3

Laser Cladding Equipment

The laser cladding process requires the following equipment: a laser, a powder feeder along with delivery nozzles, and a positioning device equipped with CAD/CAM software. It is essential to understand the construction of these devices and their performance under different working conditions for the laser cladding process to be successful. This chapter provides a comprehensive comparison of available lasers, powder feeders, and nozzles to demonstrate their potential and suitability for use in laser cladding technology. The chapter also includes a brief review of available positioning devices and CAD/CAM systems suitable for this process.

3.1 Lasers

In the early 1960s, an enormous contribution was made to technology with invention of the first working laser. The word "laser" stands for light amplification by the stimulated emission of radiation. Miaman [40] invented the first ruby laser, which was the result of considerable discovery of Einstein [115], who demonstrated that lasing action should be possible.

In general, the light emitted by lasers is different from the ordinary light sources such as incandescent bulbs, fluorescent light, and high-intensity arc lamps. Laser light has the following characteristics:

- **Highly monochromic**. All regular light sources emit light (e.g., incandescent and fluorescent light) of many different wavelengths. Ordinary colored light consists of a broad range of wavelengths covering a particular portion of the visible-light spectrum. The beam of a laser, on the other hand, consists of an extremely narrow range of wavelengths within one single color portion of the spectrum meaning that it consists of light of almost a single wavelength. This nearly "monochromatic" or "single-colored" property is unique to laser light.

- **Highly coherent.** The light waves within a highly collimated laser beam may be defined as a source of coherent light, unlike other regular light sources. This characteristic leads to a constant phase difference in two or more waves over time. Two waves are said to be in phase if their crests and troughs meet at the same place and at the same time, whereas the waves are out of phase if the crests of one wave meet the troughs of another.

- **Highly directional.** All conventional light sources emit light in all directions, and it always diverges more rapidly than a laser beam. Directionality is the characteristic of laser light that causes it to travel in a single direction within a narrow cone of divergence. However, perfectly parallel beams of directional light (i.e., collimated light) cannot be produced even by a laser. In some applications, optical systems are employed with lasers to improve the directionality of the output beam.

- **Sharply focused.** For laser light, the focused spot can be very small; for example, an intensity of 10^{17} W/cm^2 is readily obtained by a laser, which is incredibly higher than any energy source (e.g., an oxyacetylene flame has an intensity of only about 10^3 W/cm^2).

In order to explain how a laser works, it is necessary to explain the following three processes by which the atom can move from one energy state to another:

1. **Absorption**. If the atom is placed in an electromagnetic field that is resonating at frequency f, the atom can absorb an amount of energy hf as represented by

$$hf = E_x - E_0 \tag{3.1}$$

   and move to the higher energy state. In the equation, E_x is the higher level of energy and E_0 is the ground level of energy for an atom. Figure 3.1a shows the atom in its ground and then in a higher level of energy.

2. **Spontaneous emission**. After a time, the atom will move of its own accord to its ground state, emitting a photon of energy hf in the process. This process, shown in Figure 3.1b, is called spontaneous emission because the event is not triggered by any outside influence. Usually, the mean life of excited atoms before spontaneous emission occurs is about 10^{-8} s. However, for some excited states, this means the life could be as much as 10^5 times longer; this longer state is called metastable. The light produced by the spontaneous emission of an atom is neither monochromatic and directional, nor coherent.

3. **Stimulated emission**. In this step, the atom is again in its excited state, but this time radiation with a frequency of f is present. A photon of energy of hf can stimulate the atom to move to its ground state, during the process, the atom emits an additional photon, whose energy is also hf. This process, shown in Figure 3.1c, is called stimulated emission because the event is triggered by the external photon. The emitted photon is in every way identical to the stimulating photon. The waves associated with the photons have the same energy, phase,

polarization, and direction of travel. Therefore, stimulated emission produces light that is monochromatic, directional, and coherent; this light appears as the output beam of a laser-stimulated emission for a single atom.

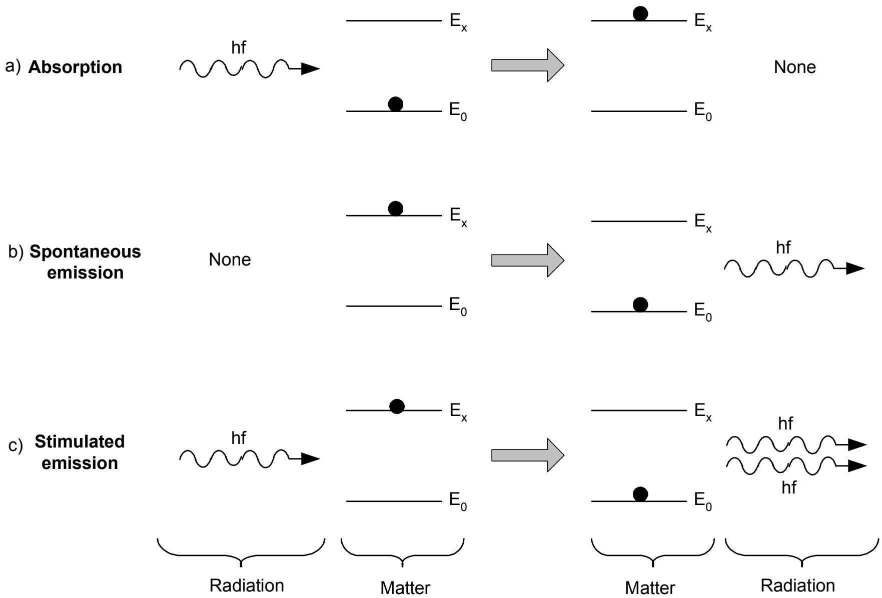


FIGURE 3.1

Interaction of radiation and matter in a) absorption, b) spontaneous emission, and c) stimulated emission.

In practice, generation of laser is subject to the interaction of a large number of atoms in the excitation field. Ludwing Boltzmann's theorem shows that the number of atoms in a state of higher energy N_x is a function of the number of atoms in their ground state N_0 and their corresponding energies, as represented by

$$N_x = N_0 e^{-(E_x - E_0)/\sigma T} \tag{3.2}$$

where σ is Boltzmann's constant, E_0 is energy of ground state, E_x is energy of atoms in a higher state, and T is thermal equilibrium temperature. This equation indicates that $N_x < N_0$ because $E_x > E_0$. As a result, there are fewer atoms in the excited state than in the ground state. If a flood of atoms with photons of energy $E_x - E_0$ is generated, as shown in Figure 3.2a, photons will disappear via absorption by ground state atoms. Einstein showed that the probabilities per atom for these two processes are identical. Therefore, because there are more atoms in the ground state, the net effect will be the absorption of photons. However, to produce laser light, the number of emitted photons should be more than absorbed photons. To accomplish this, a situation in which stimulated emission dominates should be occurred. The direct way to cause this is to begin with more atoms in the excited state than in the ground state, as shown in Figure 3.2b. This phenomenon is called population inversion. However, such a population inversion is not consistent with thermal equilibrium. Therefore, it is necessary to consider appropriate ways to improve the population inversion phenomenon in any laser type.

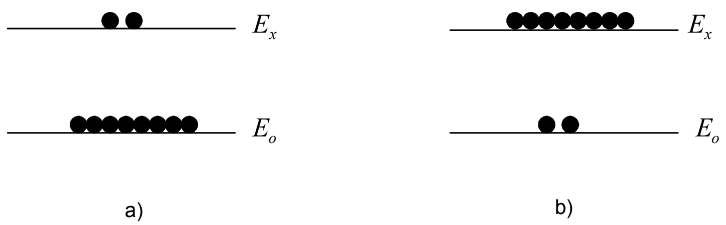


FIGURE 3.2
a) equilibiruim distribution of atoms between the ground state E_0 and excited state E_x, b) inverted population.

3.1.1 Laser Types

The numerous laser types can be categorized based on physical and operating parameters, which are involved in the laser beam generation. There are several ways to classify laser types; however, the most common way is to classify them based on their physical state of the active material. According to this criterion, lasers can be categorized as follows:

- Gas lasers
- Excimer lasers
- Solid-state lasers
- Semiconductor lasers
- Liquid dye lasers
- Fiber lasers

These classes of lasers can provide different wavelengths from ≈ 1 mm to ≈ 1 nm. Output powers cover even greater range of values. For continuous wave (CW) lasers, typical powers range from a few mW, used for signal sources; to tens of kW, used for material processing; and to a few MW, used in some military applications. In pulsed lasers, peak power can be much greater than in CW lasers. It can reach values as high as 1PW (10^{15} W). The pulse duration can vary from a ms level, typical of lasers operating in the so-called free-running regime (i.e., without any Q-switching or mode-locking elements in the cavity), to about 10 fs for some mode-locked lasers.

In the following sections, the construction of the above-mentioned classes of laser will be briefly explained and their potential applications to the laser cladding process will be addressed.

3.1.1.1 Gas Lasers

Gas lasers utilize a gas or gas mixture as the active medium and may be operated in either CW or pulsed modes. Gas lasers are grouped into four categories according to the type of gas used: neutral-atom gas, ionized gas, and molecular gas. Excitation is usually achieved by applying current through the gas.

Neutral-atom gas lasers employ electrically-neutral gas atoms as the active medium. The HeNe laser is the most common neutral-atom gas laser. Ion lasers contain ionized gas molecules as their active medium. The most common lasers of this group are the argon and krypton gas lasers. Some lasers, such as helium-cadmium (HeCd), include metal ions in a gas. CO_2 is, by now, the most common molecular laser, but several other molecular gases are employed as well, such as CO, HE, and OF. Figure 3.3 depicts the basic construction of a CO_2 laser with different sources of excitation: RF and DC. As seen, different sources of excitation can be embedded in the gas tubes.

The wavelength of a CO_2 laser is 10.24 μm and output power of the commercial CO_2 lasers can be even more than 45 kW. The optical efficiency of this type of laser is about 40 percent and their wall plug efficiency is about 20 percent. These efficiencies are strong functions of temperature.

Regardless of low efficiency, CO_2 lasers have a better beam quality and focusability than other types of lasers with the same power. CO_2 lasers also have the advantages of being very well absorbed by organics, glass and ceramic materials and are relatively color independent. As a result, selecting a CO_2 laser is a trade-off between economical issues and the performance of the laser in different industrial applications. Although the high maintenance cost and low wall plug efficiency are two restrictions for applications of CO_2 lasers, this laser has been widely adopted for usage in industrial applications such as welding, cutting, cladding, and processing of glass, ceramics, and organic (e.g., polymer textile, paper, tissue material, and food) materials.

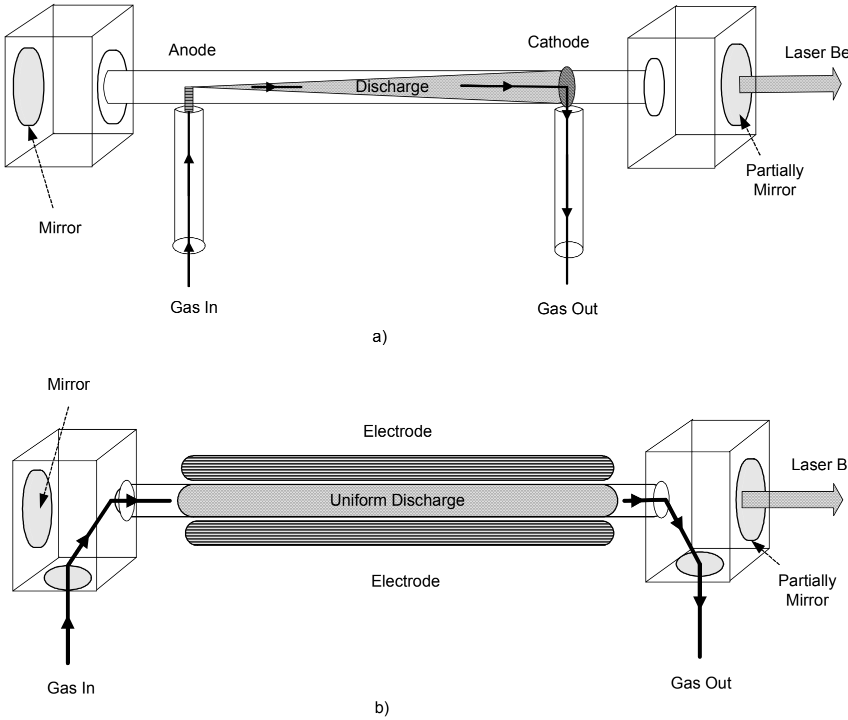


FIGURE 3.3
A schematic of CO_2 laser with a) DC excitation, b) RF excitation.

3.1.1.2 Excimer Lasers

Excimer stands for "excited dimer". The principle of operation of an excimer laser is a chemical reaction. The excimer laser is very often dedicated to the generation of a single wavelength.

Each molecule of the active medium of an excimer laser is composed of an inert gas atom and a halogen gas atom. Among others, these include krypton fluoride (KrF), xenon fluoride (XeF), argon chloride (ArCl), argon fluoride (ArF), krypton chloride (KrCl), and xenon chloride (XeCl). The rare-gas halide (compound made from a halogen) laser, which emits in the ultraviolet wavelength (126 to 558 nm), operates on electronic transitions of molecules with repulsive ground states, until a diatomic (having two atoms within one molecule) occurs. In general, the excimer laser is generated by combination of two identical atoms or molecules, one of which is excited and the other is at a ground state. For this laser, excitation can be accomplished by E-beam or electric discharge. Figure 3.4 shows the construction of an excimer laser, including electrodes, supplying and storing electrical lines, mirrors, lenses and a chamber for chemical reaction.

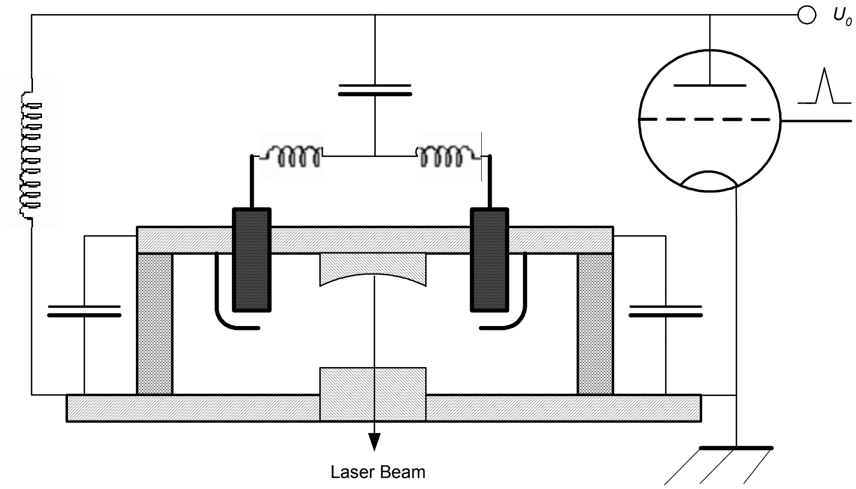


FIGURE 3.4
A schematic of an excimer laser.

Typical average output powers of excimer lasers range from less than 1 W up to approximately 700 W. This is two orders of magnitude less than traditional Nd:YAG or CO_2 lasers, which operate in the infrared part of the spectrum. The high intensity beam of an excimer laser is the product of pulse energy with 10 to 1000 mJ and the pulse duration of approximately around 10ns.

Excimer lasers are widely used in medical technology as well as micromachining, as they provide the ultimate method for skiving, ablation, and micromachining of flex circuits, plastics, and ceramics. With these lasers, the ability to control depth in microns provides an easy and cost effective method for removing excess material, exposing leads and pads, removing oxide coatings, and providing controlled depth cavities.

3.1.1.3 Solid-State Lasers

Solid-State (SS) lasers use a solid crystalline material as the lasing medium, and are optically pumped. These lasers have lasing material distributed in a solid matrix (e.g., the ruby). Solid-state lasers use a pumping source to excite the atoms and supply energy to the crystal rods; typical pump-sources can be flash lamps or diode lasers. Figure 3.5 shows a typical construction of a solid-state laser along with pumping source.

The first laser, invented in 1960, was a solid-state laser [40]. It used a synthetic ruby rod (chromium-doped aluminum oxide) with mirrors on both ends (one semitransparent) pumped with a helical xenon flash lamp surrounding the rod. The lamp was similar to those used for indoor and high speed photography. The intense flash of blue-white light raised some of the chromium atoms in the matrix (the aluminum oxide is just for structure and is inert as far as the laser process is concerned) to an upper energy state from which they could participate in stimulated emissions.

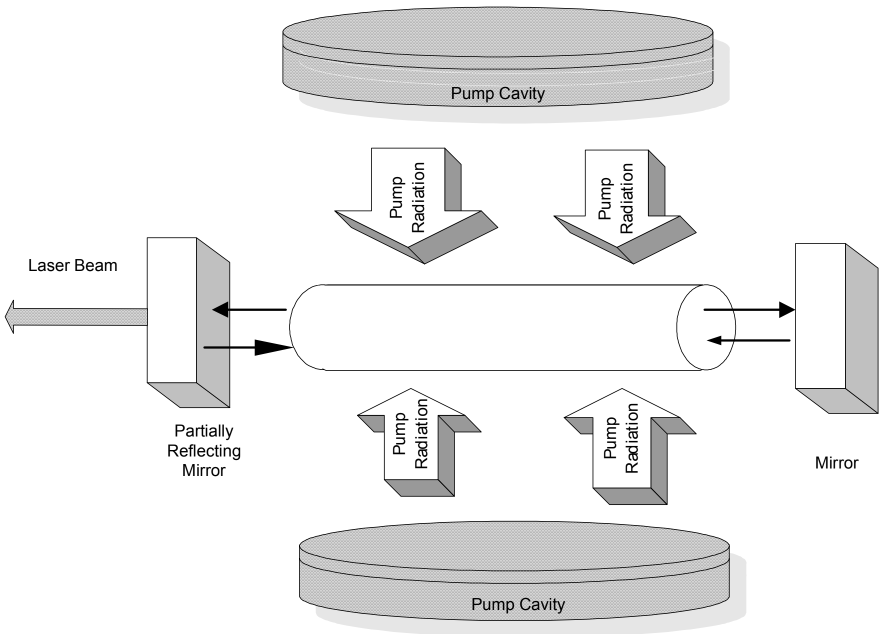


FIGURE 3.5

A typical construction of a solid-state laser along with pumping source.

Modern solid-state lasers are not too different from the original prototype. The majority of modern solid-state lasers use neodymium (Nd) doped materials such as Nd:YAG (yttrium aluminum garnet, which is $Y_3A_{15}O_{12}$), Nd:YVO_4, Nd:Glass, and others. These materials have a much lower lasing threshold than ruby as well as other desirable physical and optical properties. The strongest output wavelength of neodymium-doped lasers is approximately 1064 nm which is close to IR (infrared), and it is totally invisible.

The exact wavelength of the strongest lasing lines depends on the actual host material. In addition to Nd:YAG and Nd:YVO_4 at 1064 nm, there are types of solid-state lasers that lase at slightly shorter wavelengths such as Nd:LSB at 1062 nm, Nd:Glass at 1060 nm, Nd:YLF at 1053 nm, and Nd:$NiNbO_3$ (neodymium-doped lithium niobate) at 1092 nm. Other materials include holmium-doped YAG (Ho:YAG) or Ho:YLF, which provide laser light at approximately 2060 and 2100 nm, respectively.

Among the above-mentioned materials used as the main crystal in solid-state lasers, Nd:YAG and Nd:YVO_4 are becoming increasingly important for high-power lasers (e.g., 4 kW at 1064 nm).

Solid-state lasers can be pulsed, CW, or quasi-CW. In a pulsed solid-state laser, Q-switching (Q stands for quality) is used to stabilize and boost peak power output by preventing the laser cavity from resonating (e.g., one of the mirrors is blocked or forced to be misaligned by a mechanical mechanism) until the population inversion is built up fully.

CW solid-state lasers may use xenon or krypton arc lamps or other sources of intense broad spectrum light. However, the trend today is toward the use of arrays of high-power laser diodes for pumping. These can be designed to have a wavelength that matches an absorption band in neodymium (around 800 nm), making for very efficient excitation. The diode pumped technique is rapidly taking over due to their higher efficiency than flash one. This results in lower power consumption and heat dissipation, reduction in size, as well as an increase in reliability and decrease in maintenance. This type of laser is further discussed in the next section.

Quasi-CW solid-state lasers are actually pulsed lasers but operating with a pulse repetition rate (PRR) that is high enough to appear to be continuous.

3.1.1.4 Semiconductor Lasers

Semiconductor lasers, which are also called diode lasers, are not solid-state lasers. These electronic devices are generally very small and use a low amount of power. They may be built into larger arrays such as the writing head in some laser printers or compact disc players. Figure 3.6 shows the construction of a diode laser.

Some of the properties of diode lasers include wide spectrum band (2-20 nm), large beam divergence (up to 40 half-angle), non-symmetrical beam distribution (2.5-6 times difference in beam divergence in the two orthogonal axes), and lower energy intensity per area.

Diode lasers use nearly microscopic chips of gallium-arsenide or other exotic semiconductors to generate coherent light in a very small package of laser. These materials are based on semiconductors of group III-V components. The energy level differences between the conduction and valence band electrons in these semiconductors are what provide the mechanism for laser action. Population inversion, as a result of electron transitions from the valency band to the conduction band of a doped semiconductor, is achieved by forward biasing the p-n junctions. Spontaneous emission and stimulated emission occur when electrons in the conduction band recombine with the holes in the valency band. The optical cavity in a diode laser is formed by splitting two opposite facets of the semiconductor wafer to form a Farby-Perot lasing cavity [116].

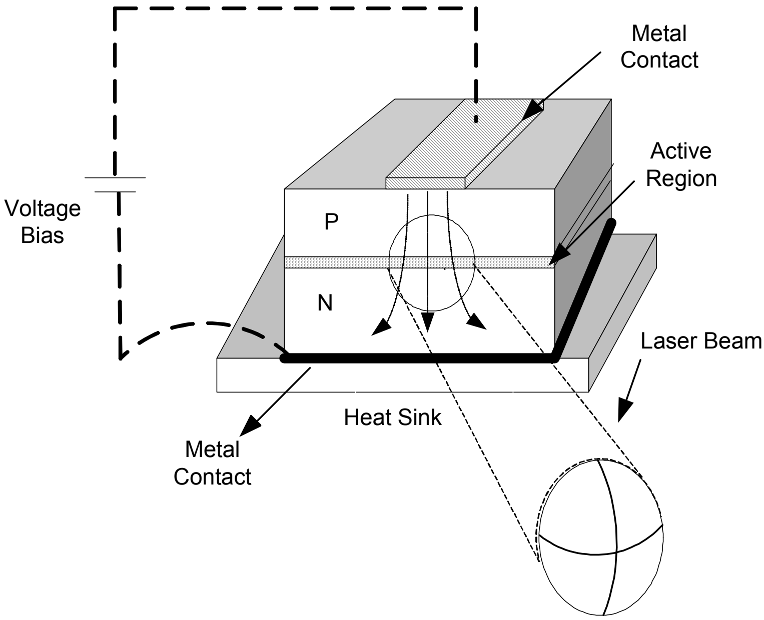


FIGURE 3.6
A schematic of a diode laser.

The active element in a semi-conductor laser is a solid-state device not all that different from an LED. The first type of this laser was developed quite early in the history of lasers but they became widely available and more economical in the early 1980s. Today, there are various diode lasers in terms of output power. The most common types, found in popular devices like CD players and laser pointers, have a maximum output in the 3 to 5 mW range. The new generation of high-power diode laser (HPDL) can produce 4 kW. The high-power terminology is used for CW diode lasers with output power in excess of 0.5 W.

Diode lasers have several disadvantages such as poor beam coherence and symmetry. These disadvantages can be overcome by a diode-pumped solid-state laser such as a diode-pumped Nd:YAG laser as well as the use of optical fiber beam delivery.

Diode-pumped Nd:YAG lasers are an integration of crystal and diode pumping unit, as it was mentioned in the last section. A schematic of a typical type of this laser is shown in Figure 3.7. In this laser, the p-polarized diode light, which is transmitted into the rod with low loss on the surface of the rod, is used to pump the YAG rod. The diode light can be sent to the rod through three different orientations. The laser crystal is mounted inside a flow-tube whose outer surface has AR (anti reflective) and HR (high reflective) coatings for the diode wavelength [117].

The diode pumped Nd:YAG is an established tool for micro-cutting applications; however, there are several disadvantages of diode pumped solid-state lasers such as low wall plug efficiency, high running costs, and poor thermal stability.

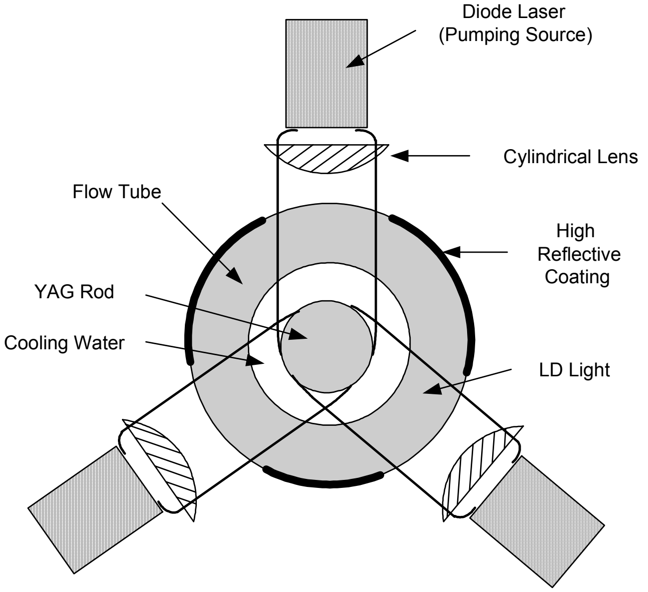


FIGURE 3.7
A schematic of a diode-pumped Nd:YAG laser, which has three source of diode pumping [117].

3.1.1.5 Liquid Dye Lasers

Dye lasers are unique due to the use of liquid as the lasing medium. Depending on the particular dye used, the output laser beam can be at a wide range of wavelengths spanning the visible spectrum and beyond.

Commercial dye lasers are often pumped by other lasers. For example, rhodamine-B, a common dye used in dye lasers for the red region, is often pumped with an argon ion laser at 514 nm for CW operation or with a doubled YAG laser at 532 nm when pulsed. An intensive flash lamp can also be used as a pump source. Figure 3.8 shows a schematic of a liquid dye laser.

The most useful feature of dye lasers is their tunability. The lasing wavelength for a given liquid may be varied over a wide range. Taking advantage of the broad fluorescent linewidths (50-100 nm) available in organic dyes, a diffraction grating can be used as a wavelength-dispersive optical element in the laser cavity to perform selective tuning. Such tuning can yield extremely narrow linewidths.

The hazards of dye lasers are relatively moderate. Some of the organic dye materials used in this type of laser are toxic, and a high voltage power supply (low current but a large energy storage capacitor) is required to fire the flash lamp.

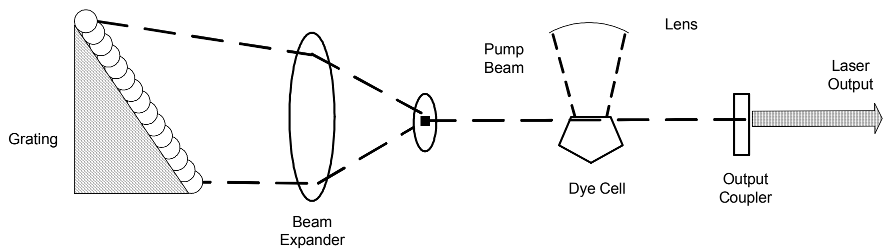


FIGURE 3.8
A schematic of liquid dye laser.

3.1.1.6 Fiber Lasers

For the past decade, rare-earth-doped fibers have received widespread attention for their applications as laser sources and amplifiers. With wall-plug efficiencies greater than 20 percent, a huge increase in the output power of fiber lasers has been reported in recent years. The new development in fiber lasers is high-power output, which works at eye-safe wavelengths. In addition, advances in ultrashort pulsed fiber lasers, based on photonic crystal or holey fibers, have opened up an entirely new set of applications in sensing, materials processing and biomedical sciences.

A fiber laser for producing very short pulses is formed by placing a laser fiber in a resonant cavity. The fiber laser is formed of two different types of fibers, which are joined in series. They are a gain fiber, which contains the laser gain medium, and a pulse shaping fiber, which uses the phenomenon of solution pulse shaping to shorten the pulses. An initially formed pulse is recirculated many times in the resonator. On each pass, the pulse is both amplified and shortened until it reaches steady-state. The zero dispersion wavelength of the pulse shaping fiber is chosen to be slightly less than the laser wavelength. The fiber is pumped by a continuous source, particularly CW laser diodes [118]. Figure 3.9 shows a schematic construction of a typical fiber laser.

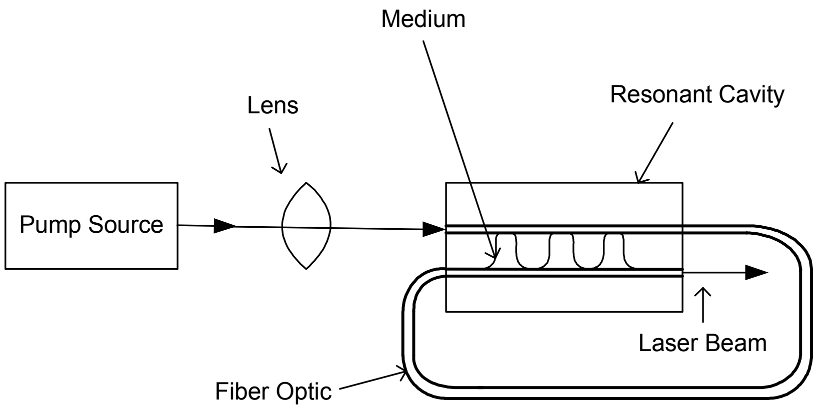


FIGURE 3.9
A schematic construction of a typical fiber laser.

The first 2 kW continuous-wave fiber laser has been produced and immediately used in automotive applications in 2003 [119]. The spot size of this 2-kW laser is 50 μm giving a power density of 100 MW/cm^2. The size of the unit is only 110 $\times$ 60 $\times$ 118 cm, including the power supply and air-cooling system. This new high-power laser is seen as a replacement for solid-state Nd:YAG or CO_2 lasers because of the scalable power and a beam quality that is up to ten times better. Investigations show that the single-mode fiber laser is an efficient, reliable and compact solution for micro-machining. Fiber lasers are more easily integrated into industrial processes in comparison with conventional lasers for a number of reasons: standard wall plug operation and high electrical efficiency, no water cooling required, single mode fiber delivery line, high quality focusable beam, high repetition rate, optimized pulse duration, exceptionally high reliability, and maintenance-free operation.

3.1.2 Laser Beam Characteristics

Laser beam characteristics play an important role in laser material processing including laser cladding. There are many parameters that indicate the quality of a laser beam. Several important laser beam parameters are beam parameter

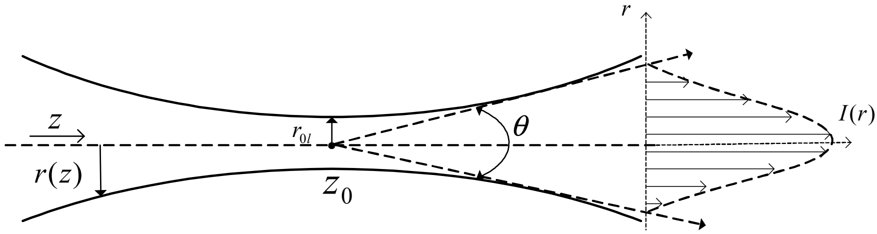


FIGURE 3.10
Laser beam geometry.

product (BPP), laser beam mode, energy distribution over the beam spot area, polarization, and focusability.

The beam parameter product (BPP) is important because it provides an indication of the focused beam size and the focal depth. It is represented by

$$BPP = \frac{r_{0l}\theta}{2} \tag{3.3}$$

where r_{0l} is the beam spot radius in the waist of the laser beam and θ is the far-field full divergence angle, as shown in Figure 3.10. The argument is that reducing the divergence by using a beam expander would increase the beam spot size.

Based on Figure 3.10 and Equation (3.3), it can be concluded that a low divergence angle produces a smaller focused spot and greater depth of focus.

The laser energy can be distributed in a uniform or Gaussian form over the laser beam spot area. However, generation of Gaussian energy intensity is easier than the uniform energy intensity.

In order to achieve a good beam quality, it is necessary to resonate the beam in a resonator. In the resonator, the distribution of the amplitude and phases of the electromagnetic field can be reproduced due to the repeated reflections between mirrors [116]. These specific field shapes produced in the resonator are known as transverse electromagnetic modes (TEM) of a passive resonator. Transverse electromagnetic modes in polar coordinates, which are also called Gaussian-Laguerre modes, are demonstrated by TEM_{pl}. The subscript p indicates the number of nodes of zero intensity transverse to the beam axis in radial direction, and the subscript l indicates the number of nodes of zero intensity transverse to the beam axis in tangential direction. The intensity distribution $I_{pl}(r,\varphi)$ of a TEM_{pl} mode can be represented by

$$I_{pl}(r,\varphi) = I_0\left(\frac{2r^2M^2}{r_l^2}\right)^l \left[L_l^p\left(\frac{2r^2M^2}{r_l^2}\right)\right]^2 \cos^2(l\varphi)\exp\left(-\frac{2r^2M^2}{r_l^2}\right) \tag{3.4}$$

where I_0 is the intensity scale factor [W/m^2], r_l is the radius of the laser beam profile, M^2 is the beam quality factor (based on the ISO 11146), and L_l^p is the generalized Laguerre polynomial of order p and index l [120]. The intensity scale factor I_0 is expressed based on node number and the average power P_l [W] as

$$I_0 = \begin{cases} \frac{2r^2 M^2}{\pi r_l^2} P_l & l = 0 \\ \frac{4r^2 M^2 p!}{\pi r_l^2 (p+l)} P_l & l = 1, 2, 3, 4, ... \end{cases} \quad (3.5)$$

Based on different TEM, various beam energy intensities are available. Figure 3.11 shows several TEMs with Gaussian energy intensities.

The other important parameters for a laser beam are the beam propagation factor and the quality factor. The radius of a radially symmetric laser beam varies along the propagation axis, which can be expressed by

$$r_l(z)^2 = r_{0l}^2 + 4\theta^2 (z - z_0)^2 \quad (3.6)$$

where r_{0l} is the beam radius of the waist [m], z_0 is the waist location with respect to an arbitrary coordinate along the propagation axis [m], and θ is the far-field divergence angle [rad]. Figure 3.10 shows the denoted parameters. The propagation can also be described by the beam propagation factor Q, or the quality factor M^2, which are related as

$$M^2 = \frac{1}{Q} = \frac{n\pi r_{ol}\theta}{2\lambda} \quad (3.7)$$

where λ is the laser wavelength in the used medium [m], and n is the index of reflection. The propagation factor k is then defined as

$$k = \frac{1}{M^2} - \frac{2\lambda}{n\pi r_{ol}\theta} \quad (3.8)$$

If $k = M^2 = 1$, the beam is Gaussian; if $M^2 > 1$, the beam is not Gaussian. However, all of the standard Gaussian propagation formulas may be used with appropriate correction factors (see ISO 11146).

In most cases, a laser application requires a laser beam with low divergence emitted in fundamental Gaussian mode (TEM_{00}). This is not guaranteed for every laser and is unlikely for especially high-power laser systems because the emission may be multimode or may be changed based on the life of laser systems. As a result, the beam quality should be measured by the available measurement devices such as laser beam analyzer (LBA), slit, knife-edge, and CCD-based instrumentation [121].

The other important parameters of laser beams are reflectivity and polarization. The values of absorptivity and reflectivity are related by the following equations:

$$R = \begin{cases} 1 - A & \text{(for opaque materials)} \\ 1 - A - T & \text{(for transparent materials)} \end{cases} \quad (3.9)$$

where R is reflectivity, A is absorptivity, and T is transmissivity. The reflectivity R for normal angles of incidence from air to opaque materials with perfect flat and clean surface is derived by

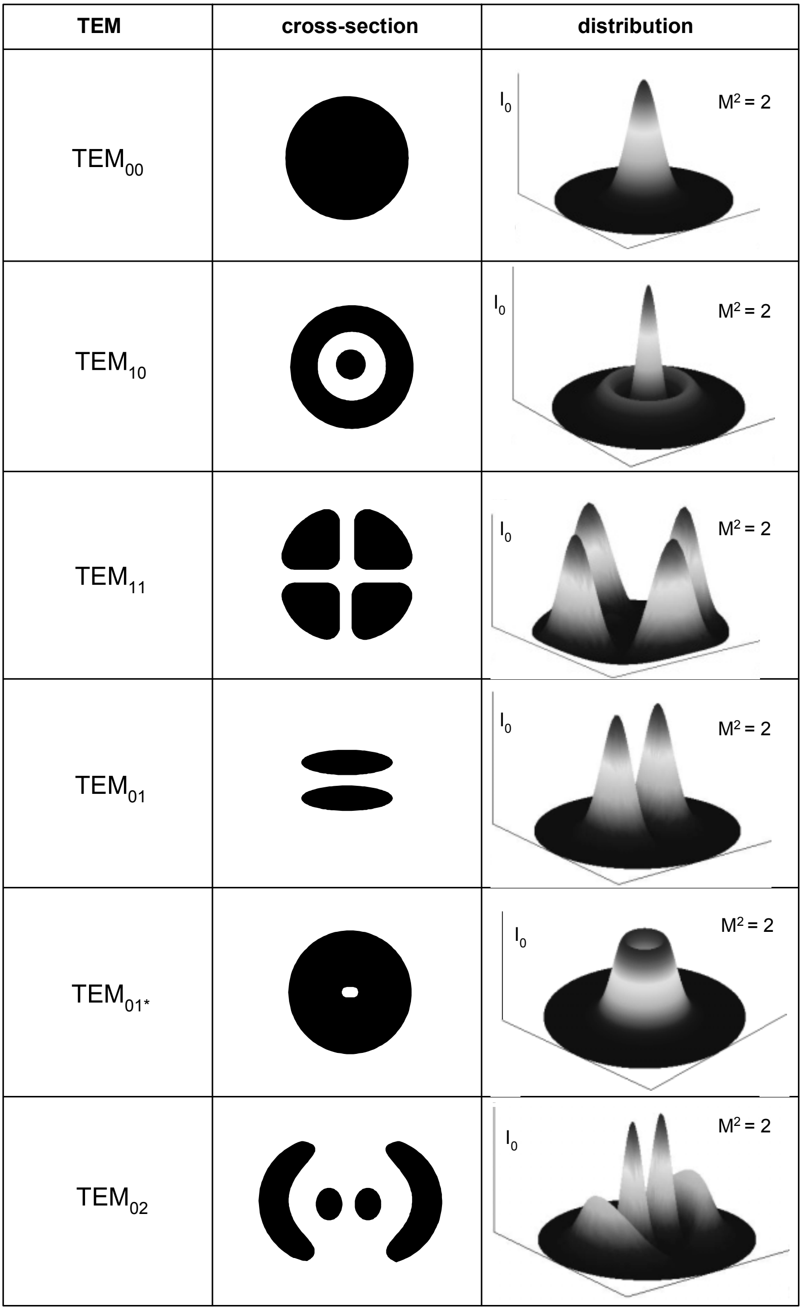


FIGURE 3.11

Several TEM modes with Gaussian energy intensity.

TABLE 3.1
Optical properties of several materials for 1.06 micron light wavelength in room temperature.

Materials	k	n
Al	8.50	1.75
Cu	6.93	0.15
Fe	4.44	3.81
Ni	5.26	2.62
Pb	5.40	1.41
Ti	4.00	3.80
Zn	3.48	2.88
Glass	0.10	0.50

$$R = [(1-n)^2 + k^2]/[(1+n)^2 + k^2] \qquad (3.10)$$

where n is the refraction coefficient and k is the extinction coefficient of material. The absorptivity, A, of an opaque metal surface can be obtained by

$$A = 1 - R = 4n/[(n+1)^2 + k^2] \qquad (3.11)$$

Table 3.1 lists the optical properties of several materials for the light radiation with 1.06 μm wavelength. It has to be considered that the optical properties will change with temperature and light wavelength.

Photons with shorter wavelengths are easier to be absorbed by the materials than photons with longer wavelengths. Therefore, R normally decreases as wavelength becomes shorter. When temperature rises, there will be an increase in the photon population. Therefore, the probability of interaction between the electrons and material increases causing a decrease in the reflectivity and an increase in the absorptivity.

Of interest is the fact that the reflectivity is a function of light polarization and angle of incidence. Light can be described as an electromagnetic wave that propagates through a sinusoidal oscillation of an electric field. The direction in which the electric field oscillates as it propagates is known as the polarization. A laser is defined as "polarized", if 90% or more of its energy is in a given polarization state such as linear, circular, or elliptical. In general, a laser pulse injects polarized electrons, whose spins have a definite orientation determined by the laser's polarization. The desired polarization state is generated by a combination of different optic systems. Figure 3.12 shows examples of two polarization states: linear and circular. In circular state, the electromagnetic wave propagates as a function of time and rotates around a reference line as shown in the figure.

Drude [122] showed a variation in reflectivity with both angle of incidence and plane of polarization. If the plane of polarization is in the plane of incidence, the beam is called a p-ray. If the beam has a plane of polarization

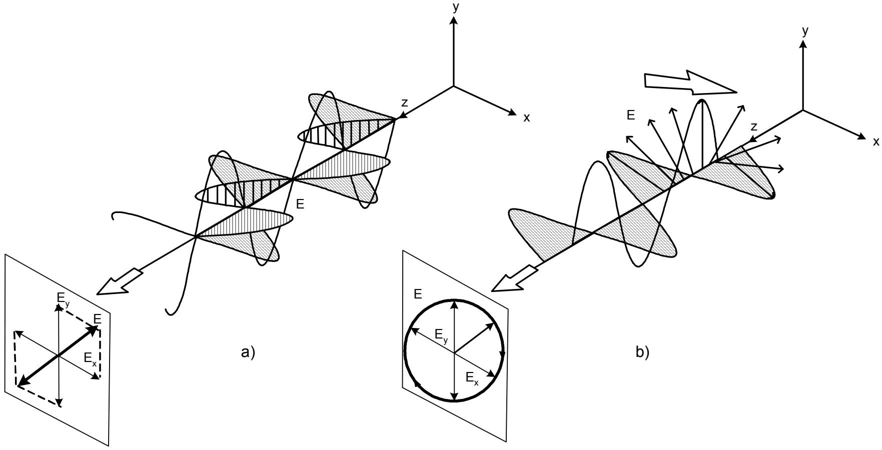


FIGURE 3.12
a) Linear polarization, b) circular polarization.

which is normal angles to the plane of incidence, it is called s-ray as shown in Figure 3.13. The corresponding reflectivities for these two types of polarized beams can be obtained by

$$R_p = \frac{[n - (1/\cos\varphi_i)]^2 + k^2}{[n + (1/\cos\varphi_i)]^2 + k^2} \tag{3.12}$$

$$R_s = \frac{(n - \cos\varphi_i)^2 + k^2}{(n + \cos\varphi_i)^2 + k^2} \tag{3.13}$$

where R_p is the reflectivity of a p-ray beam, R_s the reflectivity of an s-ray beam, φ_i is the incident angle, n is the refraction coefficient, k is the material extinction coefficient. In general, p-rays are more easily absorbed by materials than s-rays.

3.1.3 Types of Lasers and Laser Beam Characteristics in Laser Cladding Process

In the laser cladding process, it is essential to provide appropriate power density and interaction time between the laser beam and the material. Figure 3.14 shows the range of the power density and interaction time for various laser material processing techniques.

As it is seen, the laser cladding process requires a power density from 70 to 100 W/mm^2 and an interaction time of 0.01 to 1 second; any laser intended for use in the laser cladding process should provide this level of power density. In addition, the beam quality is a key factor for a successful laser cladding as

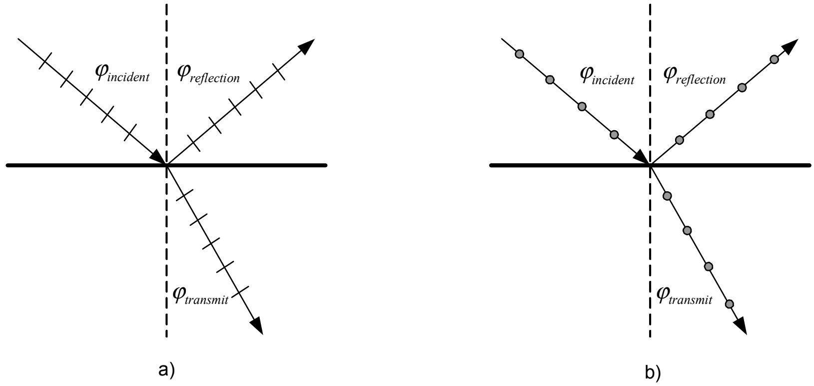


FIGURE 3.13
a) p-ray b) s-ray.

will be explained in the next section. The selected laser should provide the appropriate beam quality.

Another important issue for any laser material processing is the light reflection from the surface of metals. The reflection is strongly a function of laser wavelength and it varies from metal to metal. Figure 3.15 shows the wavelength dependency of several metals' reflection factor.

It is also important to consider the contribution of temperature in reflectivity. As the temperature of the process zone rises, an increase in absorptivity occurs, which indicates the potential of more energy absorption by the material [101].

3.1.3.1 Types of Lasers Used in Laser Cladding Process

As described in Section 3.1.1, there are many laser systems in the market. However, CO_2 lasers, lamp-pumped Nd:YAG lasers, diode-pumped Nd:YAG lasers, and high-power diode lasers (HPDL) are most commonly used in the laser cladding process.

There is no report on the use of liquid dye lasers in the laser cladding process. This laser is not widely used in laser material industry due to its low power capacity.

To the best knowledge of the authors, there is no report on the use of fiber lasers in the laser cladding process. However, fiber lasers can be adapted to the process due to its high beam quality, cost effectiveness, and efficiency in near future.

There seems to be only a few reports about the application of excimer lasers to the laser cladding process. Panagopoulos et al. [123] carried out a coating of copper on mild steel by a KrF excimer laser with a wavelength of 248 nm. The power density per pulse was varied between 150 and 430 MW/cm^2 and

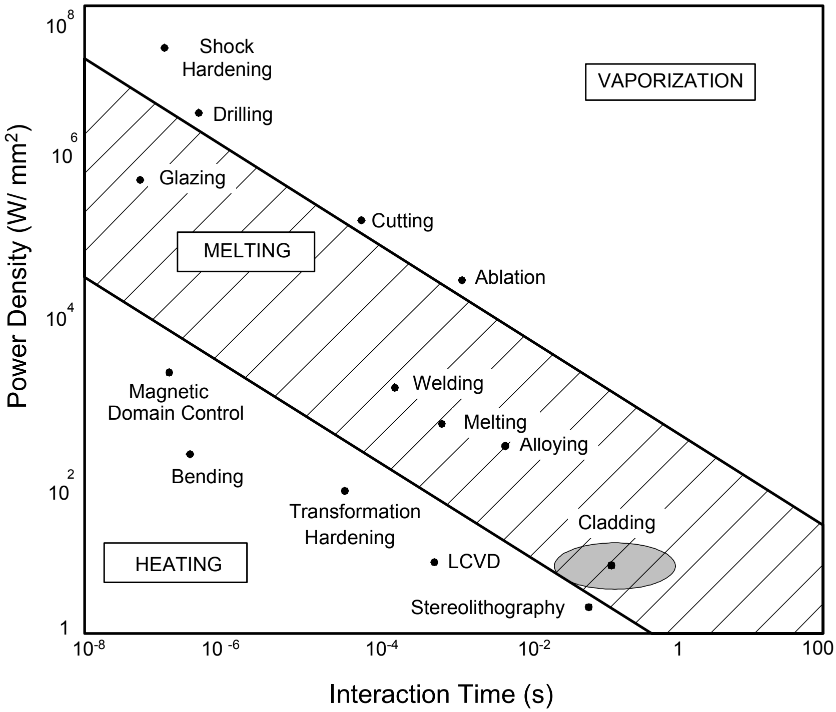


FIGURE 3.14

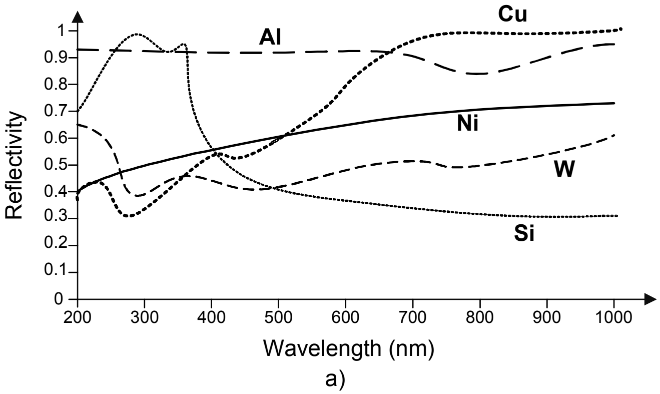
Power density and interaction time for various laser material processing [101].

the pulse frequency was 10 Hz. Except for this work, research groups and industry have not utilized the excimer laser as a source of energy for the laser cladding process due to its low average power. Although the peak power of the excimer laser per pulse is high, this high power per pulse can vaporize the powder particles. Excimer lasers, on the other hand, have the potential for use in coating of micro-devices (e.g., MEMS).

Table 3.2 summarizes characteristics of these four types of lasers which have been widely used in laser cladding.

Both pulsed and continuous wave lasers have been used in laser cladding; however, with pulsed lasers, it is necessary to maintain the peak power of each pulse in a limited range. Pulses with high peak power energy (even those with low average power) can vaporize the powder particles prior to reaching the process zone.

There are major performance differences between Nd:YAG, HPDL, and CO_2 lasers. Nd:YAG and HPDL light are emitted at wavelengths of 1.024 and $\sim$0.85 μm, respectively, which are in the near infrared, while CO_2 light is emitted at 10.6 μm. The material interactions at these wavelengths differ.



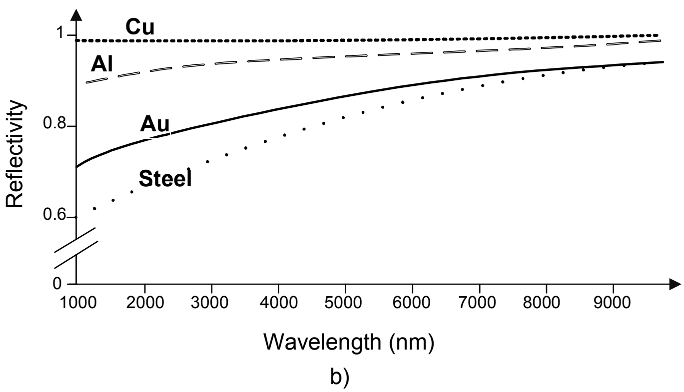


FIGURE 3.15
Correlation of reflectivity and beam wavelength for different materials in two different wavelength ranges, a) from 200 to 1000 nm, b) from 1000 to 9000 nm.

TABLE 3.2
Characteristics of common lasers used in laser cladding.

Characteristics	CO_2	Nd:YAG lamp-pumped	Nd:YAG diode-pumped	HPDL
Wavelength [μm]	10.64	1.06	1.06	0.65-0.94
Efficiency [%]	5-10	1-4	10-12	30-50
Maximum power [kW]	45	4	5	6
Average power density [W/cm^2]	$10^{6...8}$	$10^{5...7}$	$10^{6...9}$	$10^{3...5}$
Service period [hour]	1000-2000	200	5000-10000	5000-10000
Beam parameter product (BPP)[mm × mrad]	12	25-45	12	100-1000
Fiber coupling	No	Yes	Yes	Yes

Metals are more reflective at 10 μm than at 1 μm as shown in Figure 3.15; as a result, Nd:YAG and HPDL are more efficient than a CO_2 laser for metallic processing. Aluminum is relatively highly reflective compared to the CO_2 beam, whereas a beam from a Nd:YAG or HPDL laser is almost perfectly absorbed. On the other hand, most carbon steels and stainless steels absorb CO_2 and Nd:YAG beams very much the same. HPDL in comparison to CO_2 and Nd:YAG lasers has the shorter wavelength and thus higher absorption of the direct diode laser. Figure 3.15 shows the reflection factor as a factor of wavelength for several metals.

A CO_2 laser can provide a very high power such as 45 kW. Commercial Nd:YAG lasers are available with powers up to 4 kW (continuous) and pulsed Nd:YAG lasers with lower average powers (e.g., 1.5 kW) but have much higher pulse peak power. That is due to the cooling of the solid rod of solid-state lasers, which is a difficult task [116]. As a result, the solid-state lasers have problems with high average powers. In contrast, CO_2 lasers do not have a serious problem with thermal lensing; therefore, they can be fabricated in high power capacity with a good beam quality [116].

CO_2 laser beams are focused to smaller spots and they are more symmetrical, which improves the clad width. A 1-kW CO_2 laser can be focused to a 100 μm spot, whereas a 1-kW Nd:YAG is generally used with fiber optics for beam delivery and cannot be focused smaller than 400 μm. A HPDL laser provides a wide beam distribution and has a low beam quality. As a result, HPDL can be used only for coating in which a lower energy per area is required. HPDL lasers in today's market cannot be used for high melting temperature materials. It is reported that a HPDL laser can be used for laser cladding; however, it is applicable to a limited number of materials and coating thicknesses [124].

Another important issue in selecting a laser is the beam delivery. It is impossible to transport the CO_2 beam through a fiber optic cable due to its wavelength (i.e., 10.6 μm). As a result, the maneuverability of a motion system along with a CO_2 laser is very limited. Although, a flying optic can be integrated into a CO_2 laser to provide an extra degree of freedom, its usage in fabrication of complex parts with laser cladding is still limited. In addition, the flying lenses are very sensitive to powder intrusion into the moving lenses. Nd:YAG and HPDL lasers, on the other hand, can be run through a fiber optic cable and as a result, can be connected to the end effector of a robot with any degree of freedom.

CO_2 lasers generally produce either a dot-mode (TEM_{00}) or a ring-mode (TEM_{01}) beam, which can focus down to either a single point or a very tiny ring. Nd:YAG lasers can produce a multi-mode beam (i.e., TEM_{02}, TEM_{11}, TEM_{01*}, TEM_{22}, etc.).

The time constant for a CO_2 laser is very high compared to Nd:YAG and HPDL. Therefore, a CO_2 laser is not appropriate, when the power needs to be changed in a short period of time. This weakness can be overcome by the integration of a fast shutter system into the CO_2 laser.

Diode-pumped Nd:YAG lasers have a very impressive efficiency. For small (less than 10 W) lasers, total efficiency is usually greater than 50 percent. Diode-pump Nd:YAG lasers with average power above 4 kW are being introduced to the market.

High-power diode lasers HPDL are particularly compact and at the same time, highly efficient. The development of lasers with an output power of over 1 kW opened a gate towards the use of diode lasers in laser cladding processes. HPDL lasers have been used for generating and repairing molds and motor parts. With HPDL, it is necessary to use a standard lens to achieve an appropriate working distance from the focus point. This distance provides enough space for the cladding modules (powder and inert gas nozzles). There is, however, a very high risk that the protective glass and the lens quickly become dirty or even damaged by the powder particles. It is also not possible to process surfaces with complex shapes (e.g., crankshafts). As a result of this shortcoming, researchers have undertaken projects to develop an appropriate lensing system. There are several claims about the higher dilution between the substrate and the clad layer when a HPDL is used [125, 126]. This is mostly due to the higher energy absorbed in the case of HPDL. However, using HPDL for laser cladding provides the user with a unique line source that produces clads with a controllable width without scanning many times over the surface. CO_2 and Nd:YAG lasers have a smaller spot size such that the laser must be scanned over the coated area several times. The shorter wavelength of the HPDL allows for higher absorption into the material being coated so that a higher process speed can be achieved.

Figure 3.16 shows typical cross sections of clad and the substrate region (Stellite 6 on steel) performed by HPDL and CO_2 lasers [125]. The wavelength of HPDL laser beam was 0.94 μm. The experiments for both cases performed at process speed of 900 mm/min, and the maximum clad rate was 0.5 kg/hr. The diameter of CO_2 laser beam was 4.7 mm on the substrate, and the diode beam cross section on the substrate was 4.5×4 mm$\times$mm. The laser average power in CO2 experiment was 3900 W and in the HPDL was 1400 W. As seen in the figure, the cross section of the clad region for HPDL case is 1.9 mm^2, and for CO_2 laser is 2.1 mm^2. The microstructures of both samples show a fine-dendritic structure, which are metallurgically bonded to the substrate. The power of CO_2 laser should be set to 3.9 kW to produce the same clad as produced by the 1.4 kW power of HPDL.

Table 3.3 lists the types of lasers currently used by researchers/organizations involved in the laser cladding process.

3.1.3.2 Laser Beam Characteristics in Laser Cladding

Since the processing zone in laser cladding is usually positioned below the focal point, a larger distance between the optical system and the workpiece is available, which facilitates the protection of the optical system. In general, in laser cladding, it is preferred to have a larger focal distance due to reduction of the sensitivity of the spot dimensions to the changes in beam characteristics

TABLE 3.3
Laser types of organizations/research groups involved in the laser cladding process.

Organization	Type of Laser	Application	Material used	Ref.
Fraunhofer-Institut fur Lasertechnik, Germany	HPDL, CO_2	coating, prototyping	Co and Fe-based alloy, SS 304	[125, 127]
GE Aircraft Engines, USA	CO_2	repairing of engine turbine blades	Ni alloy	[128]
Laser X. Co., Japan	CO_2	coating	Cr-Ni based materials, Stellite 6	[110]
University of Waterloo, Canada	Nd:YAG (pulsed) lamp pumped, HPDL	prototyping, coating	Fe-Al, H13	[129, 68]
Ishikawajima-Harima heavy Industries Co., Japan	Nd:YAG(CW) lamp pumped	coating	SS 304	[130]
National Research Council of Canada	Nd:YAG(pulsed and CW) lamp pumped	prototyping	SS 316L, IN-625	[19, 21]
Swiss Federal Institute of Technology, Switzerland	CO_2	prototyping, blade repairing	SS, Stellite 6, superalloy, CMSX-4	[103, 36].
Los Alamos National laboratory, USA	Nd:YAG (CW) lamp pumped	prototyping	Inconel alloy 690	[28]
University of Illinois, USA	CO_2	prototyping	Al, H13	[64, 14]
DRL Institute, Germany	CO_2	coating	Co, Al, Ni	[131]
Illinois University, USA	CO_2	coating	Ni-Al-Cr-Hf on Ni	[77]
Westinghouse, USA	CO_2	coating	Stellite 6	[55]
Sandia National Laboratories, USA	Nd:YAG (CW) diode pumped	prototyping	SS 316, SS 304L, H13, IN718,IN 600	[13]
AeroMet Corporation, USA	CO_2	low volume manufacturing	Ti, Ti-6Al-4V, Ti-5Al-2.5Sn	[34]
POM Inc., USA	CO_2	prototyping, coating,	H13, Co-based material	[82]
University of Michigan, USA	CO_2, Nd:YAG diode pumped	prototyping, coating	H13, Ti-based alloy, Copper	[14]
South Dakota school of Mines & Technology, USA	Nd: YAG (CW) lamp pumped	prototyping, coating	Ti- Ni, Ceramics	[132]

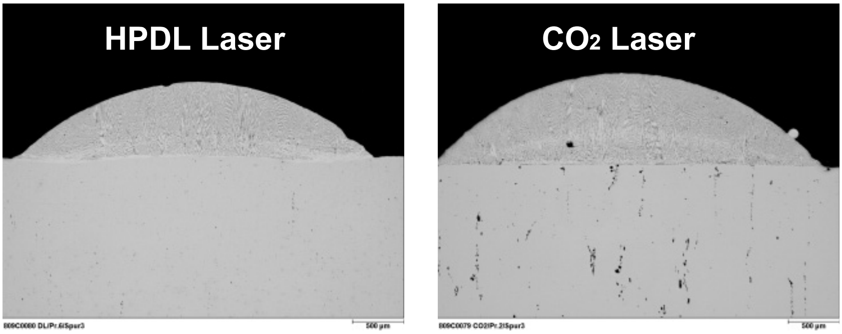


FIGURE 3.16
Cross section of a single track at process speed of 900 mm/min using different laser sources, a) HPDL laser at 1400 W, b) CO_2 laser at 3900 W (*Source*: Courtesy of Fraunhofer Institute for Material and Beam Technology, Germany [125]).

and also reduction of the peak power intensity in the spot point, which can cause plasma formation [108].

In pre-placed laser cladding, a circular laser spot with uniform power distribution seems to be more suitable than a Gaussian beam. The main reason for this is the need to transfer a homogeneous energy on the pre-placed powder layer. If a Gaussian beam were used, it would cause non-homogeneous distribution of energy, which may cause plasma formation or even an unexpected clad width.

In laser cladding by powder injection, a Gaussian beam may result in better bead quality, dilution, and homogeneity over the clad microstructure. In the case of lateral nozzle, the powder particles usually have a Gaussian distribution, which is compatible with laser power distribution as shown in Figure 3.17.

A TEM_{00} has been used in many reports dealing with laser cladding [133, 36, 134]. However, Schneider [135] claimed that a laser spot perpendicular to the direction of cladding with a homogeneous distribution provides a uniform temperature distribution over the melt pool. Also, Weerasinghe et al. [44] used a TEM_{01} mode beam in their experiments and they arrived at a uniform heating effect.

There may be cases in which the other mode shapes are preferred, especially when producing a thin wall clad. This line shape beam laser can be generated using two cylindrical mirrors or a segmented mirror [107].

Frenk et al. [136] showed that cladding using far-infrared radiation (e.g., CO_2) should be done with linearly polarized beams at angles of some 70 to 80 degree. In this way, the transmitted energy can be improved by a factor of 3 to 4.

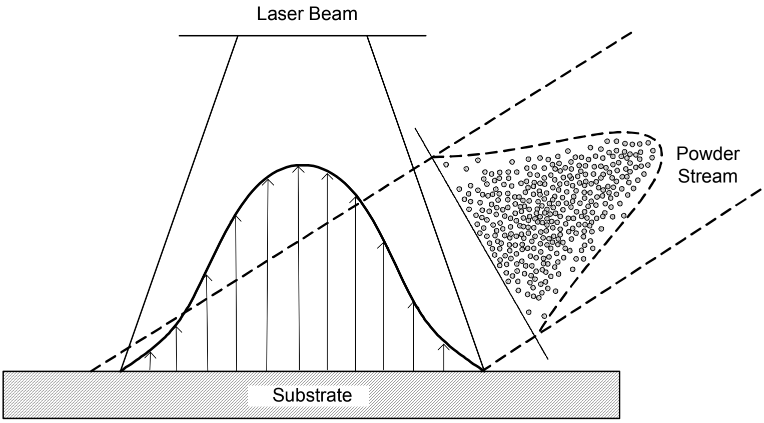


FIGURE 3.17
A Gaussian laser energy distribution versus a Gaussian powder particles distribution.

In laser cladding, it is also possible to use a rectangular spot with a uniform power intensity, as generated by a diode laser [125]. Such a spot can also be generated using a two-dimensional beam integrator. An alternative to the use of integrating optics for achieving a uniform temperature profile over the width of the track is the use of scanning optics.

High-power lasers can become instable when run for a long period in the cladding process. The laser's properties can be influenced by the process itself, causing the process to fail or be unsatisfactory. Therefore, monitoring and control of laser beam parameters is an important task in the laser cladding processes [137, 138].

3.2 Powder Feeders and Powder Delivery Nozzles

Powder feeders are among the most important pieces of equipment in a number of industrial applications involving powder conveyance, such as thermal spraying, laser cladding and advanced materials processing. As different powders have very distinct sizes, shapes, and other physical and mechanical properties, it is nearly impossible to convey each type of them with a steady-state flow using a single feeder machine. With decreasing powder grain size (e.g., ultra-fine powder with size of less than 15 μm), the flowability of the powder is decreased, which causes problems in the powder transporting. Flowability also dramatically decreases with sticky and cohesive powders. Void factor (i.e., ratio of the space of air to that of solid) also plays an important role in flowability of powder. For these reasons, different powder feeders are required for each type of powder. For example, the required powder feed rate for thermal spraying can be relatively large, whereas the required powder feed rate for prototyping by laser cladding is relatively small. Therefore, a powder feeder machine needs to be carefully controlled in order to ensure that a stable powder stream with a desired feed rate is generated.

Selection of a suitable powder feeder is a vital factor for a successful laser cladding process. A powder feeder should provide a continuous and uniform powder stream with high accuracy in terms of flow rate at a desired feed rate. It is crucial to control the feed rate in real-time with minimum time constant. Also, in a laser cladding process, particular attention has been given to minimizing pulsations and agglomerations in the powder stream. Unfortunately, the current powder feeders in the market cannot provide a low time constant (e.g., 0.5 second) and low powder feed rate at high precision (e.g., 0.1 g/min), which are two important parameters in the laser cladding technology. For this reason, special powder feeders with different control strategies have been designed and introduced [139, 140, 141, 142].

Also, researchers are developing feeders for ultra-fine powders to arrive at a continuous stream with low feed rate. These powder feeders are vibration-based or pressure-assisted feeders, which can even be used in direct-write deposition [143].

3.2.1 Powder Feeder Types

There are many types of powder feeders used in industry. In general, powder feeders can be categorized into the following classes based on different principles of operation:

- Gravity-based
- Mechanical wheel
- Fluidized-bed
- Vibrating

In some powder feeders, a combination of the above methods is used to arrive at a better stability in the powder stream. In all types of powder feeders, a carrier gas should be supplied to transport the powder particles from the starting point to the desired location. A brief explanation of the above powder feeders is provided in the following sections.

3.2.1.1 Gravity-Based Powder Feeder

The principle of operation of gravity-based powder feeders is similar to a simple sand clock. The powder feeder machine essentially consists of a load cell based electronic weighing mechanism and an orifice. Due to the weight, the material flows from hopper to the orifice if the powder particles have the required flowability. By reducing or increasing the area of the orifice, the amount of powder delivered to the nozzle decreases or increases. Figure 3.18 shows a schematic of a gravity-based powder feeder.

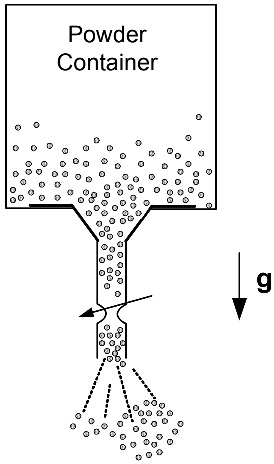


FIGURE 3.18
A schematic of gravity-based powder feeder.

In order to increase the controllability of gravity-based powder feeders, different devices such as a metering wheel can be integrated into the powder feeder. Also, a back pressure can be supplied on the powder funnel to increase the stability of the powder stream, which can be affected by the change in the height of powders in the funnel. Adding the external component for the measurement of powder is an essential device for obtaining a feed rate with high precision. One of these devices can be a rotating disk with holes around it as shown in Figure 3.19. The feeder machine consists of a powder container from which powder flows by gravity into a slot on a rotating disk. The powder is transported to a suction unit by a gas stream. The dimensions of the slot and the speed of the disk control the volumetric powder feed rate [139].

The other idea for integration of a metering wheel into a gravity-based powder feeder is shown in Figure 3.20. The size of holes around the rotating shaft and the angular velocity of the shaft determine the powder feed rate.

The other design can be an integration of a lobe gear with the gravity-based powder feeder as shown in Figure 3.21. This design is not suitable for an application requiring the low powder feed rate.

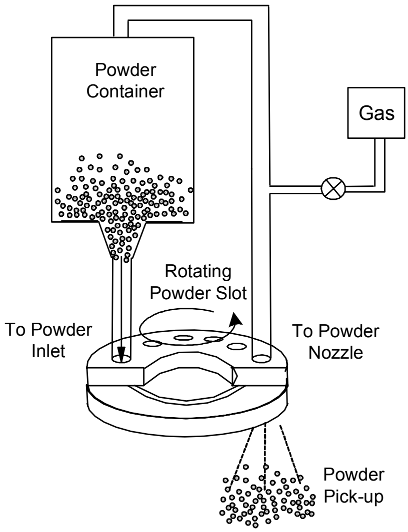


FIGURE 3.19
A typical gravity-based powder feeder with a rotating wheel for metering.

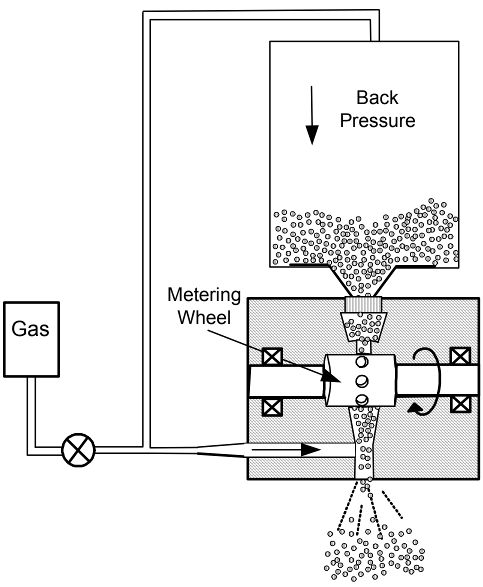


FIGURE 3.20
A typical gravity-based powder feeder with a metering wheel.

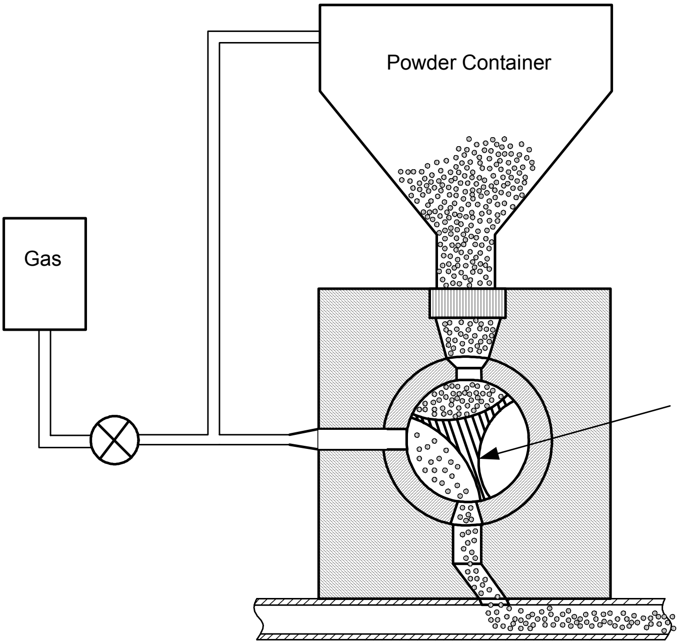


FIGURE 3.21
A typical gravity-based powder feeder with a lobe gear.

3.2.1.2 Mechanical Wheel Powder Feeder

Mechanical wheel powder feeders are also known as screw powder feeders. Mechanical wheel feeders handle a wide range of powders with different mesh sizes. They do not seal against an uncontrolled flow of fine powders and normally operate with zero or low-pressure differential between outlet and inlet. A typical mechanical wheel feeder has a pitch with different diameter ratio or a rotor which can grab powder particles from the storage area. There are many screw configurations that can be used to promote uniform flow with different feed rates. Figure 3.22 depicts two types of the configuration of mechanical wheel powder feeders.

One disadvantage of this type of powder feeder is the interaction of moving parts and abrasive powder particles, which cause rapid wear in the wheel. This can result in variations in coating quality and also increase maintenance costs.

3.2.1.3 Fluidized-Bed Powder Feeder

A fluidized powder feeder operates based on fluidics principle, which eliminates the need for mechanically moving parts to deliver powder. The fluidics

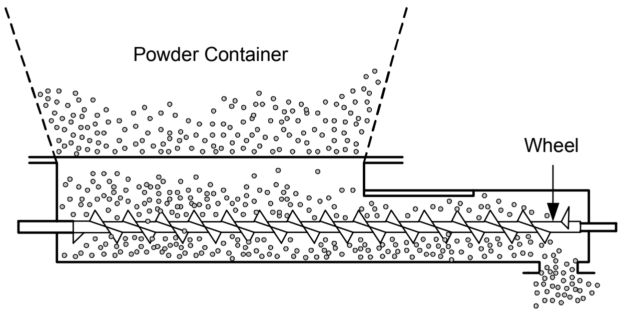


FIGURE 3.22
A schematic of mechanical wheel powder feeder.

powder feed delivery principle provides a continuous, non-pulsating feed of powder, thereby insuring the user optimum process control and improved coating quality. Another benefit is reduced maintenance and replacement part cost.

The system is designed so that a predetermined quantity of gas is delivered to a closed hopper containing powder. The hopper is constructed so that the gas is passed through a filter located at the bottom of the unit, where it is diffused through the powder, causing the powder to enter into the gas and therefore become fluidized. A powder pickup tube is positioned above the fluidizing gas inlet allowing the fluidized media to be delivered under a shed on the pickup tube through a number of controlled apertures and then to a carrier area where it is propelled by the carrier gas to the feed hose.

Figure 3.23 shows the construction of a fluidized-bed powder feeder.

3.2.1.4 Vibratory-Based Powder Feeder

A vibratory feeder, which is also called a vibratory tray feeder or oscillating feeder, consists of a shallow flat-bottomed tray. As powder flows from the hopper outlet onto the tray, an external drive vibrates the tray, throwing the powder down to control the powder feed rate into the process. A vibratory-based powder feeder can feed most powders from at least 8 g/min to 2000 g/min with $\pm 1\%$ precision.

In order to increase the precision, the vibratory powder feeder can consist of a vibrating tray with a number of plates set on a specified angle. Having these plates, the flowing of powder bulk can be controlled.

Figure 3.24 shows the construction of a vibratory powder feeder.

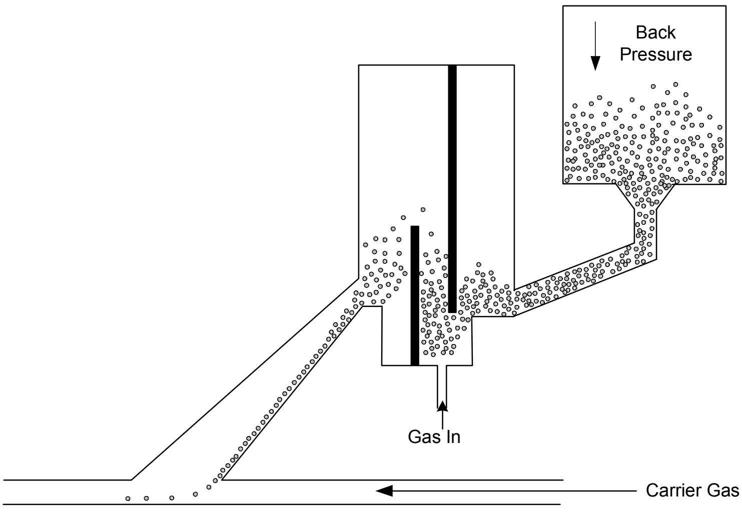


FIGURE 3.23
A typical fluidized-bed powder feeder.

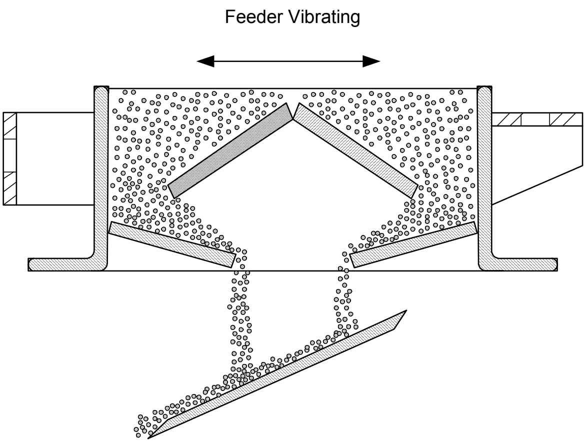


FIGURE 3.24
A schematic of a vibratory-based powder feeder.

TABLE 3.4
Powder feeder types of organizations/research groups involved in the laser cladding process.

Organization	Type of applications	Type of powder feeder	Used material	Ref.
University of Waterloo, Canada	Coating	Fluidized bed	H13, Iron-Aluminide	[3]
University of Waterloo, Canada	Prototyping	Gravity-based powder feeder along with metering wheel	H13, Ni-based alloys	–
NRC, Canada	Prototyping	Fluidized bed	316 SS, IN-625	[19]
University of Michigan, USA	Prototyping	Gravity-based powder feeder along with metering wheel	H13, Ti-based alloys	[14]
Sandia, USA	Prototyping	Fluidized bed	Ti-based alloys, SS	–
University of Missouri at Rolla, USA	Prototyping	Mechanical wheel powder feeder	H13	[141]
University of Liverpool, UK	Coating	Mechanical wheel powder feeder	Al, 316 SS	[144]

3.2.2 Applications of Powder Feeders to Laser Cladding

So far, different types of powder feeders have been used in the laser cladding process. However, it is hard to say which type of powder feeder is more suitable for this process. Due to the wide range of applications of laser cladding, different powders, with different mesh sizes at various powder feed rates are required for the process. Many research groups, which are developing the laser cladding apparatus, have designed and manufactured their own powder feeder which suits their applications.

As it was mentioned, it is impossible to convey every powder with a steady-state flow using a single feeder machine. As a result, various types of powder feeders have been developed for laser cladding to provide the smooth and steady flow in the required flow rates.

Table 3.4 lists several types of powder feeders, which are being used in laser cladding by different research groups and organizations.

3.2.3 Nozzles

In laser cladding by powder injection, the powder delivery nozzle can have different configurations as

- Coaxial

- Lateral

Basic layouts of these two nozzles are shown in Figure 3.25. The coaxial supply of powder can be integrated with the optical system [145, 146]. One of the advantages of a coaxial nozzle is its independence from the direction of motion; however, experimental work has shown that its powder efficiency, which is the ratio between the deposited powder on the substrate and the delivered powder by the powder feeder in a specified period, is significantly less than that of the lateral nozzle [145]. In both types, the powder can be preheated when it passes through the nozzle to increase efficiency.

Several forms of nozzles have been invented based on the above two mentioned nozzles. Islam et al. [20] invented a multiple nozzle processing head for manufacturing and repairing of turbine blades or compressor components. Jeantette et al. [139] invented a coaxial nozzle which is used for producing complex shapes. Their developed nozzle has been licensed to Sandia Corporation. Keicher et al. [147] invented a multiple beam and nozzle system to increase the deposition rate. Their developed nozzle and laser processing head has been currently licensed to Optomec Design Company.

The interactions of powder particles, the laser beam and the inert gas with the melt pool are important parameters for arriving at a good quality clad. The interactions of powder particles with different surfaces in the process zone may result in different impact phenomena as [148]

- Solid particles to solid surface impact causing a ricochet

- Solid particles or liquid particles to liquid surface of melt pool causing catchment

- Liquid particles to solid surfaces causing catchment

The adhesion behavior of powder particles on solid or liquid surfaces surrounded by turbulent streams have been carried out by Zimon [149].

The type of nozzle, the angle of powder stream with respect to a reference line, the powder profile in the process zone, and powder stream diameter in the melt pool area will influence the interaction of powder particles with surfaces. An appropriate nozzle is the one that provides the minimum solid particles with solid surfaces. Minimizing impact between the solid particles and solid surfaces increases the powder catchment efficiency.

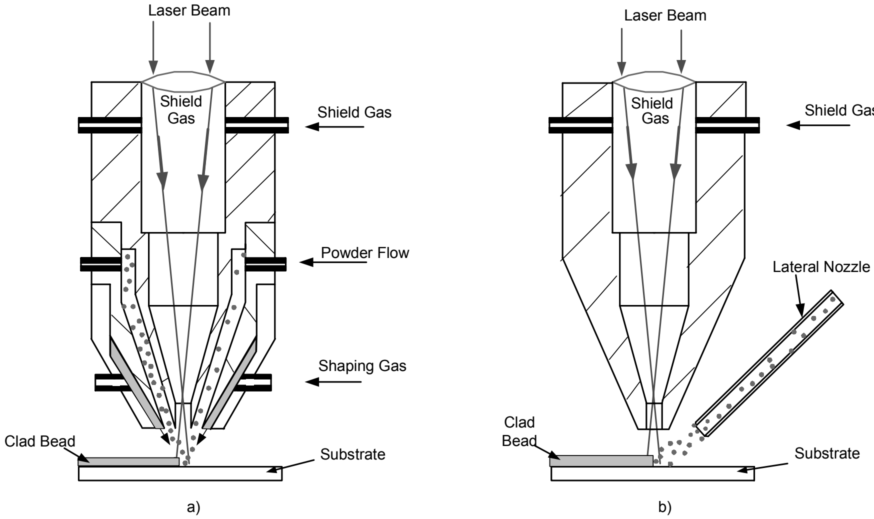


FIGURE 3.25
a) Coaxial nozzle, b) lateral nozzle.

3.2.3.1 Lateral Nozzle and Powder Profile Quality

The powder delivery system plays an important role in the clad quality. Regardless of the type of the nozzle, knowledge of the intersection of powder stream and laser beam, diameter of powder stream on the workpiece, stability of powder feed rate, homogeneous shape of powder profile and velocity of powder particles are crucial to a successful process.

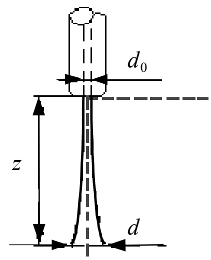
In order to address the effect of nozzle diameters on the above-mentioned parameters, a simple measurement test rig was developed to take pictures of the powder stream. The images were then processed to find the profile characteristics of the powder stream in terms of the distance from the tip of the nozzle. It was found that the profile of the powder stream can be approximated by a parabolic equation as

$$d = \lambda z^2 + d_0 \tag{3.14}$$

where d is the profile diameter at any z [mm], λ is the powder profile quality coefficient [1/mm], z is the distance of desired point from the nozzle tip [mm], and d_0 is the nozzle diameter [mm].

In the study, several nozzles of PRAXAIR with serial number of TWEP2250 with diameters of 0.8, 1, 1.2, 1.4 and 1.8 mm were used. Figure 3.26 shows the identified parameter corresponding to each nozzle. As it is seen in the table, λ is valid for a specific range, which represents the range of stable powder stream.

d = profile diameter at any *z* (mm)
d_0 = nozzle diameter (mm)
z = distance from the nozzle tip (mm)



Powder Feed rate (g/min)	Shield gas Feed rate (m^3/s)	$d_0 = 0.8\,mm$		$d_0 = 1\,mm$		$d_0 = 1.2\,mm$		$d_0 = 1.4\,mm$		$d_0 = 1.8\,mm$	
		λ (1/mm)	Valid for	λ (1/mm)	Valid for	λ (1/mm)	Valid for	λ (1/mm)	Valid for	λ (1/mm)	Valid for
1	1.56e-5	9.03e-3	$z<21$	1.27e-2	$z<24$	1.29e-2	$z<24$	1.62e-2	$z<29$	2.39e-2	$z<32$
1	2.34e-5	1.25e-2	$z<19$	1.45e-2	$z<21$	2.02e-2	$z<21$	2.05e-2	$z<25$	2.42e-2	$z<28$
1	3.12e-5	1.30e-2	$z<18$	1.98e-2	$z<20$	2.06e-2	$z<20$	2.17e-2	$z<23$	2.47e-2	$z<26$
1	3.9e-5	1.42e-2	$z<15$								
2	1.56e-5	1.04e-2	$z<21$	1.80e-2	$z<25$	1.92e-2	$z<25$	1.93e-2	$z<30$	2.16e-2	$z<30$
2	2.34e-5	1.20e-2	$z<18$	2.17e-2	$z<20$	2.41e-2	$z<20$	2.51e-2	$z<29$	2.23e-2	$z<29$
2	3.12e-5	1.24e-2	$z<17$	2.27e-2	$z<19$	2.45e-2	$z<19$	2.57e-2	$z<25$	2.42e-2	$z<25$
2	3.9e-5					2.46e-2	$z<18$	2.59e-2	$z<23$	2.58e-2	$z<23$

FIGURE 3.26

Powder feed profile characteristics/dimensions.

Figure 3.27 shows a typical powder stream for 1 mm nozzle. As seen, the powder stream is expanded due to the interaction between the air resistance and powder flow and finally is spread out in the space.

3.2.3.2 Coaxial Nozzle

The invention of the coaxial nozzle had a great impact in laser cladding technology. The first important feature of this nozzle is the path independence. Also, better powder efficiency can be obtained by this nozzle. In order to build the clad with accurate dimensions and high efficiency of the powder deposition in a coaxial laser cladding, it is essential to analyze the powder flow structure. In the coaxial nozzle, three streams are involved, which impinge on the solid surface. These are shield gas, powder stream and shaping gas, as shown in Figure 3.25.

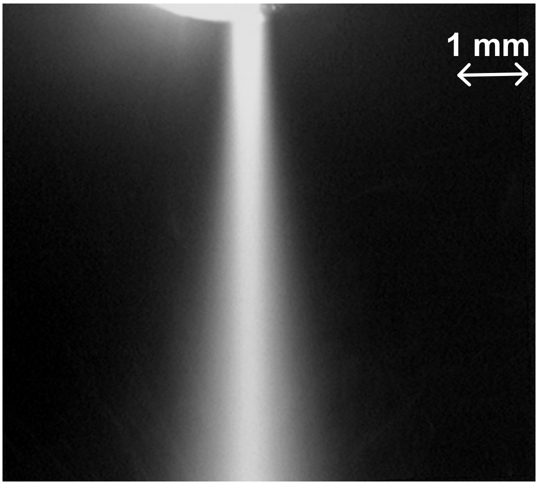


FIGURE 3.27
A typical view of a powder stream when nozzle diameter is 1 mm, powder feed rate is 2 g/min, and shield gas feed rate is $2.34e - 5$ m^3/s.

A powder stream is formed around the laser beam, which has to be distributed homogeneously. A homogeneous distribution of powder particles is a key factor in the formation of a good quality clad. It is essential to hold the powder stream in a laminar flow, parallel to the laser beam profile, to arrive at a homogeneous powder stream in the outlet of the nozzle [85].

To provide good powder efficiency and high quality clad, the powder stream's focus point must be at the level of the melt pool [85]. The role of the tip of the nozzle in formation of laminar or quasi-laminar flow of powder stream is also important. As seen in Figure 3.28, several nozzles with different tips are available, which provide different powder stream profiles and powder focus points.

Figure 3.29 shows the powder stream in exit of the coaxial nozzle connected to the end-effector of a robot. As seen, the powder profile has a homogeneous shape for a distance, and then spread out in the space.

3.3 Positioning Devices

Laser cladding can be used for a variety of applications, such as rapid prototyping, coating and repairing. For all of these applications, a solid model of the desired part is required. This model should be then sliced by a CAM soft-

FIGURE 3.28
Different coaxial nozzles with different tips (*Source*: Courtesy of Fraunhofer Institute for Material and Beam Technology, Germany [85]).

FIGURE 3.29
Coaxial nozzle connected to a robot end-effector (*Source*: Courtesy of Fraunhofer Institute for Material and Beam Technology, Germany [85]).

ware based on the trajectory planning algorithm to identify the required paths for fabrication or coating of the desired part. A positioning device should not only provide enough workspace and maneuverability for the required paths, but also provide the appropriate velocity, which is a major process parameter.

The positioning device can be a CNC table or a multi-DOF robot manipulator. In both cases, the dynamics constraints should be carefully considered to arrive at desired velocities and accelerations in different points of trajectory. Also, in the case of a robot, the singularity of the robot's joints is another main constraint for developing the desired trajectory. The singularity will happen if one or more joints no longer represent independent controlling variables, causing a limitation on the workspace of the robot. As a result, fabrication of a complex shape using laser cladding, where a robot is selected as a positioning device, strongly depends on the DOF and kinematics of the selected robot.

In general, the number degrees of freedom plays an important role in a positioning device used in laser cladding. In fabrication of complex shapes, it is necessary to deposit the layer in a non-planar fashion. Having said that, the higher degree of freedom provides the capability of non-planar motion.

Process speed of a laser cladding process varies from 1 mm/s to about 20 mm/s based on the laser power and powder feed rate available. As a result, the dynamic of any positioning device selected for the process should meet the desired range of velocity.

In fabrication of parts, the paths trajectories are extracted through a CAD/CAM software. This program provides a sequence of discrete points representing the desired paths, which are then fed into the motion controller. As a result, a positioning device should be controlled through a point-to-point (PTP) control mode, as long as the speed is also tunable at any time during the motion. This method of control can encounter an oscillatory motion. To overcome the oscillatory motion, many different motions' algorithms have been developed. For instance, a trapezoidal velocity profile is used in a high efficient algorithm. The slope of such a curve at the initial and final ramp are the maximum acceleration and deceleration. The top level of the trapezoid is the maximum velocity. This kind of profile gives a continuous acceleration, but there might exist jerks in the motion [150]. The algorithm, which is based on trapezoid velocity, is called PVT (position, velocity, and time). This algorithm is based on a second-degree polynomial of trajectory over the time. Figure 3.30 shows such an example with the desirable velocities at different positions which are depicted by the slope of the arrows. The dashed line provides a feasible trajectory that satisfies these position-velocity constraints.

As seen in the figure, a trajectory can be simply described by expressing the position and velocity as a function of time. However, in the laser cladding process, velocity is an independent variable of time. This issue arises from the fact that the process speed should be changed during the laser cladding process to overcome the influence of disturbances in the process. The changes in the process speed should not, however, affect the pre-specified trajectory.

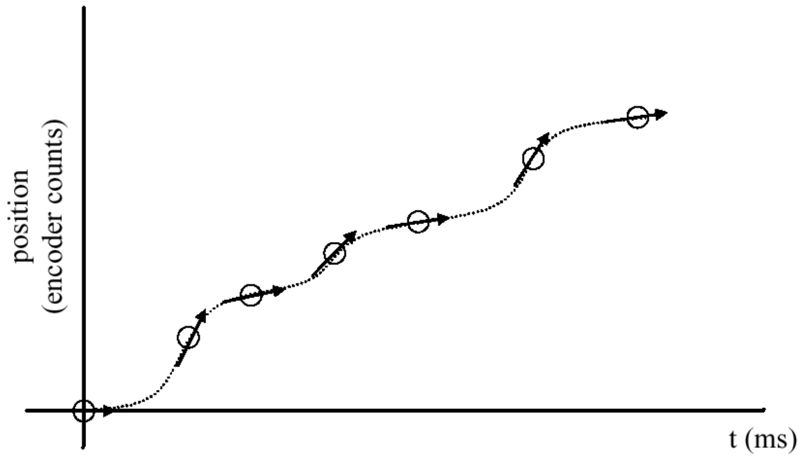


FIGURE 3.30
A typical position-velocity trajectory.

This type of motion results in infinite solutions. As a result, a method of approximation needs to be taken. A possible approximation or constraint on the motion system is to have a constant acceleration between consecutive points. Using piecewise interpolation, a feasible trajectory can be given in terms of series of second-degree polynomials such as $p_1(t)$, $p_2(t), p_3(t)$, etc.

Assuming the terms are in a second degree of polynomial, the trajectory can be represented as

$$p(t) = at^2 + bt + c \tag{3.15}$$

Therefore, the velocity will turn into

$$v(t) = 2at + b \tag{3.16}$$

where a, b, and c are constant coefficients. Having the positions and velocities at initial time of t_0 and t_1 (which represents two successive points) provides four equations, which are enough to obtain four unknowns $a, b, c,$and t_1.

Performing the above analysis iteratively for all position-velocity points results in a trajectory with a smooth velocity.

3.3.1 CAD/CAM System for Trajectory Generation

Like other rapid-prototyping processes, laser cladding is a way to fabricate a three-dimensional object designed with a computer aided design (CAD) software. Most existing prototyping processes are adapted into slicing technology, in which a CAD model is represented by a stack of flat and thin layers.

In many layered manufacturing methods, such as stereolithography, all points on each layer are deposited in a one-step growing procedure; however, in prototyping by laser cladding, each sliced layer should be resliced into paths, which represent the trajectory of the end-effector. This re-slicing is due to the nature of laser cladding for producing layers. In fact, by overlapping the clad's tracks, a thin and flat layer of the final part can be produced.

3.3.1.1 CAD Formats

Several CAD model formats are available for developing 3D objects in a computer. The most popular formats are IGES, SAT, DXF, STP and STL.

IGES, which stands for "initial exchange specification" is an ANSI standard that defines neutral file format for the exchange of CAD drawings or models in different CAD programs. Due to its comprehensive structure, it is not commonly used by low-end CAD software. Instead, it is most common among expensive high-end CAD software [151]. IGES does not support solid models. Although IGES files can be relatively large, they are very well compressible.

SAT, which stands for "standard ACIS text" is also called ACIS. It has been supported by many solid model programs. SAT can store modeling information in external files. These files have an open format such that external applications, even those not based on ACIS, can have access to the ACIS geometric model, which is one of the most important advantages of this format. SAT files are ASCII text files that may be viewed with a simple text editor. A SAT file contains carriage returns, white space and other formatting that makes it readable to human eyes [151]. As with other solids translators, the SAT translator does not include the history tree, which is used to create the solid model.

DXF, which stands for "drawing exchange format", is one of the properties of AutoCAD® company. DXF is probably one of the most widely supported vector formats in the world today. DXF files are relatively easy to parse since they are tagged and text based, and therefore human readable. Tagged data means that each data element in the file is preceded by an integer number that is called a group code. A group code's value indicates what type of data element follows. This value also indicates the meaning of a data element for a given object (or record) type. Virtually all user-specified information in a drawing file can be represented in the DXF format [151].

STP, which stands for "STEP", is an emerging format. This format, not only includes the drawing points, facet and geometry, but also a large amount of machining information, including the model, material and tool information. Although this format is anticipated to become more widespread in the future, it is not currently used as widely as other formats, such as IGES. In addition, most packages that currently output STP files do not output all of the associated information that STP is intended to support [151].

STL, which stands for "stereolithography", is an ASCII or binary file used in manufacturing. It is a list of triangular surfaces that describe a computer-

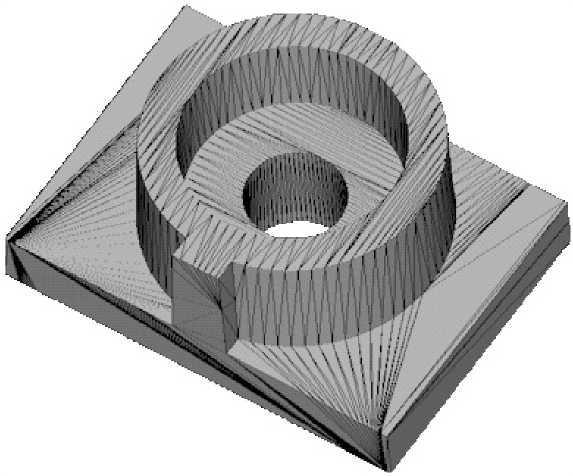


FIGURE 3.31
A typical STL file, in which the density of triangle facets change according to the geometry (STL file is generated by MATLAB).

generated solid model. It is composed of triangular facets of data that represent 2D and 3D shapes. This is the standard input for most rapid prototyping machines. Although STL files represent 3D shapes, they do not actually contain the surface or the solid model data. In addition, STL files can be very large if a small tolerance is required [151].

Among these mentioned formats, STL format has been widely adapted with layered manufacturing. An STL file consists of a list of facet data. Each facet is uniquely identified by a unit normal (a line perpendicular to the triangle and with a length of 1.0) and by three vertices (corners). The normal and each vertex are specified by three coordinates each, so there is a total of 12 numbers stored for each facet. More technical details of the STL file format have been given in [152]. Figure 3.31 shows a typical STL file, which the density of triangle facets changes according to the geometry.

3.3.1.2 Slicing Technology

Slicing technology is formed to serve the needs of layered manufacturing technologies. Several trajectory planing algorithms have been developed to produce the required paths. In many of them, regardless of the part geometry or process used to produce the part, the slice thickness remains constant. Under this strategy, a given solid model is sliced horizontally into a set of planar layers, and these planar layers are then built one at a time from bottom up. In this case, planning the build sequence of a given model is no more than

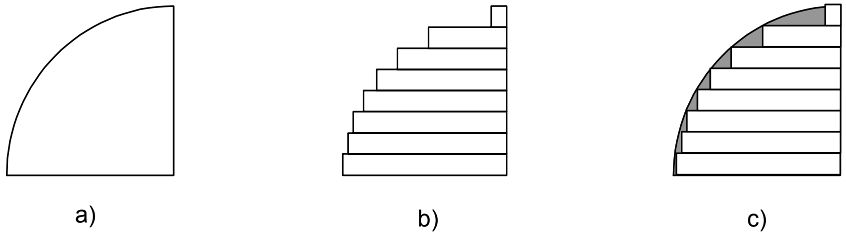


FIGURE 3.32
a) Desired solid model, b) layered part, c) layering error.

listing the sliced layers along the build direction, which is straightforward and can be automated easily. However, several issues limit the application of this technology. First, parts built by this technology generally show stair steps on the layer-to-layer boundaries [153]. Figures 3.32 shows the layering errors due to the regular slicing technology. This lack of continuity on the part surfaces is undesirable especially for parts made of ceramic materials, because each stair step can serve as a crack initiation point. In addition, the mechanical properties of parts will be affected by the bonding between layers. It has been reported that reducing the number of layers by increasing the slicing interval can improve the mechanical properties. However, the surface polishing of the fabricated parts may become worse as the interval between layers becomes larger. As a result, a trade-off has to be made case by case [32, 154].

Slicing the layers in a fixed thickness fashion does not usually conform to the part geometry, therefore, the slice thickness may be changed manually, which increases the production time and sacrifices the part quality. As a result, researchers have developed algorithms that allow the slice thickness to be adapted as a function of both the CAD model geometry and the process used to produce the part. This method is called adaptive slicing technology. By incorporating the geometry (the slope and curvature) of the part with the characteristics of the forming process, the optimum slice thickness is automatically selected. By merging these characteristics, the optimum slice thickness is automatically selected without human intervention. In using the algorithm, the surface texture can be controlled, production time decreases, the part quality increases, and the slicing process becomes more efficient [155].

In laser cladding, the deposition path generation is dependent on the nature of the deposition process. Deposition of paths in each layer which have fine and homogeneous distributed clad are somewhat independent of geometric complexity. Also, the properties of the deposited material are influenced by the deposition path trajectory. Thus it is important to develop an appropriate path planning to reduce the path effect on the mechanical and metallurgical characteristics of the parts. Also, one of the factors that limits the quality of parts in laser cladding is the accumulation of residual thermal stresses. It might be possible to reduce this effect by selecting an appropriate deposition path.

In general, several factors will affect the type of deposition path, which are:

- **Thermal stress:** Thermal stress accumulates if there is an unbalanced heating in the surface. Therefore, if the deposition path is not symmetrical, it will result in thermal stress.

- **Number of clad's tracks:** If there are many discontinuous deposition tracks, the laser shutter should be switched on and off between different tracks. It is desired to reduce the number of activation of shutter in the process.

- **Robustness**: The deposition paths should be robust enough to be generated irrespective of the complexity of the geometry.

- **Non-planar material deposition:** Redepositing the same points in the path should be avoided as this will result in extra material deposition causing the associated reheating. Therefore, a non-planar coating may overcome this shortcoming especially for fabrication of curved shape.

- **No gaps in the path:** Having gaps will result in low quality parts. As a result, the deposition path should be continuous as much as possible.

The above items make the deposition path generation a more constrained problem compared to regular cutting manufacturing and therefore alerts a different approach. The deposition paths are generated for the 2-D cross section obtained by the XY projection of the object. These cross sections have to be set by a certain distance before generating the deposition paths.

The deposition paths are classified into two classes:

- **Zigzag paths**: The path tracks correspond to back and forth motions in a fixed direction within the boundary of the 2-D cross section (see Figure 3.33a).

- **Spiral paths**: The path comprises of a series of contours that are parallel to the boundary of the 2-D cross section (see Figure 3.33b).

It is possible to arrive at a variety of deposition path patterns from these two classes. Some research groups have studied the influence of these two classes of paths in the microstructure of the final product. Hua et al. [16] showed that the pore/void level can be well suppressed by proper design of deposition tool-path. Figure 3.34 shows different tool trajectories which are used to fabricate a cubic components. They showed that the level of porosity/void may be increased especially in the case of zigzag-xy tool-path. That is due to irregular surfaces caused by clad track.

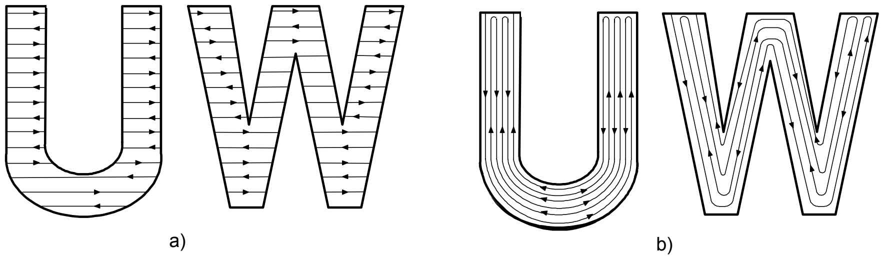


FIGURE 3.33
Different path patterns for fabrication of a logo (UW): a) zigzag paths, b) spiral paths.

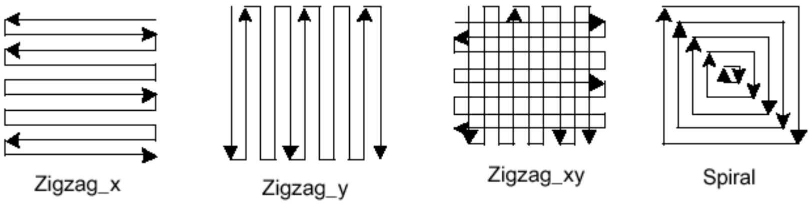


FIGURE 3.34
Different tool trajectory patterns used for fabrication of a cubic component (*Source*: Courtesy of Professor J. Choi, Department of Mechanical and Aerospace Engineering and Engineering Mechanics, University of Missouri at Rolla).