LASERS IN TECHNOLOGY

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Contents

Summary

This article introduces the applications of high-power lasers in production processes. Precision manufacturing with high-power lasers includes cutting, welding, drilling, surface engineering, micromachining, marking, bending, laser-assisted machining, and rapid prototyping/tooling. This article provides basic process characteristics, physical principles, and scientific backgrounds involved in various laser materials processing applications.

1. Introduction

Laser-based manufacturing processes are used in many industrial sectors to improve the quality of human life on our planet. Engineering components involving features manufactured by high-power lasers can be found in a variety of products today. For example, digital information is put onto compact disks (CDs) by using lasers; safety airbags in some automobiles are welded with lasers; serial numbers on some drink cans are marked by lasers; some razors are spot-welded by lasers, and effusion cooling channels in most jet engine nozzle guide vanes are drilled by lasers. The aim of this article is to provide an introduction to laser materials processing science and technology in order to help the reader understand the precision manufacturing processes involving high-power lasers.

2. Industrial High-Power Lasers

2.1. Introduction

The basic principle of lasers and their characteristics can be found in *Optical Sources and Detectors*. This section introduces special features of high-power (up to tens of kilowatts in power) lasers used for materials processing.

2.2. CO_2 Lasers

CO_2 lasers are the most popular lasers used in industrial materials processing because of their high-energy efficiency and high average optical power output. A CO_2 laser uses CO_2 gas as the lasing medium. Normally N_2 and He gases are mixed with CO_2 gas. The role of the N_2 gas is to facilitate the CO_2 pumping and population inversion process by providing molecule collisions with the CO_2 gas, since pure CO_2 only *lases* weakly. The role of He gas is to facilitate (by absorbing heat) the removal of decayed molecules from their lower energy level to the ground level after the lasing process, in order to maintain the population inversion. Electric discharge (generated by the use of high-voltage and low-current electrodes) is used as a pumping source. This can be in direct current (DC) or alternating current (AC) or radio frequency current (*RF*). CO_2 lasers can reach a *Wall-plug efficiency* (100% × optical energy/input electrical energy) up to 15%.

A CO_2 laser has the following characteristics:

- Laser wavelength: 10.6 μm (for most CO_2 lasers) or 9.4 μm. They are in the far infrared spectrum. The CO_2 laser beams are thus not visible.
- The laser can be operated in *continuous wave* (*CW*) mode where the output power is at a constant level, or pulse mode where the laser output power can be pulsed.
- The laser beam is well absorbed by organic materials and ceramics but poorly absorbed by metallic materials.
- Mirrors rather than optical fibers are used for beam delivery, since normal glass or silica in optical fibers is opaque to the CO_2 laser beam.
- The average power of the laser ranges from a few mW to tens of kW.

There are various designs of industrial CO_2 lasers that have different characteristics. These are slow axial flow (excellent beam quality but normally limited to powers below 1 kW), fast axial flow (good beam quality, widely used for materials processing, but powers are limited to a maximum of 8 kW), transverse flow or gas dynamic (for very high-power lasers typically above 4 kW, poor beam quality, useful for surface treatment), TEA (transversely excited atmospheric laser, very high peak power at very short pulses, suitable for applications such as paint stripping), and slab CO_2 lasers (a compact design of laser that consumes less gas).

2.3. Nd:YAG Lasers

Nd:YAG lasers are solid-state lasers. In a Nd:YAG laser the lasing material is neodymium ions (1.5% Nd^{3+}) doped in YAG (yttrium aluminum garnet—$Y_3Al_5O_{12}$) rod. Excitation is realized by the use of arc lamps (Xe or Kr) or diode lasers. The wavelength of Nd:YAG lasers is 1.06 μm (near infrared). Efficiency of the laser is 2–3% for arc lamp pumped and up to 25% for diode laser pumped systems.

Nd:YAG lasers can have continuous wave (CW) or pulsed designs. Pulsed mode Nd:YAG lasers can deliver pulses of 0.1–10 ms pulses at frequencies of several kHz with peak powers up to tens of kW. These types of Nd:YAG laser are often used for drilling, welding, and cutting. Furthermore, Nd:YAG lasers can be *Q-switched* to give nanosecond and *mode locked* to give picosecond pulses of over 20 kHz. The average laser powers for Q-switched and mode-locked Nd:YAG lasers are normally less than 150 W. However, their peak powers can reach several megawatts. These types of Nd:YAG lasers are mostly used in marking and micromachining. Q-switched Nd:YAG lasers can be *frequency doubled, tripled, and quadrupled* by using non-linear crystals to give shorter (for example, green or UV) laser wavelengths.

One of the greatest advantages of Nd:YAG lasers is that the laser beam can be transmitted and delivered through optical fibers. This feature allows the task of processing 3-D components to be carried out much more conveniently when an industrial robot is used. Another advantage of the Nd:YAG laser is that the laser has a shorter wavelength than a CO_2 laser, which enables better beam absorption by metallic materials and generates less plasma in laser welding/drilling applications.

Disadvantages of the Nd:YAG laser are that the laser beam absorption varies with the color of the workpiece material, and it has higher capital and running costs than CO_2 lasers.

2.4. Nd:Glass Lasers

Nd:glass lasers work in a similar manner to Nd:YAG lasers, except that Nd:glass lasers use glass as a host for neodymium ions. Glass rods are more economical to produce than YAG rods. In addition, a much higher concentration of neodymium ions can be doped in glass than in YAG. Therefore, Nd:glass lasers can produce pulses with much higher energy (up to a few hundred joules per pulse). However, since glass is a poor thermal conductor (around 15 times lower than the Nd:YAG crystals), the laser can only operate under pulsed mode at very low repetition rates (a few Hz). In addition, the laser beam quality is poor because of the high thermal gradient in the glass rods. Nd:glass lasers are available with average powers of below 150 W. The overall efficiency of the laser is 2%–5%. Nd:glass lasers are not widely used in materials processing, but can be seen in shock processing and drilling applications.

2.5. Excimer Lasers

Excimer lasers use rare halides such as ArF, KrF, XeCl, and XeF as lasing materials. These materials only exist in excited states, with a typical lifetime of a few nanoseconds.

They repel each other at the ground state. Therefore the lower state population is nearly zero. Excimer refers to *exci*ted di*me*r. In excimer lasers the excimer gases are mixed with buffer gases (90%–99%) such as He, Ne, or Ar to mediate the energy transfer. The laser operates with sealed-off gases at near, or higher than, atmospheric pressure. Pumping is carried out by pulsed electric power, transversely excited. The laser only operates at pulsed mode at nanosecond pulses up to a few kHz repetition rates. Excimer lasers emit at ultraviolet wavelengths: 0.193 μm (ArF), 0.248 μm (KrF), 0.308 μm (XeCl), and 0.351 μm (XeF). Pulse peak power can reach a few megawatts. Optical feedback is almost unnecessary because of the short lifetime of the excimers. Excimer lasers have an operating efficiency of 3%–5%. Excimer lasers have the advantages of the UV laser wavelengths, which can be absorbed well by most materials. For most organic materials, excimer lasers can cause photo-ablation to removal materials without generating heat. Excimer lasers are typically used for micromachining, thin film deposition, and marking.

2.6. Semiconductor Lasers

Semiconductor lasers use III-V type semiconductors such as gallium arsenide (GaAs), indium phosphate (InP), GaAs/AlGaAs, and InP/InGaAsP as lasing materials. The resonant cavity consists of a semiconductor rod with polished ends. Excitation is by electric current, forward biased. The gap between the P–N junctions in these semiconductors is around 0.05–1.4 eV. When an external voltage forward biases the P–N junction, the N type is excited by having more electrons in the conductor band. When they go through the P–N junction, electrons and holes (in P type) recombine, which results in photon emission. The wavelength of high-power semiconductor lasers is 810 ± 10 nm μm (GaAlAs) or 940 ± 10 nm (InGaAs). Diode lasers of up to several kW powers are seen in materials processing applications. Most high-power diode lasers are operated in continuous mode. The laser has the advantages of being highly compact, having high efficiency (up to 40%) and low running cost, and that the laser beam can be delivered through optical fibers. The disadvantages of diode lasers include low beam coherence and high beam divergence. Industrial high-power diode lasers are made of arrays of laser diodes. Rectangular beam geometry is normally seen in these lasers. Optical fiber-delivered beams are circular in shape. Diode lasers cannot be focused to a very small beam size because of their poor beam coherence. They are normally used directly for surface treatment, welding, and marking/engraving applications. More often they are used to pump Nd:YAG lasers.

2.7. Copper Vapor Lasers

Copper vapor lasers use copper (20%) as the lasing material. An inert gas, such as neon or helium, is added (at around 5 mbar pressure) to improve the discharge quality. Pumping is by electrical excitation. Ignition first takes place with He, then copper vapor is generated. The copper vapor molecules collide with electrons and become excited. When they fall down to a lower energy level, photons of 0.51 μm (green) or 0.578 μm (yellow) are emitted. These molecules further rapidly decay to the ground level by wall collisions with heat radiation (around 10 ns). The optical cavity is sealed off, although fresh supplies of copper have to be added periodically (every few hundred hours). Average laser powers of up to 200 W is achievable with the laser. The laser can only operate at pulsed mode with a few nanosecond pulse widths and a peak power of a few 1 MW. The laser has the advantage of having very high beam quality with high repetition rates: 10^3 to 10^5 Hz. The laser can be focused to a very small beam size (diffraction limited) and can be absorbed well by most metallic materials. Efficiency of the laser is around 2%. Copper vapor lasers have found applications in the micromachining of metallic materials.

3. High-Power Laser Beam Characteristics and Beam Absorption

3.1. Beam Quality Parameters

High-power laser beams may have various intensity or phase distribution across the beams. *Transverse electromagnetic mode ($TEM_{m,n}$)* is used to describe laser beam cross-sectional intensity/phase distributions, where *m* and *n* denote the numbers of minimums along two perpendicular axes (radial and azimuthal).

TEM_{00}–*Gaussian beam* is the desirable beam shape for most applications in materials processing where tight beam focusing is required. The intensity distribution of a Gaussian beam can be described by:

$$I(r) = I_0 \cdot e^{-\frac{2x^2}{r^2}} \qquad (1)$$

where I_0 is the maximum intensity of the beam, r is the radius of the beam and x is the distance from the beam axis. A Gaussian beam distribution can be maintained throughout the beam.

TEM_{01*}–*Donut mode* is made from an oscillation between two superimposed orthogonal TEM_{01} modes, both of which are *first order modes*. Modes higher than the first order are called *high order modes*. The high-order mode beam changes with distance and time. The transverse mode of a laser affects beam divergence, focal spot size, and beam distributions at focus.

For a Gaussian mode beam, the *beam diameter* is defined as the length across the beam between two points at which the beam intensity is $1/e^2$ (13.5%) of the maximum intensity I_0. For other mode beams, the laser beam diameter is defined as the distance across the beam with its isointensity contour containing $1-e^{-2}$ (86.5% volume) of beam power. This corresponds to 95% area coverage for a 2-D beam contour.

A laser beam coming out of a laser cavity normally diverges slightly over distance (typically 1–2 mm per meter distance of travel for most industrial lasers). Therefore the laser beam diameter at different locations in the beam path may not be the same. The beam radius (half of the beam diameter), $W(z)$, at a distance, z, along the beam axis, from the beam waist, W_0, (the smallest beam radius in the beam path) can be found from:

$$W(z)^2 = W_0^2\left(1+\frac{z^2}{b^2}\right) \quad (2)$$

where b is called *Rayleigh length*, which can be found from:

$$b = \frac{\pi W_0^2}{\lambda M^2} \quad (3)$$

where. λ is the laser wavelength, M^2 is called *beam quality factor* which is always a positive number: $M^2 = 1$ for a Gaussian beam mode and $M^2 > 1$ for other modes. The smaller the M^2, the better the beam quality is. When $z \gg b$, the laser beam is in the *far field* and when $z \ll b$, the laser beam is in the *near field*. The Gaussian beam properties are kept the same in the near and far fields, while high-order mode beams have different properties in the near and far fields. In the far field $(z \gg b)$ the *beam radius,* W_{ff}, can be found from:

$$W_{ff} = \frac{\lambda z}{\pi W_0} M^2 \quad (4)$$

From Eqs. (2) to (4), it can be seen that the larger the value of M^2, the larger the beam radius will be at distance z from the beam waist, that is, higher M^2 values result in larger *beam divergence*. The laser beam divergence angle is the defined as the angle of opening of a laser beam. That is, the radius (corresponding to *half angle beam divergence*) or diameter (corresponding to *full angle beam divergence*) increases per unit beam length. Since the high-power laser beam divergence angle is very small (typically 0.5–1.5 mrad), the half angle beam divergence at far field can be found from:

$$\theta_{half} \approx \frac{W_{ff}}{z} = \frac{\lambda}{\pi W_0} M^2 \quad (5)$$

The beam divergence angle is therefore proportional to beam wavelength and M^2. Also the larger the beam waist, the smaller the beam divergence. A Gaussian beam has the smallest beam divergence. Since most real industrial laser beams are not pure Gaussian , that is, $M^2 > 1$, the beam quality factor, M^2, can thus be defined as the ratio between the actual beam divergence angle, θ_{act}, and the Gaussian beam divergence angle, $\theta_{Gaussian}$, that is,

$$M^2 = \frac{\theta_{act}}{\theta_{Gaussian}} \quad (6)$$

A laser beam can be *polarized*, that is, it has a preferred orientation of electrical field.

Linear polarization is defined as a beam with an electrical field oscillating in one direction and not changing with time. If the beam polarization is parallel to the target surface norm, it is called *P polarized*. If the beam polarization is perpendicular (German: *senkrekt*) to the target surface norm, it is called *s polarized*. When the field vector is of constant amplitude and changes its direction with a constant angular velocity, it is called *circular polarized*. Most industrial lasers are polarized either linearly or circularly. The polarization of laser beams can affect the beam absorption and processing quality, depending on the beam traverse directions over the target material.

Another important property of the laser beam is *beam parameter product* (BPP):

$$BPP = \theta_0 d_0 = 4\theta_{half} W_0 = \frac{4\lambda}{\pi} M^2 \quad (7)$$

where θ_0 denotes the full divergence angle $\left(= 2\theta_{half}\right)$ and d_0 is the beam waist diameter $\left(= 2W_0\right)$.

3.2. High-Power Laser Optics

A laser beam coming out of a laser cavity is not used directly for materials processing. Normally it requires mirrors or optical fibers to deliver the beam to the workpiece. Also focusing lenses or focusing mirrors are used to reduce the beam diameter in order to increase the energy density. The *diffraction limited spot size* (minimum possible spot diameter), $d_{\min}$, achievable with a focusing lens or a focusing mirror is

$$d_{\min} = \frac{4\lambda f M^2}{\pi D} \quad (8)$$

where D is the beam diameter on the lens (or mirror) before focusing.

The *focusing number*, F is defined as:

$$F = \frac{f}{D} \quad (9)$$

Combining Eqs. (7), (8) and (9) gives:

$$d_{\min} = (\theta_0 d_0)F = (BPP)F \quad (10)$$

The *depth of focus*, z_f, is defined as the length along the beam axis above or below the focal point under which the focal spot size changes by 5%. This can be found from:

$$z_f \approx \pm 0.08\pi \frac{d_{\min}}{\lambda M^2} \tag{11}$$

Sometimes the focal spot radius is also referred to as “beam waist,” and *Rayleigh range* is used here to provide a measure of the depth of focus. The Rayleigh range in this context defines the distance (from the focal position) within which the beam cross-sectional area and hence the laser power density varies by a factor of 2 (or beam diameter varies by a factor of $\sqrt{2}$). The Rayleigh range or depth of focus in this context can be found from:

$$z_R = d_{\min}F = \left(\theta_0 d_0\right)F^2 = \left(BPP\right)F^2 = \left(4\frac{\lambda}{\pi}\right)M^2F^2 \tag{12}$$

Most practical focusing lenses are spherical for ease of manufacture. Sometimes *cylindrical lenses* (they may be spherical in shape) are used to produce a line beam, as these lenses focus in one direction (x or y) only.

Other commonly used *transmissive* optics in high-power laser materials processing include beam integrators (lenses consisting of multiple elements to enable a uniform beam intensity distribution, normally a rectangular beam, to be produced at the focal plain), beam splitters (partially reflective and partially transmissive), beam collimators (change of beam diameter whilst maintaining the parallel feature of the beam), and optical fibers.

For visible and near-infrared laser beams such as those produced by Nd:YAG lasers and diode lasers, silicon glass or borosilicate crown glass (BK-7) is normally used as the lens and transmissive optical material. They normally transmit 0.4–1.4 μm. For far-infrared beams such as those produced by CO_2 and CO lasers, zinc-selenide (ZnSe, transmission 0.58–22 μm) and potassium chloride (KCl, transmission from visible to far IR) are normally used as lens and transmissive optical materials. ZnSe lenses are more suitable to high-power beams and are more stable but more costly. KCl lenses are sensitive to moisture but are lower cost than ZeSe, and are normally used for lasers up to 2 kW power. Normal glasses are opaque to the far-IR beams. For UV beams such as those produced by excimer lasers, quartz, synthetic fused silica (UVGSFS) (transmissive within 0.18–2 μm) and sapphire (transmissive within 0.2–3 μm) are used as lens materials.

Optical fibers are used to deliver visible and near-IR beams such as those produced from Nd:YAG and diode lasers. Optical fiber beam delivery enables multiple dimensional laser materials processing to be carried out using conventional industrial robots. Far-IR beams such as those produced by CO_2 lasers cannot be delivered with optical fibers, thus they would require multiple mirrors at the elbows of a robot or a beam guide for 3-D applications. Due to the limitation of the optical damage threshold of optical fibers, Q-switched beams with over 10^7 W peak power are usually not transmissible with optical fibers. For industrial lasers, optical fiber core diameters are within 0.1–2 mm. Typically 10–25% energy losses are seen for the optical fiber beam delivery of high-power industrial laser beams. The practical industrial laser optical fiber cores are normally protected by a plastic coating which is further strengthened by kefler and surrounded with a metal spiral to prevent sharp bending.

Mirrors are used to change the direction of the laser beam transmission as well as for focusing at very high laser powers (for example, above 5 kW). Parabolic and spherical mirrors are normally used for focusing. Flat mirrors are used for beam bending. Furthermore, beam integrators (multiple facet mirrors) are used to homogenize the beam at the focal plain (uniformly distributed rectangular beam), with diffractive optics to produce various beam profiles at the focal position, and phase retarders (to change a linearly polarized beam to a circularly or randomly polarized beam). In a *circular polarize (depolarize or phase) retarder*, a $\lambda/4$ dialectic coating is applied on a flat mirror so the p component (reflected from the mirror face) is $\lambda/2$ out of phase with the s component (reflected from the coating). In addition, x–y *Galvo scanners* (two mirrors, each controlled by a piezoelectric motor) are often used in laser marking processes to control the beam delivery, via CNC programming, at a very high speed.

The requirements for high-power laser reflective optics materials include high reflectivity, high thermal conductivity, and low thermal expansion coefficient. Cu mirrors with Au or Ag coatings can reflect 99.4% of IR beams. Copper mirrors are normally water-cooled. These are mostly used for high-power CO_2 lasers. The use of amorphous gold coating can increase the damage threshold considerably (e.g. around 30% for CW CO_2 lasers). The uncoated copper has crystal boundaries that can initiate laser damage by dislocating and breaking away from each other. Also copper is not as chemically inert as gold. Other reflective optics include the use of Si mirrors with Ag/Au coatings which give up to 98.9% reflection to infrared beams, and have the advantages of high thermal stability and low weight. Mo mirrors with Ag coatings can reflect 98.9% of IR beams. These mirrors are durable and rugged.

For high power application, thermal distortion of laser optics can occur, which is the result of non-uniform heating of mirrors or lenses leading to shape changes of optics. The focal length can change up to 5 mm through thermal distortion.

3.3. Laser Beam Absorption

There are several different mechanisms of beam absorption by materials. These include Fresnel absorption, inverse Bremsstrahlung absorption, and photo-ablation.

3.3.1. Fresnel Absorption

Fresnel absorption refers to beam absorption at the solid/liquid surface of a material. There are several models describing the absorption mechanisms.

For beam absorption (Fresnel) by metals, the *Drude model* has been used to describe the process: the oscillating electrical field of the laser beam causes free electrons in the metal close to the surface to oscillate at the same frequency as the laser beam. The electron displacement, X_{Drude}, can be estimated from:

$$X_{Drude} = \frac{e/m}{\omega^2 + i\omega j} E_0 \exp(-i\omega t) \quad (13)$$

for the excitation electromagnetic waves (from the laser) of $E_0 \exp(-i\omega t)$, where m is the electron mass, e is electron charge, ω is the laser beam electrical field oscillating frequency $(= c/\lambda)$, and j is the collision frequency between electrons and the metal lattice.

The electron transitions in a metal due to laser absorption are within the conduction band only (*intra-band absorption*). Inter-band transitions in metals would require over 10 eV photon energy, while industrial lasers cannot provide photons of such a high energy (for example, CO_2 lasers: 0.12 eV, Nd:YAG lasers: 1.16 eV, and some excimer lasers: 4.9 eV).

The oscillating electrons will in term collide with the metal lattice, so there is a local lattice vibration. As a result, temperature rise occurs (temperature is a measure of atom/molecule vibrations). Photo energy is thus converted into thermal energy.

For nonmetallic materials, the *Lorenz model* has been used to describe the process. In this case the bonded electrons are modeled as attached the atoms by springs. The electron displacement can be estimated using:

$$X_{Lorence} = \frac{e/m}{\omega_0^2 - \omega^2 - ir\omega} E_0 \exp(-i\omega t) \quad (14)$$

where ω_0 is the resonance frequency of the atom (corresponding to exciting energy) and r is the oscillator strength, which equals the recombination probability of electrons. The vibrating electrons will cause the vibration of atoms, causing temperature rise and thus converting optical energy into thermal energy. The absorbed energy is conducted to the interior part of the material by thermal conduction. *Inter-band absorption* takes place in nonmetallic materials since much smaller energy gaps exist.

For opaque materials, the optical absorption length, δ_{ab}, (at which the laser intensity drops to $1/e$ of its value at the surface) can be estimated using:

$$\delta_{ab} = \frac{\lambda}{4\pi kn} \quad (15)$$

where λ is laser wavelength, k is extinction coefficient of the material and n is the refractive index of the material.

For most metals the absorption length is on the order of 0.1 μm. Therefore, the absorption length for metals and other opaque materials is often called *skin depth* optical penetration.

The *reflectivity* (percentage of light reflected), r_f, of a material with an ideal surface (mirror polished) to a laser beam in air can be estimated by:

$$r_f = \frac{(1-n)^2 + k^2}{(1+n)^2 + k^2} \tag{16}$$

For an opaque material, beam transmission loss is zero. It is therefore possible to estimate beam absorption, A, for an opaque material by:

$$A = 1 - r_f \tag{17}$$

For a polarized beam, beam absorption for each polarizing component is different:

$$A_p = \frac{4n\cos\theta}{\left(n^2 + k^2\right)\cos^2\theta + 2n\cos\theta + 1} \tag{18}$$

And

$$A_s = \frac{4n\cos\theta}{n^2 + k^2 + 2n\cos\theta + \cos^2\theta} \tag{19}$$

where A_p is beam absorption for the P component and A_s is beam absorption for the S component. θ is the incident angle of the laser beam. Therefore, beam absorption can be dependent on the beam incident angle for a polarized beam.

Surface temperature and laser wavelength can also affect the beam absorption. These are described by the *Bramson (Hagen–Ruben) formula*:

$$A_\lambda(T) = 0.365\left[\rho_r(T)/\lambda\right]^{1/2} - 0.667\left[\rho_r(T)/\lambda\right]0.006\left[\rho_r(T)/\lambda\right]^{3/2} \tag{20}$$

where $A_\lambda(T)$ is the laser beam absorption (emissivity) under different wavelengths and temperatures, $\rho_r(T)$ is the material electrical resistively, and T is temperature. Higher surface temperature can result in higher beam absorption.

For metallic materials, normally the shorter the laser wavelength, the higher the beam absorption, and vice versa for nonmetallic materials. Therefore CO_2 lasers are not well absorbed by metallic materials compared with Nd:YAG lasers, but CO_2 lasers are much better absorbed by nonmetallic materials.

Absorbent (carbon and so on) coatings, higher surface roughness, and oxidation films can be used to improve beam absorption. Higher laser intensity can also increase laser beam absorption. The increase of beam absorption by a rougher surface arises from larger surface areas and possible multiple reflections.

3.3.2. Inverse Bremsstrahlung Absorption and Plasma Generation

When laser beam intensity is high (>10^6 W cm^{-2}), high temperature plasma (ionized gas) can be generated by heating the material vapor or surrounding gas. This could be initiated through the presence of a low density of "seed" electrons produced through thermal ionization and thermionic emissions. In this case the electrical field of the laser interacts with the free electrons to cause an avalanching absorption and generation of an ionization of the gas cloud. The inverse *Bremsstrahlung absorption coefficient*, K_v in cm^{-1}, is:

$$K_v = \frac{4}{3}\sqrt{\frac{2\pi}{3kT_e}}\frac{n_e n_i Z e^6}{hcm^{3/2}\upsilon^3}\left[1-\exp\left(-\frac{h\upsilon}{kT_e}\right)\right] \quad (21)$$

where n_e is electron density, n_i is ion density, Z is average charge of plasma, T_e is the electron temperature, c is the speed of light, ν is the frequency of the laser beam ($= c/\lambda$ where λ is the laser wavelength), e is electron charge, m is electron mass, h is Plank's constant and k is Boltzmann's constant. For CO_2 or Nd:YAG laser radiation and plasmas with $T_e \approx 8\times10^3 K$, $1-\exp(-h\nu/kT_e) \approx h\nu/kT_e$, it can be derived from Esq.(3.27) that:

$$K_v \propto \lambda^2 T_e^{3/2} \quad (22)$$

that is, the longer the wavelength of the laser, the more plasma absorption and plasma generation will take place. For example, CO_2 lasers normally produce more plasma in laser welding than with Nd:YAG lasers. $1/K_v$ is called *absorption length* (in cm) by the plasma. It gives a measure of beam penetration depth into the plasma.

3.3.3. Photochemical Ablation (Cold Processing)

When polymer materials are radiated with excimer lasers or other lasers with UV wavelengths, the laser beams directly remove molecule bonds without their going through temperature rises. This is because of the high photon energy of these UV lasers and weaker molecular links in the polymer materials. Table 1 lists the photo energies of some of the lasers and typical molecular bond energies. From this table it is clear that neither CO_2 lasers nor Nd:YAG lasers of fundamental frequency can cause photochemical ablation. Most excimer lasers can produce photons above the energy of the C–H bond that can be found in most of the organic/polymer materials. This is a nonthermal process involving photodissociation of organic molecules. The ablated particle release from the solid material leads to a rapid rise in the local particle number density in the air. This again causes a rapid rise in local pressure, which is normally released as a shock wave that ejects material fragments of gases and monomers at high speeds from the irradiated zone. Often the ejected fragments themselves are excited and fluoresce in a flamelike manner to give the appearance of a plume of light coming from the exposed site.

Lasers	**Photon energy, eV**	**Molecular bonds**	**Bond energy, eV**
CO_2	0.12	C-H	3.4
Nd:YAG (1.06 μm)	1.16	O-H	4.4
XeF	3.4	H-H	4.5
XeCl	4	C-C	6.2
KrF	5	N-O	6.5
KrCl	5.6	C-N	7.8
ArF	6.4	C-O	11.1

Table 1. Laser photon energy and some molecular bond energies

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(see: *Optical Fiber Sensors* and *Optical Sources and Detectors*, population inversion, eximer, (p-n) junction, coherence, optical cavity, polarization, bremsstrahlung, degradation, thermal conductivity, thermal diffusion, latent heat, thermodynamic equilibrium, ionization potential, detonation wave, combustion wave, surface tension, austenization, hardening, amorphization, relaxation time, lithography)

Biographical Sketch

Professor **Lin Li** holds a chair of Laser Engineering at UMIST (the University of Manchester Institute of Science and Technology), UK. He was born in 1959 in China. He obtained a B.Sc. in Control Engineering from Dalian University of Science and Technology, China in 1982, and Ph.D. in Laser Engineering from Imperial College, London in 1989. He was then employed by the University of Liverpool as a Research Associate to work on laser material processing, and laser process monitoring and control. He became a member of the academic staff (Lecturer, later Reader) at UMIST in 1994. In April 2000 he was promoted to a Chair of Laser Engineering, and was appointed as the Director of the Laser Processing Research Centre at UMIST. He is the coauthor of a book on laser processing, author and coauthor of over 200 publications on laser processing, and inventor/co-inventor of 30 patents on the application of lasers in industry. He has been teaching laser materials processing for over eight years at both postgraduate and undergraduate levels.