Chapter 34

LASER MATERIALS PROCESSING

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(1)34.1 OVERVIEW

LASER is the acronym of *light amplification by stimulated emission of radiation*. Although regarded as one of the nontraditional processes, *laser material processing* (LMP) is not in its infancy anymore. Einstein presented the theory of stimulated emission in 1917, and the first laser was invented in 1960. Many kinds of lasers have been developed in the past 43 years and an amazingly wide range of applications—such as laser surface treatment, laser machining, data storage and communication, measurement and sensing, laser assisted chemical reaction, laser nuclear fusion, isotope separation, medical operation, and military weapons—have been found for lasers. In fact, lasers have opened and continue to open more and more doors to exciting worlds for both scientific research and engineering.

Laser material processing is a very active area among the applications of lasers and covers many topics. Laser welding will be discussed in a separate chapter. In this chapter, laser machining will be discussed in detail while other topics will be briefly reviewed. Some recent developments, such as laser shock peening, laser forming, and laser surface treatment, will also be reviewed to offer the reader a relatively complete understanding of the frontiers of this important process. The successful application of laser material processing relies on proper choice of the laser system as well as on a good understanding of the physics behind the process.

(1)34.2 UNDERSTANDING OF LASER ENERGY

34.2.1 Basic Principles of Lasers

Lasers are photon energy sources with unique properties. As illustrated in Fig. 34.1, a basic laser system includes the laser medium, the resonator optics, the pumping system, and the cooling system. The atomic energy level of the lasing medium decides the basic wavelength of the output beam, while nonlinear optics may be used to change the wavelength. For example, the basic optical frequency of the neodymium-doped yttrium aluminum garnet (Nd:YAG) laser at 1.06 μm wavelength may be doubled or tripled by inserting nonlinear crystals in the resonator cavity, getting the wavelengths of 532 nm and 355 nm. The lasing mediums, such as crystals or gas mixtures, are pumped by various methods such as arc light pumping or diode laser bar pumping. Population inversion occurs when the lasing medium is properly pumped, and photons are generated in the optical resonator due to stimulated emission. The design of the optical resonator filters the photon energy to a very narrow range, and only photons within this narrow range and along the optical axis of the resonator can be continuously amplified. The front mirror lets part of laser energy out as laser output. The output beam may pass through further optics to be adapted to specific applications such as polarizing, beam expansion and focusing, and beam scanning. The in-depth discussion of the principles of lasers can be found in Ref. 1, information on common industrial lasers can be found in Refs. 2 and 3, a web based tutorial on laser machining processes can be found in Ref. 4, and mounting literature on laser material processing can be found from many sources.

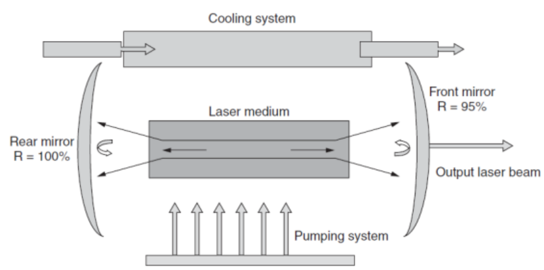

Figure 1: Illustration of a basic laser system.

Understanding the physics in laser material interaction is important for understanding the capabilities and limitations of these processes. When a laser beam strikes on the target material, part of the energy is reflected, part of the energy is transmitted and part of it is absorbed. The absorbed energy may heat up or dissociate the target materials. From a microscopic point of view the laser energy is absorbed by free electrons first, the absorbed energy propagates through the electron subsystem, and then is transferred to the lattice ions. In this way laser energy is transferred to the ambient target material, as illustrated by Fig. 34.2. At high enough laser intensities the surface temperature of the target material quickly rises up beyond the melting and vaporization temperature, and at the same time heat is dissipated into the target through thermal conduction. Thus the target is melted and vaporized. At even higher intensities, the vaporized materials lose their electrons and become a cloud of ions and electrons, and in this way plasma is formed. Accompanying the thermal effects, strong shock waves can be generated due to the fast expansion of the vapor/plasma above the target.

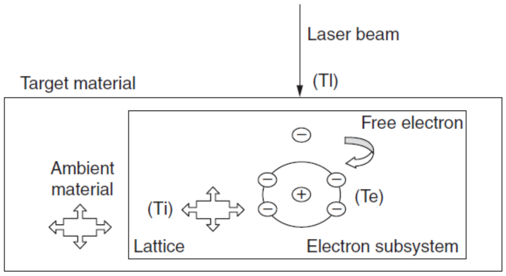

Figure 2: Laser energy absorption by target material.

Given the laser pulse duration, one can estimate the *depth of heat penetration*, which is the distance that heat can be transferred to during the laser pulse.

$$D = \text{sqrt}(4 \times alfa \times dT)$$

where D is the depth of heat penetration, *alfa* is the diffusivity of materials, and dT is the pulse duration. Laser energy transmission in target material is governed by Lambert's law:

$$I(z) = I_0 \times \exp(-a \times z)$$

where I is laser intensity, I_0 is the laser intensity at the top surface, z is the distance from the surface, and a is the absorption coefficient that is wavelength dependent. Metals are nontransparent to almost all laser wavelengths and a is about 100,000 cm^{-1}, which implies that within a depth of 0.1 μm, laser energy has decayed to 1/e of the energy at the surface. Many nonmetals such as glasses and liquids have very different a values. Laser-material interaction thus can be surface phenomena when the laser pulse duration is short and when the material has rich free electrons. Laser energy may also be absorbed over a much larger distance in nonmetals than in metals during its transmission.

When considering the laser power in material processing, the effective energy is the portion of energy actually absorbed by the target. A simple relation for surface absorption of laser energy is: $A = 1 - R - T$, where A is the surface absorptivity, R is reflection, and T is transmission. For opaque material, $T = 0$, then $A = 1 - R$.

It's important to understand that reflection and absorption are dependent on surface condition, wavelength, and temperature. For example, copper has an absorptivity of 2 percent for CO_2 lasers (Wavelength = 10.6 μm), but it has much higher absorptivity for UV lasers (about 60 percent). Absorption usually increases at elevated temperatures because there are more free electrons at higher temperatures.

(1)34.2.2 Four-Attributes Analysis of the Laser Material Processing Systems

Laser material interaction can be very complex, involving melting, vaporization, plasma and shock wave formation, thermal conduction, and fluid dynamics. Modeling gives the in-depth understanding of the physics in the study of laser material processing processes. Many research centers are still working on this task and volumes of books and proceedings are devoted to it. We won't cover modeling in this chapter, but as a manager or process engineer, one can get a relatively complete picture of the laser material processing system following the *four-attributes analysis*—time, spatial, magnitude, and frequency.[4]

Time Attribute. Laser energy may be continuous (CW) or pulsed, and laser energy can be modulated or synchronized with motion. For CW lasers, the average laser power covers a wide range, from several watts to over tens of kilowatts, but their peak power may be lower than pulsed lasers. CW lasers may be modulated such as ramping up or ramping down the power, shaping the power, or synchronizing the on/off of the shutter with the motion control of the system. The common range of pulse duration is in the ms level, and the smallest pulse duration is normally larger than 1 μs. CW lasers can operate in pulsed mode with the shutter in open/close position. Despite these quasi-pulsed modes, the laser is still operating in CW mode inherently, in which lasing is still working in CW mode. No higher peak power than CW mode is expected normally. For a CW laser one should understand its capability of power modulations, focusing control, and energy-motion synchronization.

There are many types of pulsed lasers. The major purpose of pulsating the laser energy in laser material processing is to produce high peak laser power and to reduce thermal diffusion in processing. Taking Q-switched solid-state lasers for example, lasing condition of the cavity is purposely degraded for some time to accumulate much higher levels of population inversion than continuous mode, and the accumulated energy is then released in a very short period—from several nanosecond (10^{-9} s) to less than 200 ns. Even shorter pulse durations can be achieved with other techniques as discussed in Ref. 1. Lasers with pulse duration less than 1 ps (10^{-12} s) are referred as *ultrashort pulsed lasers*. Pulsed lasers have wide range of pulse energies, from several nJ to over 100 J. These pulses can be repeated in certain frequencies called the *repetition rate*. For pulsed lasers, basic parameters are the pulse duration, pulse energy, and repetition rate. From these parameters, peak power and average power can be calculated. Similar to CW lasers, one should also understand the capability of power modulations, focusing control, and energy-motion synchronization for pulsed lasers. Peak laser intensity is the pulse energy divided by pulse duration and spot irradiation-area. Due to several orders of pulse duration difference, pulsed laser can achieve peak laser intensities $>>10^8$ W/cm^2, while CW lasers normally generate laser intensities $<10^8$ W/cm^2.

Spatial Attribute. Laser beam out of a cavity may have one or several modes, which are called *transverse electromagnetic mode* (TEM) . For laser material processing, we are concerned with the spatial distribution of the beam that affects the thermal field on the target. Laser intensity usually has a Gaussian beam distribution. For Gaussian beam with beam radius r and for a material with absorption $A = 1 - R$, where R is the reflectivity and $P(t)$ is the time dependent laser power, the spatial distribution of absorbed laser intensity on the target surface is:

$$I(x, y, t) = (1 - R)I_0(t)\exp(-(x^2 + y^2)/r^2)$$

Where $I_0(t) = 2P(t)/(\pi r^2)$, is the average laser intensity. Laser energy distribution may take other shapes, such as flat-hat shape, in which the laser intensity at the center is uniform. In general, the formula for laser energy transmitted to the material at depth z is:

$$I(x, y, z, t) = A \times I_0(t)\exp(-a \times z)SP(x, y)$$

where A = fraction of laser energy absorbed by the material at the surface

$I_0(t)$ = temporal distribution of laser intensity

a = absorption coefficient

SP = spatial distribution of laser intensity

Special optics can be used to change the beam shape and spatial distribution. For example, the beam can be changed from circular to square and uniform.

Laser beam radius is normally defined as the distance from the beam center within which 86.4 percent or $(1 - 1/e^2)$ of total energy is included. Beam radius at the focus is called the *focused spot size*. Frequently spot size variation with standoff distance (the distance from the focusing lens to the target) is needed. For lower intensities, laser energy profiler can be used to directly measure the intensity distribution. The laser beam size close to the focus is usually difficult to measure directly, especially for cases when the focused spot size is below tens of microns or when the laser power is high. One crude solution for high-power lasers is to measure the diameter of laser burnt holes in suitable thin sheet material. For a Gaussian beam, a more accurate solution is to combine experimental measurements with optical calculations. The spot size at large defocus can be measured either by the profiler or the knife-edge method. More than three measurements at different locations are measured to obtain (Z_n, D_n), $n = 1, 2, 3, \ldots$, where D_n is the beam size at location Z_n. The propagation of laser beams in air satisfies the following equation:

$$D_n^2 = D_0^2 + \left(\frac{4M^2\lambda}{\pi}\right)^2 \frac{(Z_n - Z_0)^2}{D_0^2}, \qquad n = 1, 2, 3, \ldots$$

where D_0 is the beam waist, Z_0 is the beam waist location, and M^2 is the beam quality parameter. Knowing (Z_n, D_n), D_0, Z_0, and M^2 can be determined. Then one can calculate the spot size at any location along the optical axis. Knowing M^2, one can also calculate the beam divergence and *depth of focus* (DOF). Depth of focus is the range of distance over which the spot size changed from the focused spot size by 5 percent. Figure. 34.3 illustrates the propagation, the beam waist, and the DOF of laser beam.

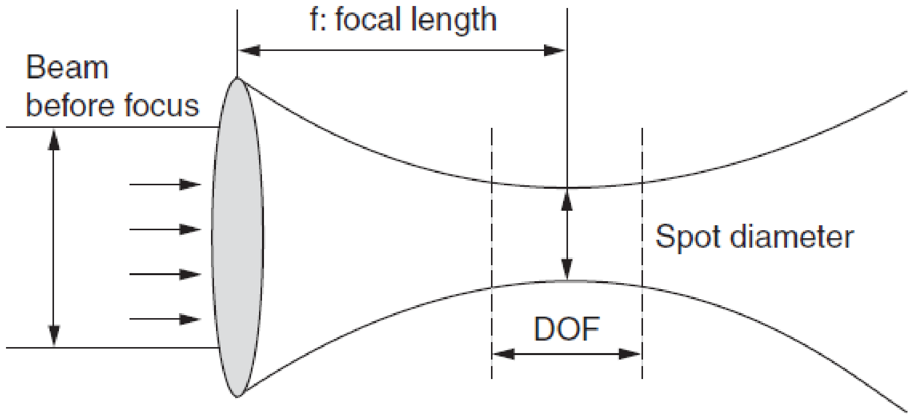

Figure 3: The DOF of laser light.

Laser intensity changes with defocus. Laser material processing is claimed noncontact because the highest intensity is at the focus while laser optics are some distance away from the target. It is not always convenient to change the focus in processing. The limited depth of focus limits laser machining to relatively thin materials (usually <15 mm).

In material processing, one can move the beam while keeping the part fixed, or move the part on a stage while keep the beam fixed, or move both of them. An XY or XYZ motorized stage is commonly used. Laser beams can be quickly scanned across specified locations by computer controlled reflection optics. This makes high-speed marking or drilling possible. The spatial resolution of laser material processing is influenced by the focused spot size. Shorter wavelength lasers are thus used for precision machining tasks.

Magnitude Attribute. Major magnitude parameters of laser energy are power (unit: watt), pulse energy (unit: Joule), and intensity (unit: W/m^2 or W/cm^2). The average power of laser is relatively low compared to other energy sources: over 1 kW is already regarded as high-power, and a pulsed laser normally has an average power of less than 100 W. The strength of laser energy is that it can have very high local energy intensity, and this intensity can be well controlled in time, space, and magnitude.

When the interaction between energy field and target is not continuous, energy intensity is usually the deciding factor. Depending on the laser type, laser pulse energy can be varied from below 10^{-9} J to far over 1 J, the spot size can be varied from sub-microns to over 10 mm, and pulse duration can be varied from several fs (1 femtosecond (fs) = 10^{-15} s) to over 1 s. For pulsed lasers, the laser intensity is equal to $E_0/(t_p \times pi \times R^2)$, where E_0 is pulse energy, t_p is pulse duration, and R is beam radius. For laser pulse energy of 0.1 J, if the pulse repetition rate can vary in the range from 1 Hz ~ 4 kHz, then the average power is 0.1 ~ 400 W. Let's vary the pulse length and the acting area and compute the peak intensity. With R = 0.5 μm, peak intensity of a 10 fs pulse is 10^{22} W/cm^2, the intensity of a 10^{-6} s pulse is10^7 W/cm^2 and the intensity of a 0.001 s pulse is only 10^4 W/cm^2. It is clear that laser intensity can be flexibly controlled to achieve a very wide range of laser intensities.

Depending on the absorbed laser intensity, different physical phenomena are involved. Applications at various laser intensities and deposition times are briefly shown in Table 34.1.

Applications	Intensity (W/cm^2) and laser material interaction
Laser surface transformation hardening, laser forming, laser assisted machining, etc.	<10^5 W/cm^2, target heated below melting temperature, phase transformation may occur that can harden the material, elevated temperature can soften the material. Pulse duration >10^{-3} s, CW lasers are used.
Laser welding, laser cladding and alloying, rapid tooling, and laser machining	From 10^6 W/cm^2 to 10^8 W/cm^2, material melts, some vaporization and plasma formation possible. Pulse duration normally >10^{-3} s. CW lasers are used.
Higher intensity laser machining—marking, grooving, drilling, and cutting	From 10^7 W/cm^2 to 10^9 W/cm^2, material melts and strong vaporization occurs, shock wave and plasma formation possible. Pulse duration normally <10^{-3} s, 10^{-9} to 10^{-6} s pulse duration are common, while for micromachining even shorter pulses are used. CW lasers or pulsed lasers are used.
Laser shock processing, laser surface cleaning	Intensity >10^9 W/cm^2 and pulse duration <10^{-7} s, very intense surface vaporization induces strong shock pressure toward the target.

Table 1: Applications of Lasers in Material Processing

Many material properties such as thermal conductivity and reflectivity vary with material temperature and state, which are further decided by the magnitude of energy input. We tacitly assume that only one photon is absorbed by one electron at a specific time at normal laser intensities, but when the laser intensity is extremely high as in the case of ultrafast lasers (pulse duration <10^{-12} s), more than one photon can be absorbed by one electron simultaneously. This is termed as multiphoton absorption. Material optical property is then highly nonlinear and is very different from single photon absorption. Material can act as if it were irradiated by a frequency doubled or tripled laser source. In this meaning, we can say that extremely high magnitude of laser intensity can be equivalent to shorter wavelengths.

Optical filters, polarizers, attenuators, and beam expanding and focusing systems can be used to modulate laser intensity and intensity spatial distribution so that one can match the laser output to a specific application without disturbing the internal laser source.

Frequency Attribute. The characteristic frequency of energy field is important because materials may respond very differently to energy fields at different frequencies. The characteristic frequency of laser is its EM oscillation frequency, and more frequently we use its equivalence—wavelength. The frequency decides the individual photon energy of the laser beam. Lasers usually have very narrow spectral width, while other energy sources may have very broad and complex spectral distributions.

The diffraction limited spot size is proportional to wavelength. For circular beams, the focal spot size is: $Dmin = 2.44f \times \lambda/D$, where f is the focus length, λ is wavelength, and D is the unfocused beam diameter. Thus for high-precision applications, shorter wavelength lasers are preferred. UV laser ablation of organic polymers can be very different in mechanism compared to infrared or visible laser ablation. The infrared and visible laser ablation is mainly photo-thermal degradation, while UV laser ablation may involve direct photo-chemical dissociation of the chemical bonds.

Materials show very different absorption properties at different wavelengths. Metals tend to have low absorption at far infrared (CO_2 laser 10.6 μm) while absorption increases with decreasing wavelength. Nonmetals such as ceramics and liquids have strong absorption at far infrared, much decreased absorption at visible wavelengths, and increased absorption at UV. At deep UV (some people call it *extreme UV*), almost any material has very strong absorption. That's why different materials may need to use lasers at different wavelengths for high energy coupling efficiency.

Keep in mind that absorption also depends on temperature, purity, and surface condition. Thin layers of black coating can be used to increase the energy coupling of CO_2 laser into metals. Defects or impurity in a transparent media may strongly absorb laser energy and thus create a local thermal point and finally break down the transparent condition. Also keep in mind that at high enough laser intensity, multiphoton absorption may occur, material reacts nonlinearly to the irradiation, and the beam acts as if its frequency is doubled or tripled. And once the surface temperature rises, absorption tends to increase, which forms a positive feedback. In this meaning, very high laser intensity may be regarded as wavelength-independent in material processing.

In general, the four attributes analysis can be applied to other energy forms. From here one can see the advantages and the limitations of a process and realize that many things are relative rather than absolute, such as the energy coupling efficiency and wavelength. Laser material processing can be very complex and modeling work is still actively going on around the world to better predict the process. Caution should be used when collecting the material properties from literature. In laser material processing, material properties are highly temperature-, wavelength-, geometry-, and intensity-dependent.

(1)34.3 LASER SAFETY

Lasers used in material processing are usually high-power lasers that may inflict hazards to both the operator and the visitor. Strict safety rules must be followed to prevent such potential hazards. Once proper safety practices are followed, laser material processing is as safe as other material processing techniques.

The most common danger is the damage to the eye. Laser light, even at very low power level, can be much brighter than normal light sources. Laser light can be focused into smaller spot sizes by the lens structure of human eyes. Light in the range of 0.4 to 1.4 μm can be focused on the retina and cause damages, while light in the far infrared can cause thermal damage of the cornea. There are three major cases of eye damage. The first is the direct beam damage in which the eye is within the light path. Since the beam is collimated, this is extremely dangerous. This usually happens during laser alignment. The second case is the specula beam damage in which case light from reflective surfaces is reflected into the eye. The reflected light can still be collimated and is as dangerous as the direct beam. Mirrors, metal surfaces, or even a wristwatch, and the like can all be the potential reflective surfaces that cause specula beam damage. The third is the diffusely reflected beam. These beams are usually diverged and are less dangerous than the previous two cases. But for high-power lasers used in material processing, even the diffusely reflected beams can cause damage to the eye and skin.

Laser beams may do harm to skin in the form of skin burning. CW high-power lasers and pulsed lasers are especially dangerous for the skin, and even a short exposure in the beam can cause serious skin burning. Specula and stray beams are also dangerous in the case of high-power lasers. Skin absorption of laser energy is wavelength and intensity dependent. Far infrared and UV light are well absorbed while visible light has relatively higher reflection and transmission. For this reason, high-power CO_2 lasers are more dangerous than Nd:YAG lasers at the same power level.

There are other potential hazards associated with laser material processing. Some of these risks are electric shock from the laser power supply, possible explosion of the pumping arc light tube, leakage of the gases and liquids used in laser system, and possible toxic vapor or powder in material processing, and the like.

Due to the potential risks in laser material processing, installation of laser material processing system should be guided by the laser safety officer, only trained and qualified personnel should be allowed to operate lasers, and safety procedures must be followed in both laser operation and laser component disposition.

Some good practices are:

Never put your eyes in the beam path.

Wear coats and suitable safety goggles in laser processing.

Minimize the hazards of reflected light: try to contain the laser light.

Post warning signs and warning signal.

Restrict access, install interlock systems and flash light to prevent accidental intrusion into the dangerous working zone.

Try to have at least two people in the processing.

Have emergency treatment close by.

Routinely check the eye and skin health of the operator.

Report any accident immediately and treat it seriously.

Laser safety eyewear is applicable only to specified wavelengths, and is not assumed to apply to those out of that range. Even under the protection of the safety eyewear, one should never look into the laser beam directly. Laser safety eyewear is specified by the *optical density* (O.D.) numbers which are defined as O.D. = $\mathrm{Log}_{10}(I_0/I_1)$, in which I_0 is the incident light intensity and I_1 is the transmitted light intensity. Thus the higher the O.D. number the higher the decay. An O.D. of 8 at 1.06 μm means 10^8 times decay of the incident light at 1.06 μm wavelength.

ANSI standard developed by the Z-136 Committee of America National Standard Institute is the most widely accepted laser safety standard.[13] *Maximum permissible exposure* (MPE) levels to laser light, laser safety classification, and definition of safety practices for each kind of laser are included. According to the ANSI standard, lasers are divided into four classes.

- *Class 1 laser*. Laser irradiation exposure is below the levels in which harmful effects will occur. Examples are CW He-Ne laser with power much less than 10 μW Class 1 laser can also be a high-power laser that is interlocked in such a manner that the user cannot access the beam.
- *Class 2 laser*. They are low-power visible lasers that do not have enough output power to injure a person accidentally, but may produce retinal injury when stared at for a 1000 s exposure. Examples are mW level He-Ne and Argon lasers.
- *Class 3 lasers*. Medium power lasers for which direct beam exposure can produce immediate hazard.
- *Class 4 lasers*. They are lasers that not only produce a hazardous direct or specularly reflected beam but also can produce a skin exposure hazard, a fire hazard, or produce a hazardous diffuse reflection.

Most lasers used in laser material processing fall in the class 4 lasers. Detailed safety definition and practices should refer the standard in Ref 13. The ANSI laser safety standard is voluntary. Individual states and employers have their mandatory regulations. There are also mandatory regulations from the Food and Drug Administration (FDA), the Occupational Safety and Health Administration (OSHA).

(1)34.4 LASER MATERIAL PROCESSING SYSTEMS

A laser material processing system consists of the laser source, the beam delivery system, the motion and material handling system, and the process control system. Some systems may integrate the sensing unit to improve process quality. The individual subsystems are discussed below.

(1)34.4.1 Common Lasers Used in Lmp

There are many kinds of lasers which cover a wide range of wavelengths, power levels, pulse durations, and beam quality. Lasers can be generally divided into gas lasers, liquid lasers, and solid state lasers. Gas lasers can be further divided into neutral gas, ion, metal vapor, and molecular lasers. Table 34.2 summarized the features of common lasers. The most widely used lasers in material processing are CO_2 lasers and Nd:YAG lasers. These lasers have a wide range of laser power. CO_2 lasers can have very high CW powers, up to tens of KW, while Nd:YAG laser can have powers up to several KW. Nd:YAG system usually comes with fiber coupling which makes it very flexible in processing. Diode lasers are in rapid development. They are used in pumping of other lasers, but material processing by direct diode laser beam is now practical with over KW diode lasers commercially available. Detailed discussion of lasers can be found in many of the references of this chapter. Specific lasers relating to a process will be further described in the relevant sections.

Type	Wavelength (nm)	General feature

CO_2	10600	Power: wide range, from several watts to te Very wide applications in laser material pro nonmetals.
He-Ne	632.8	Low power, CW power 0.5 mW to 50 mW High beam quality Typical application: alignment, bar code rea recognition, and the like.
Ion lasers	Ar 514.5, 488 Kr 647.1 Xe 995-539.5	Low power, mW to several watts. Typical application: surgery, Raman spectro holography
Metal vapor laser	Cu: 511, 578	Pulsed, can have short pulse and high peak Typical application: surgery, laser microma
Excimer lasers	XeCl 308, XeF 351, KrCl 222, KrF 248, ArF 193, F_2 157	UV wavelength, beam shape is usually rectangular width from several ns to over 100 ns, puls Typical application: semiconductor and oth
Ruby laser	694.3	First laser used for diamond drilling, can be over 1 J, pulse duration in ns and ps; hole
Nd:YAG	1064, 532, 355	Power: wide range, from mW to KW, CW, delivered by fibers Very wide applications in laser material pro
Nd:Glass	1064	Can have very high pulse energy (>100 J) a (ps and fs). Applications: pulse welding, h and the like
Diode laser	UV to IR	Can have high CW power output (□1 KW) divergence. Can be coupled with fibers, ve Typical application: signal processing, pum processing

Table 2: Common Industrial Lasers

(1)34.4.2 Beam Delivery and Material Handling Considerations

Laser beam out of the laser source is delivered to the target by beam delivery systems. The location of the energy deposition is determined by the relative motion between the laser head and the material. Beam delivery schemes are summarized in Table 34.3.

Beam delivery scheme	Description	Comments
Fixed beam	Laser beam is fixed while workpiece moves on motorized stages. Optics usually contained in metal tubes.	Simple to implement, laser ex little external disturbance
Flying optics	Relevant motion between the laser head and the workpiece is realized by moving optics, such as an inclined mirror that moves with the processing head.	Beam quality may change at d locations. This change can b compensated by adaptive op
Fiber or other flexible waveguide	Laser beam is coupled into the fiber or the flexible waveguide, such flexible structure can be further mounted on robot arm.	Nd:YAG lasers, some diode l fiber coupling output, CO_2 l special waveguides such as h tube. Highly flexible in mov sources in 3D space.
Coordinated scanning of laser beam	Galvanometer-driven mirrors reflect/deflect the laser beam onto the desired location on the target	Mirrors can have much less m very high scanning speed ca achieved. Commonly used i scribing, and high-speed las

Table 3: Beam Delivery

Note that in laser material processing, some assisting gases may be used to enhance machining, protect the optics, or prevent oxidation. The gas can be integrated with the laser head in various forms, for example, concentric gas jet with the laser output, or gas jet at an angle to the target surface. Gas jet may also be outside the laser head.

Beam delivery and material handling should be an integrated part in setting up the laser material processing system. Table 34.4 summarizes the considerations of motion and material handling system. Normally linear motors, polar robot, or gantry motion systems are used to move the workpiece.

Scheme	Description	Comments
Fixed workpiece and moving laser	The whole laser moves relative to the target.	Applies to small mass lasers or wh workpiece is inconvenient to mo Diode lasers, low-power CO_2 las

		the like can use this scheme. Sma work floor requirement.
Fixed laser and moving workpiece	Laser and optics are fixed, while workpiece moves on XY stage, XYZ stage or 5-axis stations.	Applies to small to medium mass workpiece, speed is limited by th This scheme is most popular. It h advantage of little external distur the laser. Larger work floor requ
Flying optics or moving flexible waveguide and fixed workpiece	Only part of the laser beam delivery system moves relative to the workpiece.	Due to the low mass of the flying high speed and high flexibility p Small work floor requirement.

Table 4: Motion and Material Handling Schemes

(1)34.4.3 Sensing and Process Control

High quality laser material processing relies on the optimal control of many parameters such as power, stand-off distance or spot size, energy deposition time, speed, scanning contour, path planning, gas pressure, and direction. Suitable sensing system is needed to control the important parameters such as spot size and surface temperature which cannot be directly defined by the laser controller.

Attention should also be paid to experimentally validate the settings on the controller. For example, the nominal power is the power directly out of the laser source, not the power out of the final optics. In reality, the customers usually build up their own optics to adapt the laser source to their specific applications. The beam out of the laser source is normally expanded, homogenized, polarized and so forth, and finally focused or defocused onto the target surface to achieve desired focus spot size or surface temperature.

A mechanical contact or a distance sensor can be used to control the distance from the lens to the target. An ideal focus control system should have high spatial resolution and can operate in real time. One potential technique to reach this aim is the on-axis monitoring system making use of the light reflected back from the workpiece. Machining quality can be improved when the laser energy is suitably modulated, for example, one can modulate the laser power in laser cutting to avoid the negative effects of the edge or control the taper in laser percussion drilling.

The stability of the laser energy should be considered in carrying out the control schemes. Lasers usually cannot change their power in real time because they need some time to stabilize when the settings are changed. A good solution is to modulate the power externally while keeping the laser power at a stable level. With automation of these external power modulators, laser power can be modulated in real time.

In summary, the complete consideration to build a laser material processing system should consider the laser source, the material to be processed, the optics to achieve desired energy level and energy deposition, the material handling system, and the control scheme among many other things such as precision, floor space, and cost. It is usually important to synchronize the laser settings with the motion control, i.e., make the energy and motion talk to each other. To make 2D or 3D motion paths, the motion can be manually programmed or can be generated from CAD tools. The laser supplier should be consulted in building up the accessories of the system, and the literature can be referred to save some effort for a successful process.

(1)34.5 LASER MACHINING PROCESSES

Laser machining processes refers to material removal processes that use laser energy directly. In this section we will discuss the laser systems, basic mechanisms, and the process capability of typical laser machining processes. Laser material removal processes require higher laser intensities than that in laser welding and laser material processing. Complex physics is involved in laser machining. However, we won't cover the modeling of these processes, which have too much content to be fitted into this chapter. Readers interested in the modeling aspects are encouraged to refer to Chapter 3 of the LMP module in Ref. 4, and other references of this chapter. In general, laser machining processes are noncontact, flexible, and accurate machining processes applicable to a wide range of materials.

(1)34.5.1 Laser Cutting

Lasers Used in Laser Cutting. The lasers used in laser cutting are mainly CO_2, Nd:YAG, and excimer lasers. Industrial lasers for cutting typically have power levels from 50 W to 5 KW, although higher powers are used to cut thick section parts. Because CO_2 lasers have higher average powers with cheaper cost-per-watt and they also have an early history of success in industrial laser cutting, today the majority of cutting operations are carried out by CO_2 lasers, especially for nonmetals which have better absorption at far infrared wavelength. Nd:YAG laser has shorter wavelength, smaller focused spot size, and is better absorbed by metals than CO_2 lasers. Multikilowatts Nd:YAG lasers are commercially available and they usually are delivered by fibers. All these factors lead to the increasing popularity of Nd:YAG lasers in industrial laser cutting, especially for metals. Q-switched Nd:YAG lasers are dominant in pulsed laser cutting. Excimer lasers have UV wavelengths that are strongly absorbed by both metals and nonmetals, the spatial resolution are higher than visible and infrared lasers, and thus they are mainly used for high-precision laser cutting, especially for polymers and semiconductors. Recently, conventional lasers using diode pumping and direct diode lasers are reducing their size and increasing their average power quickly, which may change the dominant role of bulky conventional lasers in industrial laser cutting. For example, 1 kW direct diode lasers at 808 nm wavelength with fiber coupler are now commercially available. Although suitable for laser welding and surface treatment, they can be used in laser cutting.

In laser micromachining, a much wider variety of lasers with short pulse durations and high pulse repetition rates are used, such as frequency doubled (Green 532 nm) and tripled (UV 355 nm) Nd:YAG laser, copper vapor lasers, ultrashort pulsed lasers, and excimer lasers. The shorter wavelength and shorter pulse duration helps increase spatial resolution and reduce the heat affected zone in laser cutting, the higher pulse repletion rate at smaller pulse energy makes it easier to get a smoother machined edge. But the average power of these systems is much lower than industrial lasers, typically the powers of lasers for micromachining are less than 50 W, although higher laser intensity may be reached by using smaller focused spot size. High-power industrial lasers are commonly used to cut through larger thickness parts with sufficient speed while micromachining lasers are used to generate small features with high precision.

The laser cutting system generally consists of the laser source, the beam delivery and focusing system, the material handling system, and the process monitoring and control system. Assisting gas is commonly used in laser cutting. Selection of the beam delivery and material handling scheme depends on the type of material to be cut, the thickness and mass of the part, and the affordable investment of the cutting system. The discussion in Section 34.4 applies to the laser cutting system and will not be repeated here.

Laser Cutting Mechanisms and Quality Issues. Almost any kinds of materials can be cut with a suitable laser. To achieve successful laser cutting, the material should have sufficient absorption to the incident laser energy and the part should be within certain thickness. This thickness depends on the material type, the laser, and the process parameters. Laser cutting is mainly a thermal process in which the material absorbs the focused laser energy and gets heated, melted, and vaporized. Deep UV laser machining of polymers may also involve the photon chemical dissociation process in which the chemical bonds of the material are directly separated by individual photons that have energy comparable with the molecular bonding energy. Industrial laser cutting is mainly a thermal material removal process. The laser energy can be CW or pulsed. Thick sections are mainly cut by high-power CW lasers. Pulsed laser cutting can reduce the heat affected zone and has better control of precision features such as sharp corners.

There are traditionally three laser cutting mechanisms—laser fusion cutting, laser oxygen cutting, and laser sublimation/vaporization cutting.

In laser fusion cutting, the material is melted by the laser beam, and either a gas jet is used to blow out the molten material or a vacuum device is used to suck away the molten material. A cutting front is formed at one end of the cutting kerf—the laser supplies the energy for melting and thermal diffusion while the gas jet provides the momentum to remove the molten material. To prevent oxidation, inert gases such as argon, nitrogen, or helium are normally used.

Laser oxygen cutting applies to reactive materials such as low carbon steel and titanium. In laser oxygen cutting, the laser is used to heat the material to the point where the exothermic reaction with oxygen will begin. The material is burnt through by the chemical reaction mainly. In this process the oxygen gas jet is used. This reduces the requirements on laser power. Under the same power level, higher cutting speed and thicker section cutting can be achieved using laser oxygen cutting than laser fusion cutting.

Laser sublimation/vaporization cutting generally applies to materials with low conductivity and low latent heat of vaporization, such as organic materials. Chemical reaction with oxygen may be uncontrollable for these materials. In laser micromachining, however, this mechanism applies to a much wider range of materials, including metals and ceramics. For this mechanism, no oxygen is used and the material is vaporized or sublimated by the laser energy only. This mechanism requires highest laser power and laser intensity among the three mechanisms. Protective gas jets are commonly used to protect the lens.

Quality issues in laser cutting include recast layer, dross or attachment, redeposition, taper, heat affected zone, wall roughness and striation, possible microcracks and the like. Laser energy creates a transient high temperature field in the target, a heat affected zone remains after the processing, and the resolidification of the molten material forms a recast layer. The kerf is usually not of the strictly rectangular shape, instead a taper normally exists from the top to the bottom. The molten material may attach to the bottom of the cutting kerf and may splash over the top surface resulting in attachment and redeposition. The wall surfaces usually show striations. The surface can be very rough if not well controlled.

With suitable control of the process parameters, however, high quality cutting can be achieved. Important process parameters in laser cutting are: laser power, laser spot size, stand-off distance, focus position, scanning speed, gas pressure, gas flow rate and direction, and gas composition. The quality of laser cutting depends on both the material and the laser.

Comparison With Other Cutting Processes. Laser cutting holds the largest market share (~38 percent) of all laser applications. It has gained wide acceptance in manufacturing due to the many advantages and benefits over other competing cutting methods. Table 34.5 compares the advantages and disadvantages of popular cutting technologies. Each technology has its niche, and the user should weigh their concerns carefully when facing the choice of these processes.

Processes	Advantages	Disadvantages
Mechanical cutting—punching, sawing, turning, milling and the like.	Relatively low capital cost; high material removal rate; precision cutting front control due to direct mechanical contact; good	Have tool wear; need complex due to large reacting force in c cutting is material dependent, materials are very difficult to c

	cutting surface finish and excellent cutting kerf geometry. Matured technology, best fit for bulk material removal, wide range of precision achievable.	simply cannot be cut; too thin thick materials are difficult to to too delicate or too bulky structure ratio 1:1.
Water-jet cutting	Can cut a wide range of materials using the same system, including metals, ceramics, and organic materials; very little thermal damage; can cut thick sections; high material removal rate and good surface finish; no direct mechanical tool contact, easy fixturing in cutting.	High capital cost; have tool w spatial resolution limited by th focusing of the water jet, may taper in the cross- section.
Wire electro-discharge machining	Negligible cutting force; good tolerance control and can cut complex geometry; excellent edge finish; can cut thick metals.	Applies only to conductive ma such as metals; have electrode relatively slow cutting speed; l larger heat affected zone than cutting. Aspect ratio 1:1.
Plasma arc cutting	High cutting rate; can cut complex geometry; cut thick materials well.	Poor tolerance control, large k large heat affected zone; roug edge; may need post processin
Laser cutting	Noncontact cutting, no tool wear; small cutting kerf; versatile, almost any material can be cut; negligible cutting reaction force, easy fixturing, fast setup, and rapid design change; capability to cut complex geometry easily; high cutting speed for reasonable thickness materials; high cutting quality possible at suitable parameters; more flexible than other systems, especially with flexible beam delivery; cutting, drilling and welding can be done by one system; high spatial resolution possible; small heat-affected zone; low operating cost; very high	High capital cost; relatively sl material removal rate; difficul thick sections; inherently a the material removal process, may some quality issues such as ta affected zone, and attachment.

	reliability and repeatability; can be easily automated.

Table 5: Comparison of Common Cutting Processes

Process Capability of Laser Cutting. Organic materials such as paper, rubber, plastics, cloth, wood, and inorganic materials such as ceramics and glass have better absorption at 10.6 μm than at 1.06 μm. Thus CO_2 lasers are most commonly used for nonmetal material cutting, and a CW CO_2 laser with 100 W is adequate for many of the cutting tasks. Nonmetal materials are commonly cut directly by vaporization. Inert gas may be used to prevent scorching of organic materials in laser cutting. Fixturing is easy for laser cutting—a vacuum chuck can be used to hold the material. Table 34.6 lists some cases of nonmetal laser cutting. These data are experimental data, they give the reader some idea of the capabilities of the process but not necessarily represent the optimal processing condition.

Table 6: CO_2 Laser Cutting of Nonmetals*

Material	Thickness (in)	Laser power (W)	Cutting speed (in/min)	Gas assist	Reference
Soda lime glass	0.08	350	30	Air	19
Quartz	0.125	500	29		20
Glass	0.125	5000	180	Yes	21
Alumina ceramic	0.024	250	28	Air	22
Plywood	0.19	350	209	Air	19
Plywood	1	8000	60	None	23
Fiberglass epoxy composite	0.5	20,000	180	None	23
Acrylic plate	0.22	50	12	Nitrogen	24
Cloth	Single pass	350	2400	None	25

*See Ref. 5.

Higher average power is needed in laser cutting of metals compared to nonmetals. CO_2 lasers are commonly used for laser cutting of metals but high-power Nd:YAG lasers are increasingly widely used, especially when equipped with fiber laser energy coupling. Table 34.7 shows some experimental results of CO_2 laser cutting of metals. These experimental data do not necessarily represent optimal processing conditions, but they provide some general idea of the process capabilities.

Metal	Thickness (in)	Power (W)	Cutting speed (in/min)	Reference
Titanium	0.67	240, O_2 assist	240	19
Stainless steel 410	0.11	250, O_2 assist	10	26
Rene 41	0.02	250, O_2 assist	80	26
Aluminum alloy	0.5	5,700	30	25
Steel 304	1.0	15,000	20	27
Titanium	0.25	3000	140	25
Titanium	2.0	3000	20	25
Rene 95	2.2	18,000	2.5	27

*See Ref. 5.

Table 7: Experimental Results of CO_2 Laser Cutting of Metals, Oxygen Assisted*

34.5.2 Laser Drilling

Lasers Used in Laser Drilling. Laser drilling is a process by which holes are formed by the removal of material through laser beam and material interaction. Laser drilling is one of the oldest applications of laser machining processes. The first ruby laser was demonstrated for laser drilling of diamonds. Nowadays, laser drilling has found successful applications in automobile, aerospace, electronic, medical, and consumer goods industries. A well-known example of laser drilling is the drilling of airfoil cooling holes of aircraft engines.

High-power CW lasers are difficult to focus to small spot size because of their poor beam quality.

Lasers used for drilling require higher laser intensities than in laser cutting. With finite pulse energy, high laser intensity can be achieved by tight focus and by short pulse duration. Normally, pulsed Nd:YAG lasers or pulsed CO_2 lasers are used. Similar to laser cutting, CO_2 lasers are better fit for nonmetals and Nd:YAG lasers are better suited for metals. The laser pulse duration is normally less than 1 ms. The average power of the laser may not be as high as that used in laser cutting, but the achievable laser intensity is higher than laser cutting due to shorter pulse duration and smaller spot size. Lasers can be used to drill very small holes with high accuracy and high repeatability. The diameters of holes range from several microns to about 1 mm. For extremely small diameter holes, tighter focus is needed and green or UV lasers, such as frequency doubled or tripled Q-switched Nd:YAG lasers, are used.

When the pulse duration is short and the pulse repetition rate is high, laser can drill when the part is moving. Thus very high drilling speed is possible. Laser drilling system may take all schemes discussed in Section 4 and will not be repeated here.

Laser Drilling Mechanisms and Quality Issues. In laser hole drilling, the high-intensity laser beam is focused on the target surface or slightly under the surface. The material is quickly heated over its vaporization temperature, and is removed (ablated) through direct vaporization or removed in bulk molten droplets. Figure 34.4 illustrates various drilling techniques—*single pulse drilling, percussion drilling, trepanning, and helical drilling*. When the target is thin relative to the available pulse energy, a single pulse can drill through the material. This is the case for thin film drilling, thin foil drilling, or thin plate hole drilling. Percussion drilling is widely used when one pulse cannot drill through the sample. In this case, consecutive laser pulses with pulse duration normally less than 1 ms are applied at the same location until the hole is drilled through. Percussion drilling is commonly used in cooling hole drilling of aircraft engines. Pulsed lasers can have high repetition rate. Thus using single pulse drilling or percussion drilling, thousands of small holes can be drilled in a short period compared to mechanical drilling and EDM drilling. But the diameters of holes are limited to the focused spot size, which should be small enough to gain high enough laser intensity.

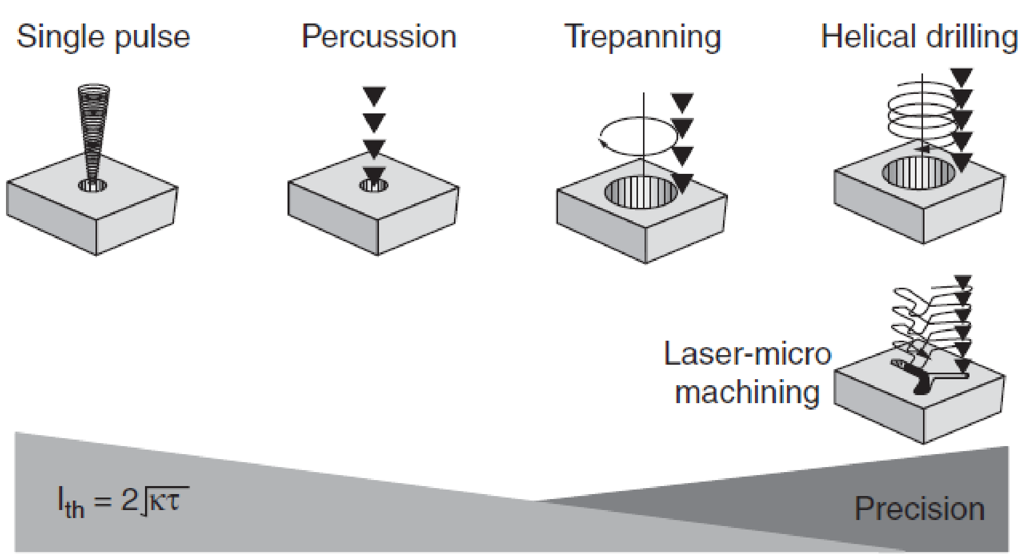

Figure 4: Various techniques in laser drilling.[12]

Trepanning is the standard technique for drilling of larger holes, such as holes over 500 μm in diameter. It is essentially a percussion drilling process followed by a cutting procedure. Using this technique, noncircular geometry can be easily realized. The application of nanosecond pulses to trepanning can increase the quality of drilling.

All of the three techniques will generate an inherent taper along the thickness section, although under proper conditions this tapering issue is not serious. To decrease the taper, the helical drilling technique can be used. In this method, the material is gradually drilled through, not drilling at each location and followed by contour cutting. This method can be used to machine out a blind feature or drilling out a larger thickness target that is impossible for trepanning.

It's important to protect the focusing lens in laser drilling because the ablated material may contaminate the lens and cause damages. A shielding gas jet is commonly used to blow away the ablated material and a protective flat glass plate can be attached in front of the lens.

Quality issues in laser drilling include: taper; deviation from the circular or desired geometry; redeposition of ablated material around the hole; microcracks due to thermal stress, especially in drilling of brittle materials. Laser can drill holes with height to diameter ratios of up to 50. At low height to diameter ratios, tapering is not an issue but when the aspect ratio is high, taper can be a concern. Because material is removed dynamically in gas and liquid form, the geometry may show deviation from circular or desired geometry. With good beam quality, however, the geometry can be very close to circular, the wall normally shows roughness less than 5 μm, and the process can be very accurate and repeatable. Redeposition of ablated material is due to the fact that a large fraction of material is ablated in bulk liquid form instead of direct vaporization or sublimation. To decrease redeposition, shorter pulses, such as nanosecond or even picosecond and femtosecond pulses instead of microsecond pulses, can be used. But keep in mind that the average power of shorter pulse lasers may be lower and the drilling rate is usually lower than longer pulses. An alternative solution to the issue of redeposition is using a cover or coating material on top of the target, and after drilling, peeling off this layer. Microcracks in laser drilling of brittle materials can be alleviated by controlling the pulse energy or elevating the target temperature so that temperature gradient in drilling is less steep.

Comparison With Other Drilling Processes. Laser drilling has many advantages that make it very useful in practical hole drilling operations such as:

High throughput leading to low-cost processing

Noncontact and no tool wear

Material hard to drill by other methods, such as ceramics and gemstones can be drilled with high quality

Heat affected zone is small around the hole

Smaller holes can be drilled in thin materials

Capacity for a high degree of beam manipulation, including the ability to drill at shallow angles and to drill shaped holes

Highly accurate and consistent process quality

Can be easily automated

The same laser system can be used for multiple purposes such as cutting, drilling, and marking.

It is economical to drill relatively small holes that can be drilled through by lasers in a short period. Larger diameter holes can be drilled by mechanical method. Aspect ratio >25 is usually a challenge for laser drilling, drilling of thick sections can be very difficult due to multiple reflection and the limited depth of focus of the laser beam. Table 34.8 compares laser drilling with its major competing processes, namely mechanical drilling and EDM drilling.

Process	Advantages	Disadvantages
Mechanical drilling	Matured process for large and deep hole drilling; high material removal rate; low equipment cost; straight holes without taper; accurate control of diameter and depth. Applicable to wider range of materials than EDM but narrower range of materials than laser drilling. Typical aspect ratio 1.5:1.	Drill wear and breakage; lo throughput and long setup t limited range of materials; difficult to drill small holes high aspect ratio holes; diff for irregular holes.
Electrical discharge machining	Large depth and large diameter possible; no taper; low equipment cost; can drill complex holes. Mainly applicable to electrical conductive materials. Typical aspect ratio 20:1.	Limited range of materials; slow drilling rate; need to m tools for each type of hole, setup time; high operating c
Laser drilling	High throughput; noncontact process, no drill wear or breakage; low operating cost; easy fixturing and easy automation; high speed for small hole drilling; high accuracy and high consistency in quality; easy manipulation of drilling location and angle; complex geometry	Limited depth and not economical for large holes; hole taper and material redeposition for drilling of metals; high equipment cos

	possible; high quality and thick depth in drilling of many nonmetal materials. Applicable to a very wide range of materials. Typical aspect ratio 10:1.

Table 8: Comparison of Laser Drilling With Mechanical Drilling and EDM Drilling

Process Capability of Laser Drilling. Lasers can drill very small holes in thin targets with high speed. Many of the applications for laser hole drilling involve nonmetallic materials. A pulsed CO_2 laser with an average power of 100 W can effectively drill holes in many nonmetallic materials with high throughput. Laser drilling of nonmetallic materials tends to have higher drilling quality than metals because nonmetallic materials are normally less conductive and are easier to be vaporized. Laser drilling of metals may have the quality issues of taper, redeposition, and irregular geometry. Both CO_2 and Nd:YAG lasers are commonly used for drilling of metals. Nanosecond lasers or even shorter pulsed lasers are used to drill metals in order to alleviate the quality issues. Figure 34.5 shows examples of laser-drilled holes.

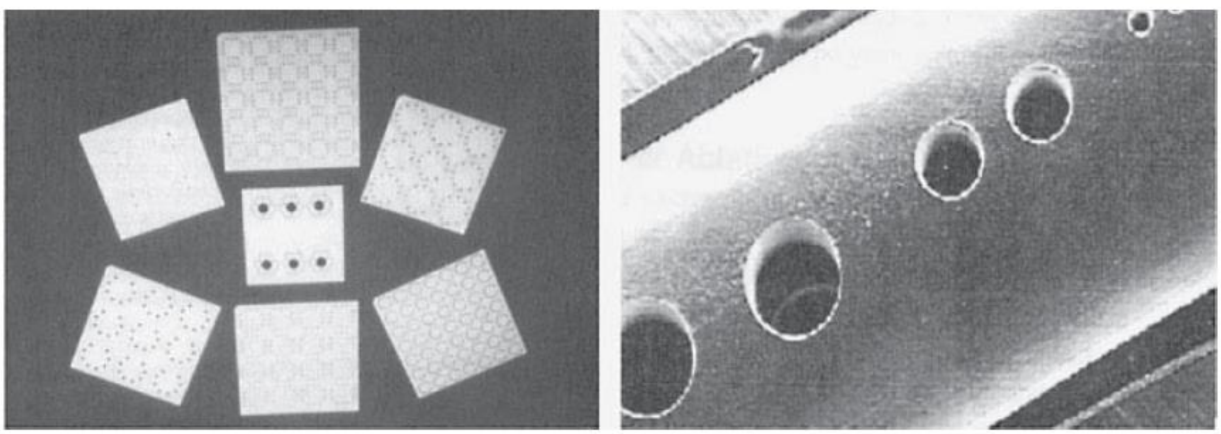

Figure 5: Left: Examples of patterns of laser-drilled holes in aluminia ceramics substrates (*Photograph courtesy of Electro Scientific Industries, Inc*.); Right: Cylindrical holes (25 μm, 100 μm, 200 μm) in catheter (*Illy, Elizabeth K, et al., 1997*).

Holes from about 0.008 in (0.2 mm) to 0.035 in (0.875 mm) can be typically percussion drilled in material thickness of up to 1.00 in with standard high-power drilling lasers. The longest possible focal length should be chosen for materials thicker than 0.15 in. Smaller diameter holes can be drilled with green or UV lasers. Larger holes can be drilled by trepanning or helical drilling.

Lasers can drill special geometry holes easily. The laser beam can be programmed to contour out the specified geometry. Lasers are also good at drilling holes on slant surfaces, which can be difficult for mechanical methods. Lasers can be flexibly manipulated to drill holes on 3D surfaces or reflected to drill difficult-to-reach areas. The taper in laser drilling is normally within 2 degrees, and the edge finish normally varies within 5 m. The aspect ratio in laser drilling can be over 20:1. The maximum depth of laser drilling for both CO_2 and Nd:YAG lasers is summarized in Table 34.9.

Materials	CO_2 lasers	Nd:YAG lasers
Aluminum alloy	6.25 mm	25 mm
Mild steel	12.5 mm	25 mm
Plastics	25 mm	Not applicable
Organic composite	12.5 mm	Not applicable
Ceramics	2.5 mm	Not applicable

Table 9: Capabilities of Laser Drilling

(1)34.5.3 Laser Marking and Engraving

Lasers for Marking and Engraving. Laser marking is a thermal process that creates permanent contrasting marks in target materials by scanning or projecting intense laser energy onto the material. In some cases, the target is removed a shallow layer to make the marks, while in other cases, strong laser irradiation can create a color contrasting from nonirradiated area. Lasers are also used to engrave features into materials such as wood or stone products. Laser marking holds around 20 percent market share of all laser applications and represents the largest number of installations among all laser applications. Lasers can mark almost any kind of material. Laser marking can be used for showing production information, imprinting complex logos, gemstone identification, engraving artistic features, and the like.

Lasers used for marking and engraving are mainly pulsed Nd:YAG lasers, CO_2 lasers, and excimer lasers.

In general, there are two fundamental marking schemes: one is marking through beam scanning or direct writing, and the other is marking through mask projection. In beam scanning or direct writing method, the focused laser beam is scanned across the target, and material is ablated as discrete dots or continuous curves. XY-tables, flying optics, and galvanometer systems are commonly used, and galvanometer systems turn out to be the most powerful. In the mask projection method, a mask with desired features is put into the laser beam path. Laser energy is thus modulated when it passes through the mask and a feature is created on the target. The mask can contact the target directly or can be away from the target and be projected onto the target by optics. The features in the mask projection method are usually produced with only one exposure. This mask projection method has been used in IT industry to produce very minute and complex features with the assistance of chemical etching. Beam scanning marking has more flexibility than mask projection marking while mask projection marking can be much faster than beam scanning marking.

Q-switched Nd:YAG lasers and excimer lasers are commonly used for beam scanning marking and CO_2 lasers operating in the range of 40 to 80 W are used to engrave features in wood and other nonmetallic materials. CO_2 TEA lasers and excimer lasers are widely used in mask projection laser marking.

Comparison With Competing Processes. Laser marking has proven to be very competitive with conventional marking processes such as printing, stamping, mechanical engraving, manual scribing, etching, and sand blasting. Beam scanning laser marking system is very flexible, it is usually highly automated, and can convert digital information into real features on any material immediately. Mask projection laser marking systems are very efficient. One can consider laser marking as a data driven manufacturing process. It's easy to integrate a laser marking system with the database, and the database has the same role as the tooling in conventional marking processes.

Compared to other marking systems, laser marking demonstrates high speed, good performance, and high flexibility, along with many other advantages, and the only downside seems to be the initial system cost. However, many practical examples show that the relatively higher initial investment in laser marking system can gain their payback in a short term. For example, an automobile and aerospace bearing manufacturer previously utilized acid-etch marking system to apply production information on the bearing. Turning to a fully automated laser marking system reduced the per piece cost by 97 percent, and the consumable and disposal materials were eliminated. In another case, a company needs to ensure close to 100 percent quality marking on the products, but failed to do so using the print marking method, which may have had problems of outdated information or poor quality of printing. Turning to laser marking, the quality is ensured and the marking information is directly driven by the production management database.

In summary, the advantages of laser marking include:

High speed and high throughput

Permanent and high quality features

Very small features easily marked

Noncontact, easy fixturing

Very low consumable costs, no chemistry, and no expendable tooling

Automated and highly flexible

Ability to mark wide range of materials

Digital based, easy maintenance

Reliable and repeatable process

Environmental friendly, no disposal of inks, acids, or solvents

Low cost of operation.

Figure 34.6 shows some examples of laser marking.

Figure 6: Laser marking examples. (Left) A PC keyboard; (Middle) graphite electrode for EDM; and (Right) Laser marking of electronic components. (*Courtesy of ALLTEC GmbH Inc.*)

(1)34.6 REVIEW OF OTHER LASER MATERIAL PROCESSING APPLICATIONS

Laser energy is flexible, accurate, easy to control, and has a very wide range of freedom in spatial, temporal, magnitude, and frequency control. This unique energy source has found extraordinarily wide applications in material processing. In this section, we will review some important applications other than the more well-known processes described in previous sections.

(1)34.6.1 Laser Forming

When a laser beam scans over the surface of the sheet metal and controls the surface temperature to be below the melting temperature of the target, laser heating can induce thermal plastic deformation of the sheet metal after cooling down without degrading the integrity of the material. Depending on target thickness, beam spot size and laser scanning speed, three forming mechanisms or a mixture of the mechanisms can occur. The three mechanisms are the *temperature gradient mechanism* (TGM), the *buckling mechanism* (BM), and the *upsetting mechanism* (UM).[14] Lasers used in laser forming are high-power CO_2 lasers, Nd:YAG lasers, and direct diode lasers.

Laser forming (LF) of sheet metal components and tubes requires no hard tooling and external forces and therefore is suited for dieless rapid prototyping and low-volume, high-variety production of sheet metal and tube components.[15] It has potential applications in aerospace, shipbuilding, automobile, and other industries. It can also be used for correcting and repairing sheet metal components such as prewelding "fit-up" and postwelding "tweaking." Laser tube bending involves no wall thinning, little ovality and annealing effects, which makes it easier to work on high work-hardening materials such as titanium and nickel super-alloys. LF offers the only promising dieless rapid prototyping (RP) method for sheet metal and tubes. Figure 34.7 shows pictures of laser-formed sheet metal and tubes. With strong government support and active research work, laser forming of complex 3D shape will be feasible in the near future.

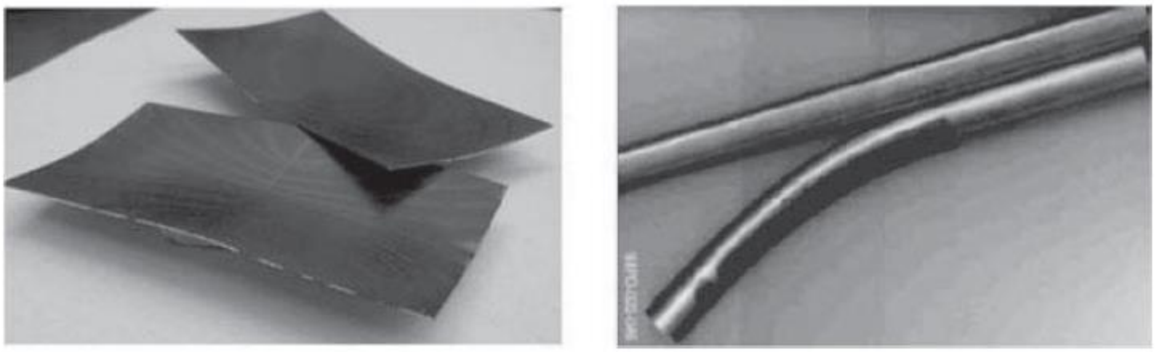

Figure 7: Laser forming of sheet metals and tubes. (*Courtesy of MRL of Columbia University and NAT Inc.*)

(1)34.6.2 Laser Surface Treating[5]

Lasers have been used to modify the properties of surfaces, especially the surfaces of metals. The surface is usually treated to have higher hardness and higher resistance of wear.

Laser Hardening. In laser hardening, a laser beam scanning across the metal surface can quickly heat up a thin top layer of the metal during laser irradiation, and after the irradiation it quickly cools down due to heat conduction into the bulk body. This is equivalent to the quenching process in conventional thermal treating. When favorable phase transformation occurs in this laser quenching process, such as in the case of carbon steels, the top surface hardness increases strikingly. Laser hardening involves no melting. Multikilowatt CO_2 lasers, Nd:YAG lasers, and diode lasers are commonly used. The hardened depth can be varied up to 1.5 mm and the surface hardness can be improved by more than 50 percent. Laser hardening can selectively harden the target, such as the cutting edges, guide tracks, grooves, interior surfaces, dot hardening at naps, and blind holes. The neighboring area can be uninfluenced during laser hardening. By suitable overlapping, a larger area can be treated.

Laser Glazing. In laser glazing, the laser beam scans over the surface to produce a thin melt layer while the interior of the workpiece remains cold. Resolidification occurs very rapidly once the laser beam passes by, thus the surface is quickly quenched. As a result, a surface with special microstructure is produced that may be useful for improved performance such as increased resistance to corrosion. The surface layer usually has finer grains and may even be amorphous.

Laser glazing of cast iron and aluminum bronze has demonstrated much enhanced corrosion resistance.

Laser Alloying. In laser alloying, powders containing the alloying elements are spread over the workpiece surface or blown over to the target surface. By traversing the laser beam across the surface, the powder and the top surface layer of the workpiece melt and intermix. After resolidification, the workpiece has a top surface with alloying elements. Surface alloying can produce surfaces with desirable properties on relatively low cost substrates. For example, low carbon steel can be coated with a stainless steel surface by alloying nickel and chromium.

Laser Cladding. Laser cladding normally involves covering a relatively low performance material with a high-performance material in order to increase the resistance to wear and corrosion. In laser cladding, the overlay material is spread over the substrate or continuously fed to the target surface. Laser beam melts a thin surface layer and bonds with the overlay material metallurgically. The difference with laser alloying is that the overlay material doesn't intermix with substrate. Cladding allows the bulk of the part to be made with low cost material and coat it with a suitable material to gain desired properties. Good surface finish is achievable. Compared to conventional cladding processes, such as plasma spraying, flame spraying, and tungsten-inert gas welding, laser cladding has the advantage of low porosity, better uniformity, good dimensional control, and minimal dilution of the cladding alloy.

(1)34.6.3 Laser Shock Processing or Laser Shock Peening (LSP)

High intensity (>GW/cm^2) laser ablation of materials generates plasma that has high temperature and high pressure. In open air, this pressure can be as high as sub GPa and the expansion of such high-pressure plasma imparts shock waves into the surrounding media. With the assistance of a fluid layer which confines the expansion of the plasma, 5 to 10 times stronger shock pressure can be induced. This multi-GPa shock pressure can be imparted into the target material and the target is thus laser shock peened. Laser shock processing can harden the metal surface and induce in-plane compressive residual stress distribution. The compressive residual stress refrains from crack propagation and greatly increases the fatigue life of treated parts. Compared to mechanical shot peening, LSP offers a deeper layer of compressive residual stress and is more flexible, especially for irregular shapes. It has been shown that LSP can improve fatigue life of aluminum alloy by over 30 times and increase its hardness by 80 percent.[16,17] Materials such as aluminum and aluminum alloys, iron and steel, copper, and nickel have been successfully treated. Laser shock processing has become the specified process to increase the fatigue lives of aircraft engine blades.

Conventional laser shock processing requires laser systems that can produce huge pulse energy (>50 J) with very short pulse duration (<50 ns), and Q-switched Nd:YAG lasers are commonly used. Such laser systems are expensive and the repetition rate is low (several shots per minute). Historically this has restricted the wider application of LSP in industry. This situation is improving with more and more cheaper high-power systems becoming commercially available. On the other hand, this technique can be extended to low pulse energy lasers with short pulse duration and tight focus. Two key requirements for a successful processing are the over GW/cm^2 laser intensity and short enough pulse duration (<50 ns). Microscale LSP using micron-sized laser beam has been developed and has been successfully applied to microcomponents. Microscale LSP has higher spatial resolution, is more flexible, and is low cost to implement. It is shown that the copper sample treated by a UV laser with 50 ns pulse can be increased by more than 300 percent.[18]

(1)34.6.4 Other Applications

There are many other laser material processing applications in which difficult problems are solved by lasers, such as laser assisted machining of super-alloys and ceramics, laser assisted etching, laser surface cleaning, and laser coating removal. In laser assisted machining, laser is used to locally heat the work material prior to the cutting tool in an attempt to improve machinability of difficult-to-machine materials such as supper alloys and ceramics. It has been experimentally shown that laser assisted machining can extend the tool life, increase the removal rate, and also improve the surface quality of the machined surface. Etching rate is sensitive to temperature, thus laser beam can be used to enhance etching rate locally. This is in fact one way of direct writing. With the combination of laser heating and chemical etching, semiconductor devices can be etched 10 to 100 times faster using laser assisted chemical etching than that with conventional procedures. Laser induced shock wave can be used to clean very minute particles on a silicon wafer, and laser ablation has also been used to remove rust or peel off coatings. In these applications, only a very thin surface layer is affected. Lasers are indispensable energy sources in the majority of *rapid prototyping manufacturing* (RPM) and *rapid tooling* (RT) manufacturing systems. In RPM and RT, laser energy is used to cure the liquid material, melt solid material, or cut the contour of laminated material, and then manufacture complex 3D parts layer by layer. All these are possible because laser energy can be accurately controlled spatially and temporally by digital information.

(1)34.7 CONCLUDING REMARKS

Laser material processing (LMP) processes have become indispensable engineering solutions in many cases. We have seen many dazzling applications of lasers. These processes are still in dynamic evolution due to the dynamic progress of laser sources. High initial capital cost is one of the major obstacles in choosing the laser material processing processes. This situation may change in the future. High-power lasers already have the same order of output power as mechanical systems (15 KW), and higher processing rates will be feasible with lower capital costs. Diode lasers offer great potential for increased power and lower costs. If the beam quality can be improved, diode lasers may change the world of material processing drastically. Extensive research work on LMP is going on throughout the world and the reader is encouraged to explore these processes by going to the references and browsing the world wide web. One has good reasons to expect seeing a constantly and fast improving world of laser material processing, such as higher machining rates, deeper holes, thicker section cutting, improved thermal coupling, and much improved quality.

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