electrical energy into a high-energy density beam through stimulation and amplification. Stimulation refers to the excitement of the electrons, which results in a stream of photons with identical wavelength, direction, and phase. Amplification refers to the further stimulation of the photons through an optical resonator to yield a coherent beam.

The study of light can be first traced back to Newton's work in the 1700s, who characterized it as a stream of particles, and later to Maxwell's work on electromagnetic theory. In the early 1900s, Einstein propounded the quantum concept of light, which lead to the theory of quantum mechanics in the early 1920s. The first device utilizing stimulated emission is attributed to J. P. Gordon, H. J. Zeiger, and C. H. Townes (1955). The first laser device is attributed to T. H. Mainman (1960). Most of today's modern laser devices were developed, subsequently, in the first half of 1960s, with the exception of the "excimer" laser developed in mid-1970s.

The three primary classes of lasers, classified based on the state of the lasing material, are gas, liquid, and solid. All lasers operate in one of the two temporal modes: continuous wave and pulsed. The three most commonly used lasers in manufacturing are

Nd:YAG: The neodymium-doped yttrium–aluminum–garnet ($Y_3Al_5O_{12}$) laser is a solid-state laser. Although very low in efficiency, its compact configuration, ease of maintenance, and ability to deliver light through a fiber-optic cable has helped it to be widely used (app. 25%) in the manufacturing sector. A Nd:YAG laser can provide up to 50 kW of power in pulsed mode and 1 kW in continuous wave mode.

CO_2: The carbon dioxide laser is a (molecular) gas laser that emits light in the infrared region. It provides the highest power for continuous wave mode operations (up to 25 kW versus 1 kW for Nd:YAG) and is the most commonly utilized laser source in manufacturing (though not with fiber optics).

Excimer: These short-wavelength gas lasers, though not as nearly as powerful as CO_2 or Nd:YAG lasers, can focus the light beam into very small spots. The term excimer is a shortened compound word for excited dimer, meaning two molecules (dimer) of the same (exci) molecular composition, such as H_2, O_2, N_2, and C_2. Common excimer lasers, however, have diatomic molecules of two different atoms, such as argon fluoride (ArF), and krypton chloride (KrCl). The laser vessel is normally prefilled with a mixture of gases, including argon, halogen, and helium.

9.2.1 Laser Beam Drilling

Like other solid-state lasers, Nd:YAG lasers are best suited for operation in a pulsed mode for maximum energy output. That is, energy is stored until a threshold value is reached and then rapidly discharged at frequencies of up to 100 kHz (but typically operated below 1 kHz for maximum pulse energy output). Owing to their preferred pulsed mode operation at high-energy outputs, Nd:YAG lasers are best suited for drilling operations (besides welding and soldering). They can, however, also be used for (continuous) contour cutting in continuous wave mode for low-power applications, whereas the CO_2 laser would be used for high-power applications.

In drilling, energy transferred into the workpiece melts the material at the point of contact, which subsequently changes into a plasma and leaves the region (Fig. 13). A gas jet (typically, oxygen) can further facilitate this phase transformation and the departure of material. (A pulsed mode laser can cause a microdetonation effect as repeated pulses hit the workpiece.)

Laser drilling can be utilized for all materials, though it should be targeted for hard materials and hole geometries that are difficult to achieve with other methods. For example, using a robot and an Nd:YAG laser, holes can be drilled at any inclination on a solid part without the need to orient the part—the robot end effector that carries the end point of a fiber-optic cable attached to the laser source can orient it with a five-degree-of-freedom mobility (x, y, z, ϕ, ψ) anywhere within its workspace (Fig. 14). Furthermore, laser drilling can also be used for superfast hole drilling, at rates above 100 holes per second, of diameters of as low as 0.02 mm, when using a fast-moving mirrors/optics arrangement Fig. 15b in Sec. 9.2.2 below. Large holes can be achieved by a "trepanning" approach, where the laser starts at the center of the hole and follows a spiral path that eventually cuts the circumference of the circle in a continuous wave mode.

Typical past examples of laser drilling have included small nickel–alloy cooling frames for land-based turbines, with almost 200 inclined holes; gas-turbine combustion liners for aircraft engines, with up to 30,000 inclined

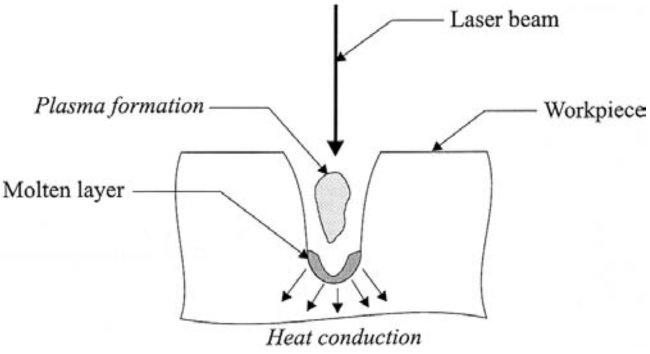


FIGURE 13 Interface region for laser drilling.

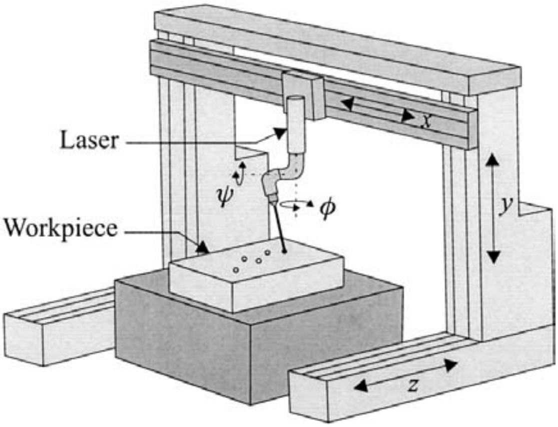


Figure 14 Five-degree-of-freedom laser drilling.

holes; ceramic distributor plates for fluidized bed heat exchangers; and plastic aerosol nozzles. Some more recent cases of laser drilling include bleeder holes for fuel-pump covers and lubrication holes in transmission hubs in the automotive industry, and fuel-injector caps and gas filters in the aerospace industry.

9.2.2 Laser Beam Cutting

The term laser cutting is equivalent to (continuous) contour cutting in milling: a laser spot reflected onto the surface of a workpiece travels along a prescribed trajectory and cuts into the material. Multiple lasers can work in a synchronized manner to cut complex geometries.

Continuous wave gas lasers are suitable for laser cutting. They provide high average power and yield high material removal rates and smooth cutting surfaces, in contrast to pulsed-mode lasers that create periodic surface roughnesses.

The CO_2 laser has dominated the laser cutting industry since the early 1970s. Since CO_2 lasers cannot be easily coupled to fiber-optic cables, CO_2-based cutting systems come in three basic configurations: moving laser, moving optics, and moving workpiece (Fig. 15). Moving laser systems cannot operate at large speeds and are normally restricted to flat-sheet cutting. Moving optics systems can provide cutting speeds in excess of 100 m/min (owing to fast moving mirrors) and can machine three-dimensional static or moving workpieces. Moving workpiece systems are equivalent to

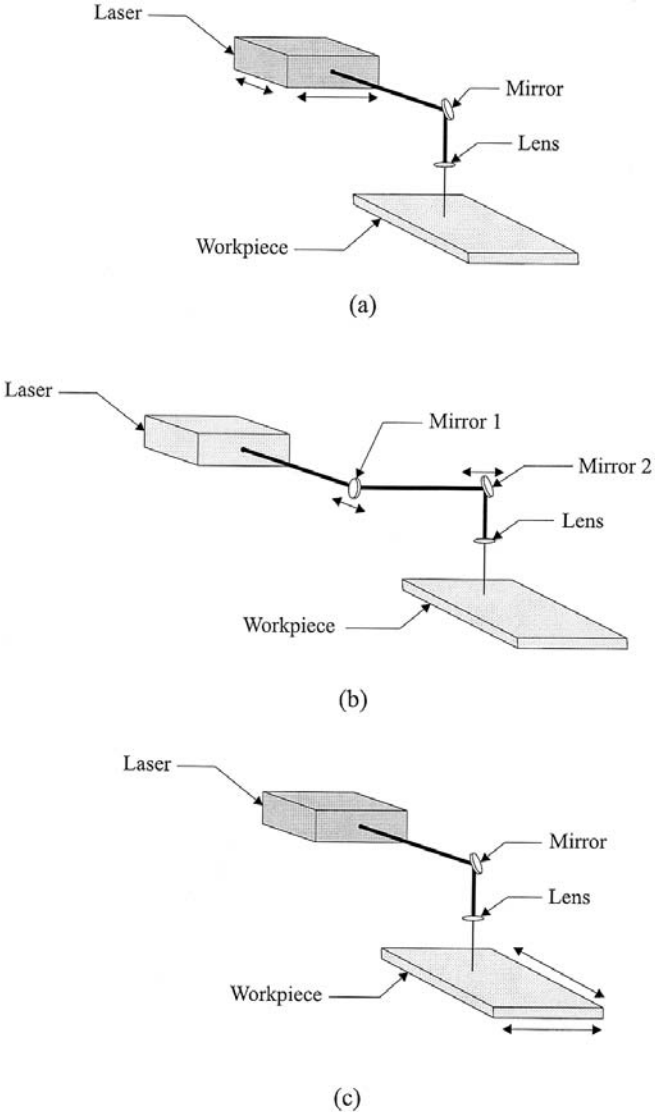


FIGURE 15 Continuous laser cutting: (a) moving laser; (b) moving optics; (c) moving workpiece.

traditional turning (rotational machining) and milling (prismatic machining) machine tools.

The material removal mechanisms in laser cutting are similar to those in laser drilling: in steady-state operation, the input energy is balanced primarily by the conduction energy that melts and vaporizes the material. As the light beam moves forward, a continuous molten (erosion) front forms because of high temperature gradients (Fig. 16). The kerf (narrow slot) left behind has parallel walls: for thin-walled metal workpieces the kerf width is typically less than 0.5 mm, so that there is very little material waste. In a large number of cases, fast-flowing gas (e.g., oxygen) streams are utilized to assist laser cutting: they remove material and keep the focusing lens clean and cool.

Although most metals can be cut by lasers, materials with high reflectivity (e.g., copper, tungsten) can pose a challenge and necessitate the application of an absorbent coating layer on the workpiece surface. Furthermore, for most metals, the effective cutting speed exponentially decreases with increasing depth of cut.

CO_2 and Nd:YAG lasers can also be utilized in the cutting of ceramics and plastics/composites. Overall, typical industrial applications of laser cutting include removing flash from turbine blades, cutting die boards, and profiling of complex geometry blanks.

Analysis of Laser Cutting

Over the past two decades a large number of studies have been reported in the literature on the analytical and numerical analysis of laser cutting. As mentioned above, laser machining is a thermal process, where radiant

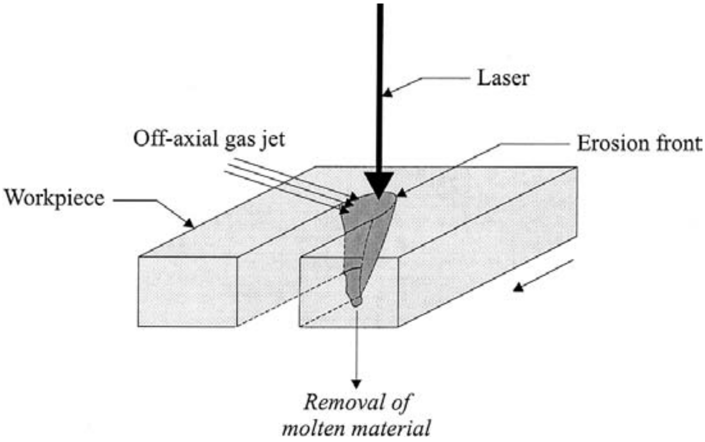


Figure 16 Material removal in laser cutting.

energy from a laser light source is utilized for material removal. As this radiant energy is absorbed by the workpiece material, the local temperature rises, leading to melting and vaporization (i.e., dissipation of heat). Although the contact region is a multiphase environment, solid, liquid, and gas, most studies have concentrated on the dissipation of heat in the solid workpiece via conduction and through the surroundings via convection (Fig. 17).

Numerical methods, commonly based on finite element analysis (FEA), are utilized to determine optimal cutting parameters for a given part material and material removal task: laser power, spot size of the laser light (as it hits the surface of the workpiece), depth of cut (for grooving tasks), and cutting speed. Naturally, a desired optimization objective would be the maximization of cutting speed—though surface quality (smooth cutting profile) and surface integrity (minimum residual stresses) can also be considered in selecting cutting parameters. One must realize that pulsed mode lasers can be modeled in the same way as continuous wave mode lasers, in which the input of energy is modeled as a function of time. In such cases, the pulsing frequency (when adjustable) becomes another cutting parameter whose value is optimized.

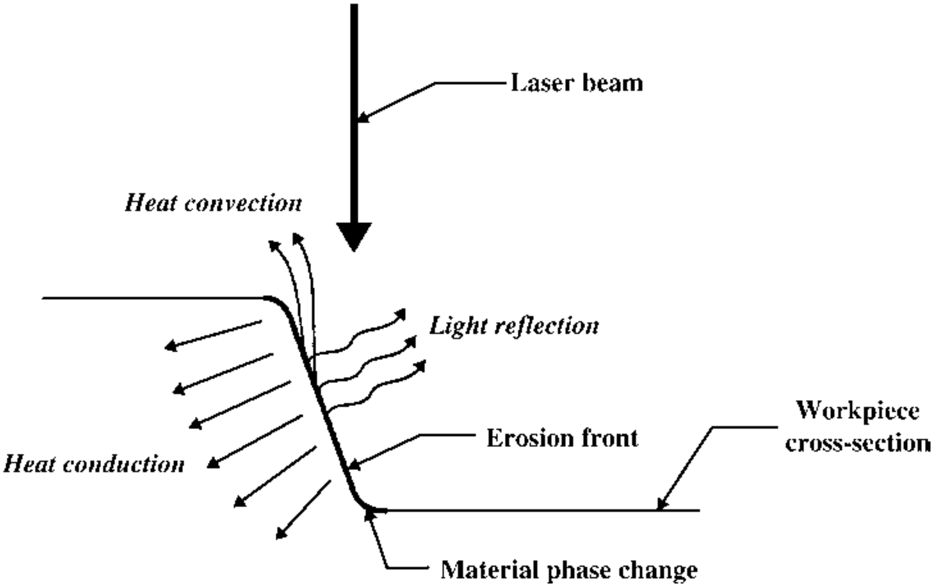


FIGURE 17 Heat transfer in laser cutting.

9.3 RAPID LAYERED MANUFACTURING

A number of material additive methods have been developed during the period of 1985 to 2000 for the rapid, layered fabrication of one-of-a-kind parts. Collectively called rapid prototyping (RP) manufacturing techniques, most such commercial systems can only fabricate parts (plastic, metal, or ceramic) for limited engineering analysis and testing purposes. On the other hand, a common primary advantage to these RP techniques is their utilization of computer-aided design (CAD) part models, where significantly shortened production times of fabrication can be obtained for complex geometry parts with almost no manual intervention during the build phase.

As will be noted later in this section, the underlying principles of today's RP techniques have been in existence and in commercial use for several decades, though they are now applied in a novel manner for the building of three-dimensional prototypes using readily available parts' CAD solid models. These principles include photolithography, sintering, and laser cutting.

Brief History

The key concept of layered manufacturing, also known as solid free-form fabrication (SFF), is decomposition of a three-dimensional CAD solid model into thin (virtual) cross-sectional layers, followed by physically forming the layers, using one of the material additive RP techniques, and stacking them up layer by layer. The creation of three-dimensional parts in such a layered fashion can be traced to the creation of the Egyptian pyramids more than 3,000 years ago. In more modern times, however, layered fabrication has been primarily used for topography and photosculpture.

The use of layered techniques in topography can be traced back to the early 1890s, when Blanther suggested a layered method for making a mold for the fabrication of topographical relief maps by stacking up layers of wax plates (cross sections cut to proper dimensions) and manually smoothing the curvatures in the third dimension. After creating the positive and negative halves of such a mold, a printed paper map is pressed between them to create a raised relief map. A similar lamination technique has also been long used by architects and urban planners for the creation of relief maps or structures by cutting contour lines on cardboard sheets and then stacking and pasting them to form three-dimensional representations.

Photosculpture refers to the creation of three-dimensional replicas of parts or human forms. The concept can be traced back to the work of F. Willème in the 1860s; he simultaneously used 24 cameras (equally spaced on the circumference of a circle) to photograph a figure and then create its replica by creating 24 individual parts of the figure and assembling them.

Although, as discussed in Section 9.1.4, photolithography has been successfully used for many decades in the creation of masks in chemical machining, H. Kodama of Japan is credited with the first reporting of a photopolymer-based, layered rapid prototyping system in 1981. This early attempt is very similar to today's commercial systems in using a UV light source for layer solidification and consecutive layer buildup by controlled submersion of the already built section of the part into a vat of liquid polymer. Within a decade of this report, the RP industry blossomed by the development and commercialization of numerous techniques. The first was the stereolithography apparatus (SLA) by 3D Systems, in around 1985; next came the selective laser sintering (SLS) system by DTM, the laminated object manufacturing (LOM) system by Helisys, and the fused deposition modeling (FDM) system by Stratasys, to mention a few.

In this section, our emphasis will be on the two most common RP techniques: stereolithography for the fabrication of plastic parts, and selective laser sintering for the fabrication of primarily metal parts. As a preamble to the detailed presentation of these two methods/systems, we will, however, first review CAD data preparation as a common task to all RP techniques.

9.3.1 CAD-Based Part Data Preparation

Layered manufacturing techniques rely on the input of a CAD system regarding the geometric information of every layer to be produced. Thus the first step in every RP process is the creation of the geometric solid model of the part to be utilized in the determination of layer data, also known as slice data. Once such a solid model of the part is available, the next step is process planning: we must determine the orientation of the part build (i.e., choose the vertical axis of build that will be normal to the planar layers), and then slice the part model into layers of desired thickness. The last step in CAD data creation is verification of information and translation into a format to be understood by the RP machine. These steps are individually addressed below.

Step 1: Solid Model of Part

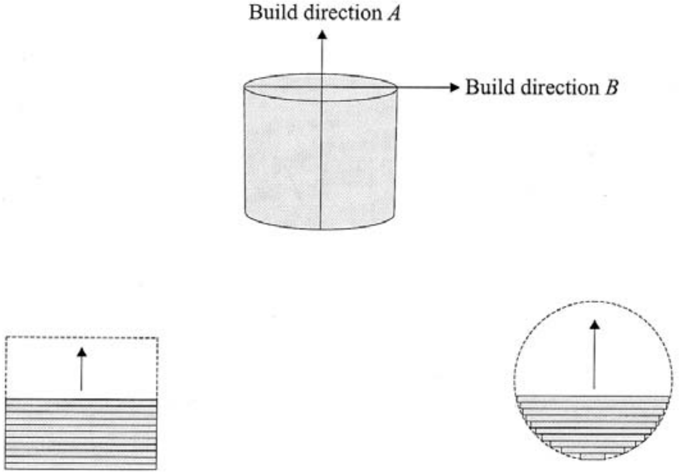
The solid model of the part to be built by the RP method can be generated using any one of the available commercial CAD packages. As expected, the CAD data must represent a valid geometric model, whose boundary surfaces enclose a finite volume.

Step 2: Orientation of Build

Determining the orientation of the build is the most important task in process planning for layered manufacturing. Three criteria are normally considered during the selection of an optimal build direction (i.e., part orientation): surface quality and dimensional accuracy, mechanical strength of the finished part, and fabrication time:

Due to the staircase effect of layered building, the curved surfaces of a part must be positioned optimally with respect to the build direction in order to minimize deviations from the desired curvature (Fig. 18). (For example, a cylindrical part built by one circular cross section stacked on top of the other would have a smooth side surface, whereas the same part built by stacking up rectangular cross sections would not.)

Since layered (laminated) structures have transversely isotropic mechanical properties (i.e., isotropic in the plane of the layer, but different in the third orthogonal build direction), the build direction (i.e., the part orientation during the build) must be chosen according to the expected future loading conditions of the part. The primary mode of failure of layered parts is assumed to be delamination due to excessive transverse shear stresses: the building direction in laminated parts has the weakest mechanical properties owing to weak interlayer bonding. FEA can be used to determine the stresses that develop in such parts.



Build direction *A*
Use of circular cross sections (desirable)

Build direction *B*
Use of rectangular cross sections (undesirable)

Figure 18 Part orientation.

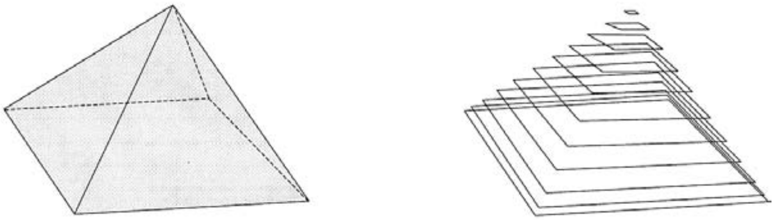
When the time spent on preparing a layer for solidification is more than the build time spent on fabricating (solidifying) it, one would be advised to minimize the number of layers by choosing an appropriate build direction, and vice versa. (For example, it would be faster to build a rectangular part with a build direction that is normal to the surface with the greatest surface area.)

Frequently, however, process planners may have to choose the build direction (part orientation) subject to all of the above criteria and others simultaneously. In such cases, one could formulate the optimization problem along the guidelines provided in Sec. 5.3 of this book.

Step 3: Slice Data

The last step in data preparation for layered fabrication of parts is the slicing of the geometric solid model of the part in order to determine the outer boundaries of individual cross sections to be solidified and stacked on top of each other. The principle of slicing is to intersect parallel planes (orthogonal to the build direction) with the geometric model of the part and determine the intersection contours between these planes and the surfaces of the part (Fig. 19).

There are numerous techniques for slicing CAD models. The most common (yet the most inaccurate) method requires solid models (generated via B-Rep or CSG techniques) to be converted into tesselated representations. In a tesselated representation, all part surfaces (curved or planar) are approximated by planar triangular elements (surfaces) yielding the commonly known STL (stereolithography) file (Fig. 20). The sizes of the triangular elements (facets) can be automatically determined by commercial CAD package translators according to a tolerance value provided by the user (i.e., maximum allowable deviation of the planar facet from the actual curved surface—along the surface normal direc-



Solid model

Sliced model

Figure 19 Slicing for RP.

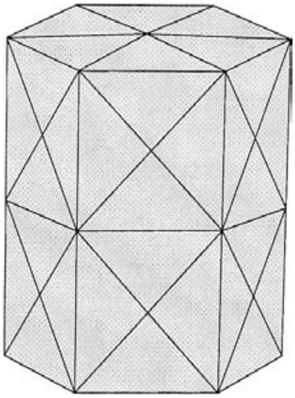


Figure 20 Tesselated object model.

tion). High accuracy requirements naturally yield very large STL files (possibly with millions of facets), where the slicing process (i.e., the intersection of the planes with the tesselated part model) would accordingly take a long time and be prone to errors.

An alternative method to generating STL files through tesselation is direct slicing of the solid model of the part and the use of NURBS (nonuniform rational B-spline) curves for approximating the intersection contours.

The cutting planes used for the generation of slice data are normally placed at equal intervals, corresponding to the constant thickness of the layer to be solidified by the RP technique. However, one can place these planes at variable distances by employing a variable layer thickness method. Larger distances (i.e., thicker layers) can be used for those sections of the part with vertical side surfaces, as limited by the power of the energy source, and smaller distances (i.e., thinner layers) for those with curved side surfaces (Fig. 21).

Once the slice data has been obtained, the RP system would determine a raster plan (i.e., path of scanning), if it uses a laser beam–based solidification/cutting source. The objective is minimum time spent on solidifying/cutting the layer at hand while ensuring dimensional integrity. This subject is RP technique dependent and thus will be detailed further in the following sections when we address the different layered manufacturing techniques.

9.3.2 Layered Manufacturing Techniques

Layered manufacturing techniques have been classified over the past decade according to the energy source, material type, material phase,

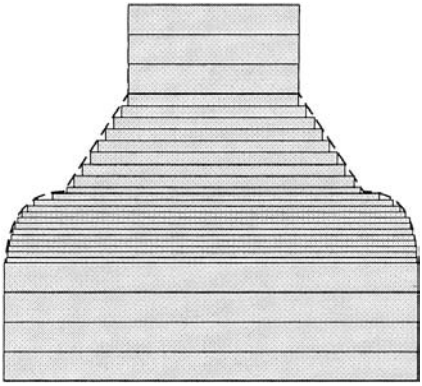


FIGURE 21 Variable layer thickness in RP.

and so on. Herein, RP techniques are grouped according to the principle of part fabrication that they utilize: lithography, powder processing, deposition, and cutting. Since these techniques are mostly targeted for the prototyping of parts of very different materials, we will not attempt to say that one is a better technique than another. The discussions will, though, attempt to include information on their specific applications in different manufacturing industries.

Lithography-Based Methods

Lithography-based layered manufacturing techniques rely on the selective solidification of a liquid monomer via UV light. The four major commercial systems are the stereolithography apparatus (SLA), U.S.A., the Stereos, Germany, the solid creation system (SCS), Japan, and the solid ground curing (SGC), Israel. The first three utilize a laser light source and are very similar in their fabrication of the layered polymer parts. The SGC system, on the other hand, is more loyal to the original photolithography systems developed several decades earlier: It uses a mask that blocks the flooded UV light from hitting undesirable regions on the liquid layer surface.

Laser lithography: Techniques that employ utilize laser lithography build parts on a platform attached to an elevator, whose vertical motion is accurately controlled. The platform is placed in a vat of photopolymer (typically acrylic- or epoxy-based): the part is built in a bottom-up approach using selective curing by a UV laser (Fig. 22).

The first step in laser lithography is the preparation of the liquid layer: The elevator is lowered into the vat (by a distance equal to the thickness of

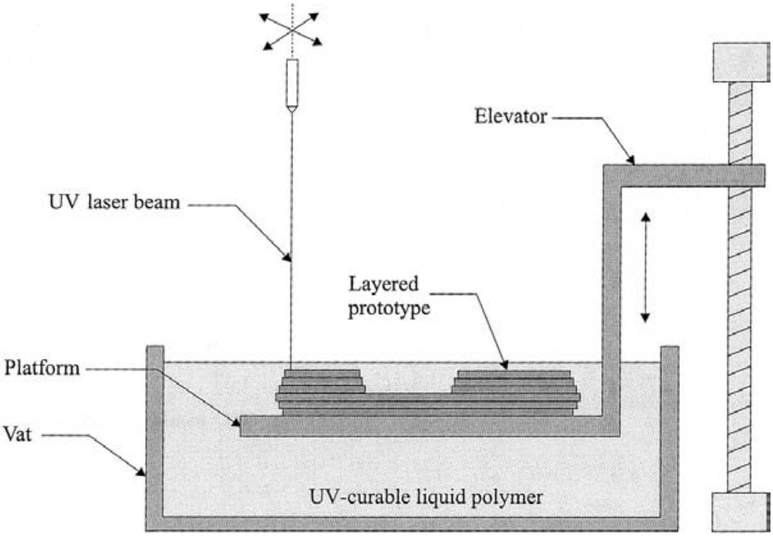
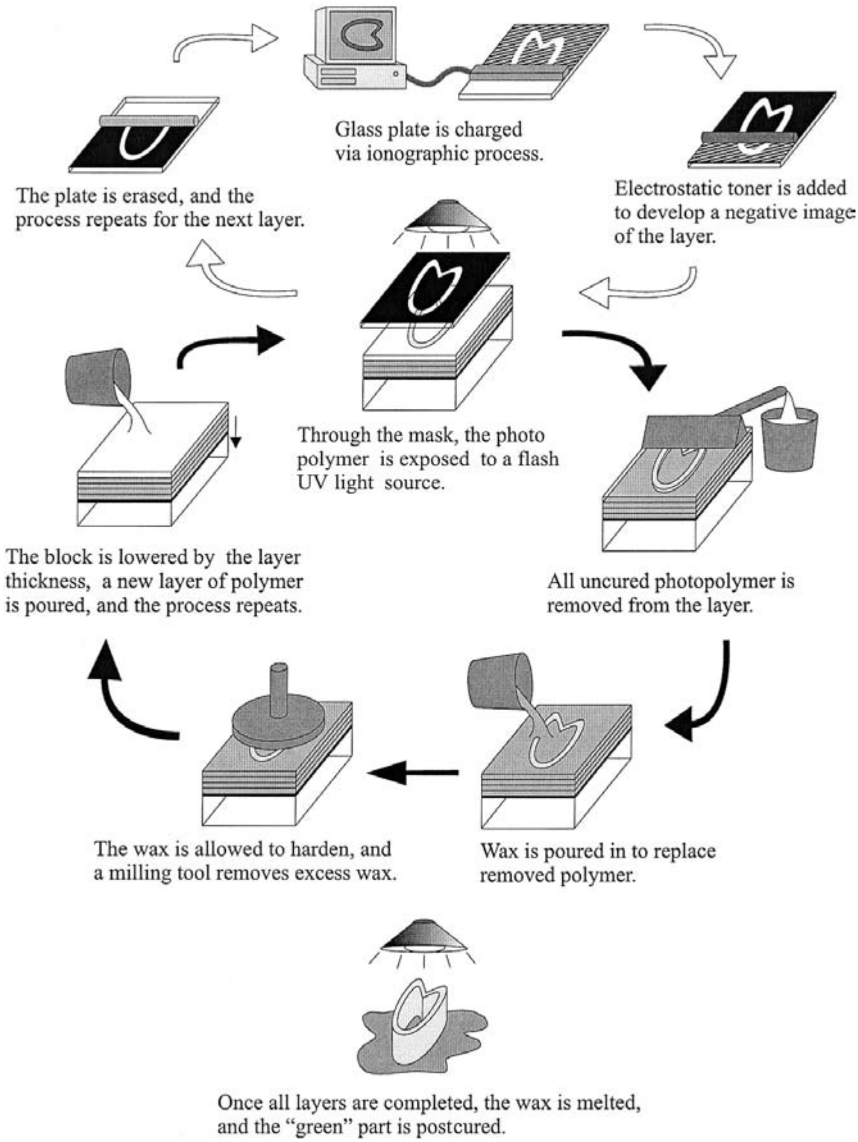


FIGURE 22 Laser lithography.

the layer to be solidified) and liquid polymer is spread (over the previously solidified part) using a coating/wiping mechanism. Next, a UV laser beam scans the surface (according to a given raster pattern) to cure the necessary regions selectively. Light beam delivery is normally achieved by using fast and very accurate servocontrolled galvanometer mirrors. The two-step process is repeated until all the layers of the part are built. The “green” part is then removed from the vat, washed, and placed in a postcuring oven for final solidification via flood-type UV light and heat.

Photolithography: Techniques that utilize photolithography for the layered manufacturing of three-dimensional parts differ from laser lithography systems, in principle, only in the method they use to solidify the photopolymer layers. Instead of laser-based selective pointwise curing, these techniques flood the liquid layer’s surface with UV light (from a strong source) that passes through an erasable/replaceable mask. In the SGC system, for example, the mask is produced by charging a glass plate via an ionographic process and then developing the negative image (of the layer to be solidified) with an electrostatic toner, just as in photocopying processes (Fig. 23).

A feature unique to SGC is the removal of excess photopolymer from the vat once a layer has been solidified and its replacement with liquid wax which is allowed to solidify before the build of the next layer (Fig. 23). The advantage of this step is the formation of a solid fixturing structure around



Glass plate is charged via ionographic process.

Electrostatic toner is added to develop a negative image of the layer.

Through the mask, the photo polymer is exposed to a flash UV light source.

The plate is erased, and the process repeats for the next layer.

All uncured photopolymer is removed from the layer.

Wax is poured in to replace removed polymer.

The wax is allowed to harden, and a milling tool removes excess wax.

The block is lowered by the layer thickness, a new layer of polymer is poured, and the process repeats.

Once all layers are completed, the wax is melted, and the "green" part is postcured.

FIGURE 23 Photolithography for RP.

the part (built in a layered manner), which ensures the part's stability in a vat of liquid, as is not the case with other lithography-based commercial systems. In SGC, once the wax has solidified and thus a totally solid structure (that includes the polymer part) is formed in the vat, a milling tool is utilized to remove excess wax and prepare the system, after the lowering of the elevator by a layer thickness, for the deposition of the next photopolymer layer. Once the iterative process of building the entire part has been accomplished, the wax is melted and the green part is postcured.

As one would expect, the layer formation step in SGC systems is quite time consuming, as opposed to the rapid solidification of the photopolymer layer. Thus, as discussed earlier, for these systems it would be beneficial to select a build direction (part orientation) that minimizes the number of layers to be built.

Powder Processing Methods

Layered manufacturing techniques that rely on powder processing methods differ primarily in the way that they bind the particles (plastic, metal, or ceramic). The two major commercial systems are selective laser sintering (SLS), U.S.A., and three-dimensional printing (3DP), U.S.A. The former utilizes a CO_2 laser for sintering the particles in selective regions of a vat of powder, whereas the latter uses ink-jet printing technology in depositing a binding material to "glue" the particles together.

Laser sintering: In laser sintering–based systems, parts are built in a chamber that can be lowered in a controlled manner for the formation of thin powder layers (Fig. 24). Typically, the following steps are followed: (1) The powder bed is lowered by the desired layer thickness; (2) a roller is used to drag a controlled amount of powder from an external material source and spread (and compact) it in the build chamber; (3) a laser is used to scan selectively the necessary regions of the deposited layer in order to bind the particles into a desired cross-sectional geometry and to bind the new layer with the old one. The layer formation and solidification steps are repeated until the entire layered part is manufactured.

Binder sintering: The 3DP process, also known as the Direct Shell Production Casting (DSPC) process, is the best known commercial binder sintering technique. The process is similar to laser sintering of powder particles, with the exception of the binding agent: a fluid binder is injected/sprayed selectively onto the powder, instead of using a CO_2 laser heat source (Fig. 25). The binder droplets are deposited using a similar technique used by the scanning head of ink-jet printers. As in selective laser sintering, the surrounding extra unbound powder provides the part with a rigid support during the build and is removed (shaken away) from the part once the

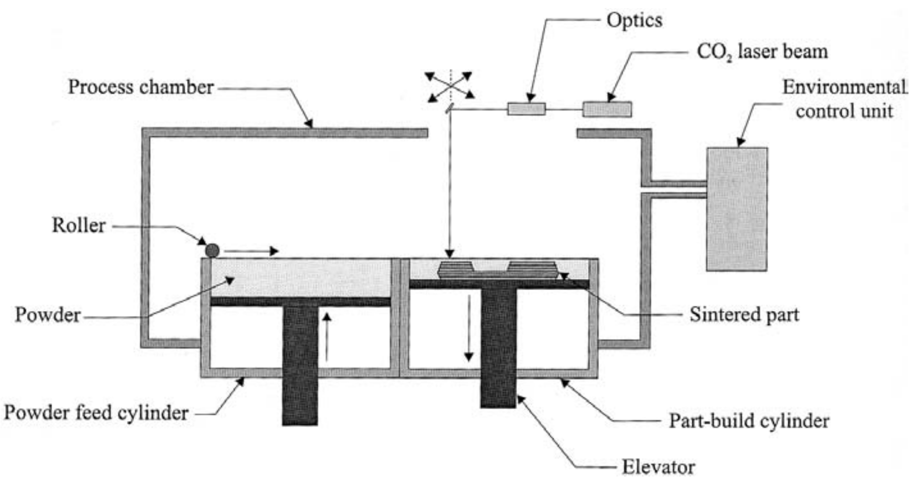


FIGURE 24 Laser sintering.

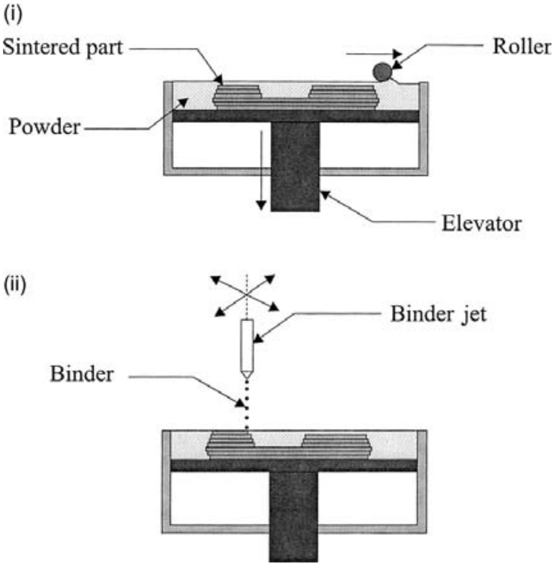


FIGURE 25 Binder sintering. (i) The elevator is lowered, and a roller is used to drag a controlled amount of powder from an external material source and spread it in the build chamber. (ii) A fluid binder is selectively sprayed onto the powder.

fabrication process is over. The green part is then treated in appropriate ovens for further densification. Typical powder materials used include stainless steel, tungsten, tungsten carbide, and ceramic alloys, which are bound with colloidal silica or polymeric binders.

Deposition Methods

Deposition-based RP techniques selectively deposit molten material for the direct building of layered parts. Although there have been many academic attempts in the past decade (the 1990s), only a very few commercial systems exist today: fused deposition modeling (FDM), U.S.A. model maker, U.S.A., and ballistic particle manufacturing (BPM), U.S.A. All three systems utilize (low-melting-point) thermoplastics. While the first method (FDM) uses a direct contact deposition (extrusion) of molten plastic, the other two use ink-jet type print heads for selective scanning of plastic droplets (similar to 3DP's binder deposition).

In FDM, a continuous filament of thermoplastic polymer (e.g., polyethylene and polypropylene) or investment casting wax is fed into a heated extruding head. The filament is raised about 1 °C above its melting point and directly deposited onto a previously built layer by the *x–y* scanning extruding head (Fig. 26). Once a layer is formed, the part (built on an elevator platform) is lowered by the thickness of the next layer. Solidification of molten material lasts about 0.1 sec, and the layered part needs no further processing.

Cutting Methods

Cutting-based methods, also known as lamination processes, use laminates of paper sheets or plastic or metal plates as the raw material for layer formation, a binding agent for gluing the layers together and a cutting mechanism (a laser or a mechanical cutter) for selectively cutting the contours of the layer's geometrical *x–y* profile. Current commercial systems include laminated object manufacturing (LOM), U.S.A., solid center (SC), Japan, and hot plot, Sweden.

In LOM, the process starts with the lowering of the platform by the layer thickness and the deposition of an adhesive binding agent on the previous layer (unless the paper has already been impregnated with heat-activated adhesive) (Fig. 27). A new layer (laminate) is rolled and pressed over the previous layer for good adhesion. Then a CO_2 laser is utilized to cut the contours of the layer selectively and crosshatch the remaining excess material for its easy removal once the part has been completely built. Postprocessing activities in LOM include sanding, polishing, painting, and sealing for moisture resistance (via urethane, epoxy, or silicon sprays).

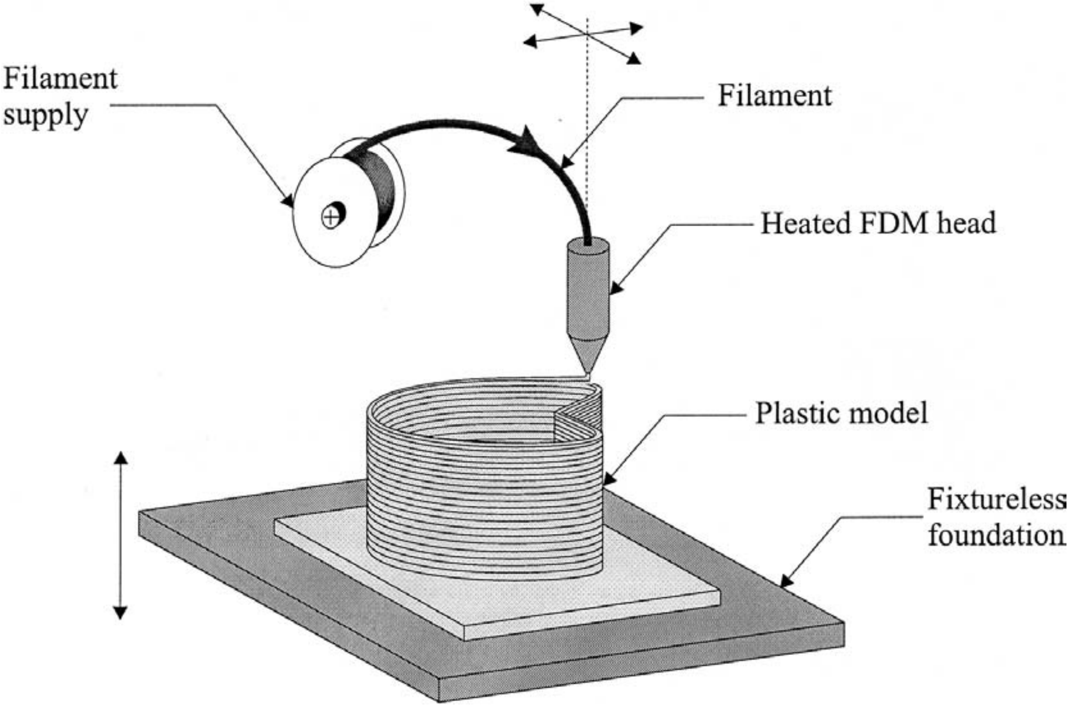


FIGURE 26 Fused deposition modeling.

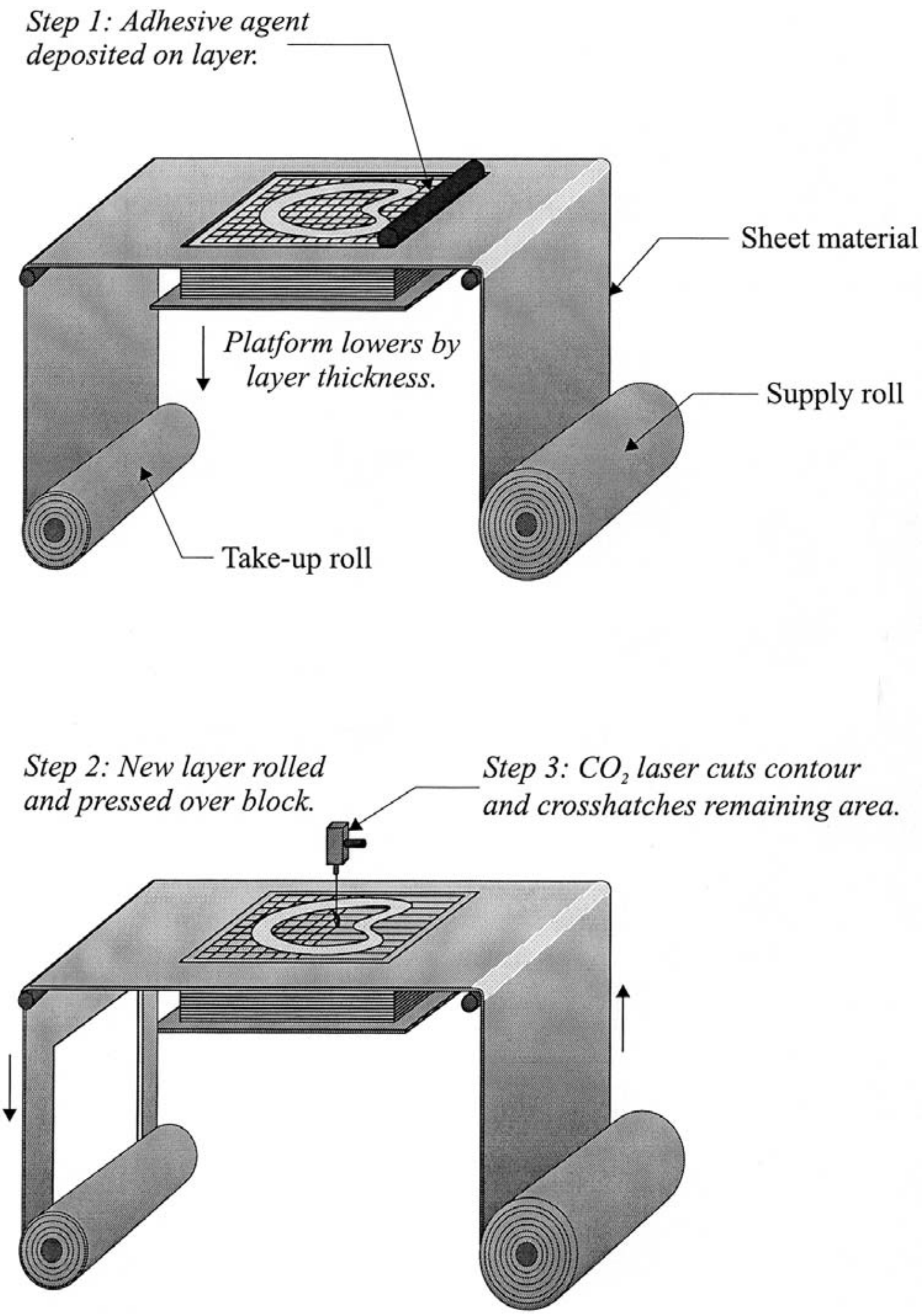


FIGURE 27 Laminated object manufacturing.

Some Industrial Examples

The industrial uses of prototypes built by the above-mentioned methods are still quite limited. However, it is expected that, with the movement of numerous metal-based layered manufacturing techniques from research laboratories to commercial enterprises, the uses of rapid prototyping in the manufacturing industry will substantially grow during 2000–2010.

Lithography: Polymer parts have been used as patterns in sand casting of wiper motor covers (Ford), engine blocks (Mercedes Benz), and so on. Polymer parts have also been used as prototypes of plastic toys, jewellery, spectacle frames, electrodes in electrical discharge machining, electric wire connectors, etc.

Powder processing: Metal parts have been used as prototypes for car engine cylinder heads (Porche), garden hedge trimmers, limited use mold cavities, automotive turbocharger housing units, etc. Ceramic parts have been used as shells for investment (lost-wax) casting, aircraft fuel control systems, etc.

Deposition: Plastic parts have been used as prototypes for ski bindings, child car seat chest clips, golf clubs, window/patio door elements, freezer light fixtures, etc.

Lamination: Laminated parts have been used as prototypes for automotive transaxle housings, crankshafts, intake manifolds, for a variety of toys, and even for footwear sole masters.

9.3.3 Stereolithography

The stereolithography (SL) process, also called initially three-dimensional printing, was developed in 1982 by C. W. Hull and commercialized in 1986 by 3D systems leading to the first stereolithography apparatus (SLA) Model 190. SLA-190 was capable of manufacturing layered photopolymer parts in a work volume of $190\times190\times250$ mm (app. $7.5\times7.5\times10$ in.) with layer thicknesses as low as 0.1 mm. A HeCd laser of 7.5 mW of power provided the system with its UV light source. The price of the unit was approximately \$70,000–\$100,000 US.

As introduced in Sec. 9.3.2, Fig. 23, the layer formation process on the original SLA machines comprised three basic steps: (1) deep dip—the elevator is lowered by a distance of several layer thicknesses to allow the viscous liquid in the vat to flow easily over the latest solidified layer; (2) elevate—the elevator is raised back up the deep dip distance minus the layer thickness (of the next layer); and (3) wipe—a recoater blade is used to level the liquid and sweep away excess liquid. In the newer SLA models, since the mid-1990s, a deposition-from-above recoater is utilized: as the wiping blade is drawn across the vat's surface, it releases the required amount of resin to cover one layer. This new technique eliminates the deep dip step and provides thinner and more uniform layers.

Selective solidification of the photopolymer layer using a UV laser light source requires an optimal hatching plan: curing of a solid cross section with maximum dimensional accuracy. This requires high fidelity to the contours specified, when tracing them with the laser light, as well as not to overhatch, which could cause unnecessary shrinkage. Since the release of their first SLA model, 3D Systems has developed a series of newer and better hatching styles, while companies such as Ciba-Geigy have developed better photopolymers (better mechanical properties, faster curing, less shrinking, etc.).

The laser light source cures the photopolymer by drawing lines (straight or curved) across the surface of the liquid layer. Since in practice, a laser spot would have a Gaussian distribution intensity (i.e., a bell curve with maximum intensity at its center), if held momentarily at one spot, it would cure a volume of a parabolic cone shape (Fig. 28a). The depth of cure (i.e., the height of the cone) is a direct function of the time the laser spot is held constant in the same position. (The stronger the energy source is, the faster the curing rate.) As the laser spot is translated along a trajectory, the small volumes overlap and yield a cured line of a semi-parabolic cylinder (Fig. 28b). The allowable speed of travel is a direct function of the energy source. (The stronger the energy source, the faster the spot can be scanned, while providing a sufficient depth of cure.) For better layer adhesion, it is advised to have cure depths larger than the layer thickness.

The accuracy of scanning is a direct function of the galvanometer, servocontrolled mirrors, and the optics configuration. The best circular shaped spot is achieved when the laser beam is in focus and orthogonal to the liquid surface. As the laser spot is translated around, the incidence angle changes and the focal distance increases. A possible solution to such spot size inconsistencies would be to place the mirror at a large distance. An alternative solution would be to use a flat field lens of variable focal length.

Table 1 provides comparative data for the various SLA machines developed over the past two decades. As is noticeable from this table, these systems have improved over the years to built parts at faster rates, with thinner layers (i.e., better dimensional accuracy) and with improved mechanical properties. In parallel to these developments, academic researchers have reported (1) on the use of SLA machines for building ceramic parts by using the monomer liquid as a matrix for the ceramic particles and then burning off the solidified polymer and (2) on the use of laser lithography for the rapid manufacturing of (glass) short fiber

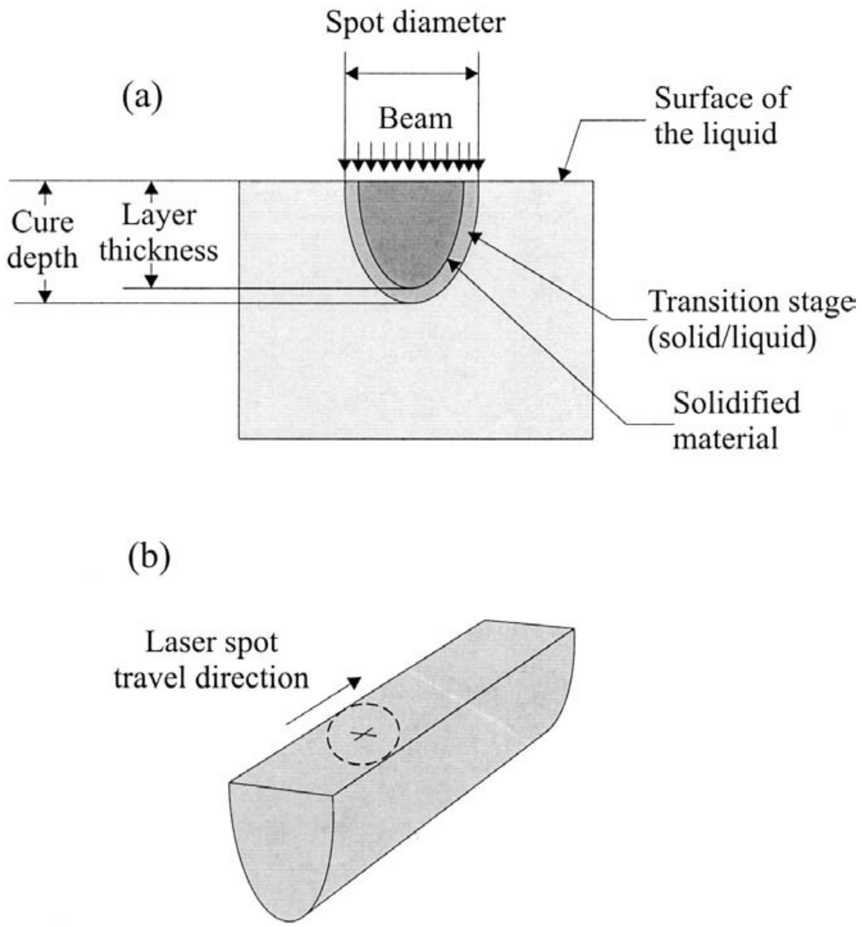


Figure 28 (a) Depth of cure; (b) line of cure.

reinforced (layered) polymer parts as direct functional prototypes for many automotive applications.

9.3.4 Selective Laser Sintering

The selective laser sintering (SLS) process was developed at the University of Texas at Austin in early 1980s by C. Deckard and commercialized by the DTM Corporation during the latter part of the 1980s. The first SLS machine, the Sinterstation 2000, was shipped in 1992. This machine used two cylindrical chambers: one for storing the raw powder

TABLE 1 SLA Specifications

Machine model	Workspace (mm×mm×mm)	Laser type (mW)	Maximum scan speed (mm/s)	Minimum layer thickness (mm)	Spot size (mm)
SLA-190	190×190×250	HeCd (7.5)	760	0.1	0.20–0.28
SLA-250	250×250×250	HeCd (6–24)	635–762	0.0625–0.15	0.06–0.28
SLA-3500	350×350×400	Nd:YVO_4 (160)	2540	0.05–0.1	0.20–0.30
SLA-5000	508×508×584	Nd:YVO_4 (216)	5000	0.05–0.1	0.20–0.30
SLA-7000	508×508×600	Nd:YVO_4 (800)	2540–9520	0.0254–0.127	0.28–0.84

material and another for building the part. For every layer, the first cylinder was raised to deposit sufficient powder in front of the powder leveling roller, to be transported to the second cylinder, which is lowered by the thickness of the layer to be solidified by the CO_2 laser (Fig. 24).

The selective sintering process occurs in the processing chamber, which is supplied with inert gas in order to prevent oxidation or explosion of fine metal powder particles. The temperature of the particles (in a region to be solidified) is raised locally to induce sintering but not melting. As in laser cutting, the continuously moving laser light transfers its radiant energy into the powder bed, where it propagates through conduction. The depth of useful heat transfer is a direct function of the laser's power and scanning speed of the spot. (The laser light is delivered from a stationary source through moving mirrors, as with a configuration used in SLA machines.)

A two-phase (liquid–solid) sintering is utilized in SLS systems for intralayer and interlayer bonding. As addressed in Chap. 6, better sintering is achieved by melting the low melting temperature component of a multicomponent powder material (liquid phase) and keeping intact the solid particles of the other material. Wetting of the solid particles can be enhanced by utilizing various types of fluxes: metal chlorides and phosphates. Possible material combinations include metal particles coated by polymers, composite (binary) metal powders (one with a lower melting temperature than the other), cermets, and composite ceramic blends:

Metal/metal: Cu-Ni, Fe-Co, and W-Mo
Cermets: Al_2O_3-Fe, Al_2O_3-Ni, and WC-Co
Ceramic/ceramic: Al_2O_3-ZrO_2

Postprocessing of laser sintered parts first have to include the burning out of the polymer binder (for coated metal and ceramic particles), followed

TABLE 2 DTM Specifications

Machine model	Workspace (mm×mm×mm)	Laser (W)	Maximum scan speed (mm/s)	Minimum layer thickness (mm)	Spot size (mm)
2000	$\phi 300 \times 381(\mathrm{H})^a$	CO_2 (50)	914	0.076–0.51	0.40
2500	$381 \times 330 \times 457$	CO_2 (25 or 100)	7,500	0.076–0.51	0.45

[a] Cylindrical vat.

by a conventional sintering method for increased density (for coated and uncoated multicomponent materials). If desired, a secondary metal component (e.g., bronze) can be added to the sintering furnace and be allowed to melt and infiltrate the pores of the part fabricated in the SLS machine for achieving near 100% density.

Table 2 gives some of the specifications of the first- and second-generation DTM Sinterstation machines.

REVIEW QUESTIONS

1. Why have numerous nontraditional machining processes been developed since the mid-20th century? What advantages do they offer over traditional material removal techniques?
2. Describe the uultrasonic machining (USM) process. What type of material is USM normally targeted for?
3. What are the advantages of electrochemical machining (ECM) over USM?
4. Discuss the setting of an optimal gap between the tool and the workpiece in ECM.
5. How can the accuracy of ECM-based drilling of holes be improved?
6. Discuss the electrical discharge machining (EDM) in die sinking applications.
7. Compare ECM with EDM.
8. Describe chemical milling.
9. Why would one use chemical blanking over other traditional or nontraditional hole making techniques?
10. Define lithography-based manufacturing and compare the four available techniques: photolithography, x-ray lithography, electron beam lithography, and ion beam lithography.
11. What is dry etching? Why is it preferable to wet etching?

12. Describe the three primary classes of lasers.
13. Describe the laser beam drilling process and discuss why would it be preferable to other nontraditional hole making processes, such as chemical blanking.
14. Describe the laser beam cutting process and discuss why would it be preferable to other traditional continuous path machining processes such as milling.
15. Discuss the data preparation process common to all layered, rapid manufacturing techniques. In your discussion pay particular attention to the optimization of build parameters (e.g., layer thickness, build orientation).
16. Compare the two most common lithography-based rapid manufacturing techniques: laser lithography (e.g., SLA) versus photolithography (e.g., SGC).
17. Compare the two most common powder processing–based rapid manufacturing techniques: laser sintering (e.g., SLS) versus binder sintering (e.g., DSPC).
18. In newer SLA machines, a deposition-from-above recoater is utilized. Justify the use of such a technique.
19. Describe the postprocessing stage in SLS machines.

DISCUSSION QUESTIONS

1. Integrated circuit (IC)–based electronic component manufacturing processes can be argued to be the modified versions of fabrication and assembly techniques that have long been in existence (e.g., photolithography). These modifications have been mainly in the form of employing optical means for the fabrication of increasingly smaller components. Do you agree with this assessment? Discuss this specific issue and expand the argument to recent rapid layered manufacturing techniques. Have there recently been any truly new manufacturing techniques developed? If yes, give some examples.
2. Material removal techniques, as the name implies, are based on removing material from a given blank for the fabrication of the final geometry of a part. Compare material removal techniques to near net shape production techniques, such as rapid layered manufacturing, in the contexts of product geometry, material properties, and economics in mass production versus small batch production environments.
3. Discuss potential postprocess defect identification schemata/technologies for parts that are layer manufactured using a lithography or powder processing method. Furthermore, discuss possible sensing technologies that can be incorporated into different lithography or powder

processing equipment for the on-line monitoring and control of the manufacturing process, while the parts are being formed.

4. Process planning in (traditional and nontraditional) machining and even in rapid layered maufacturing (in its limited definition) refers to the optimal selection of cutting parameters: number of passes and tool paths for each pass, depths of cut, feed rates, cutting velocities, etc. It has been often advocated that computer algorithms be utilized in search of the optimal parameter values. Although financially affordable for mass production environments, such (generative) programs may not be feasible for utilization in one of a kind or small production environments, where manufacturing times may be comparatively short. Discuss the utilization of group technology (GT)–based process planners in such computational time limited production environments.
5. A prototype of a product must meet some or all of its engineering specifications. These specifications can be geometric or functional. In this context, a large number of material additive techniques were developed during the period 1980 to 2000 and classified as rapid prototyping (RP) processes. Justify through examples (production techniques and product features) why such layered manufacturing techniques may indeed be used to yield prototypes.

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