

Recommended Practices for Laser Beam Welding, Cutting, and Allied Processes



American Welding Society



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Recommended Practices for Laser Beam Welding, Cutting, and Allied Processes

2nd Edition

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Prepared by the
American Welding Society (AWS) C7 Committee on High-Energy Beam Welding and Cutting

Under the Direction of the
AWS Technical Activities Committee

Approved by the
AWS Board of Directors

Abstract

This document presents recommended practices for laser beam welding, cutting, drilling, and transformation hardening. It is intended to cover common applications of the process. Processes definitions, safe practices, general process requirements and inspection criteria are provided.



American Welding Society

550 N.W. LeJeune Road, Miami, FL 33126



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Personnel

AWS C7 Committee on High-Energy Beam Welding and Cutting

P. W. Hochanadel, Chair	<i>Los Alamos National Laboratory</i>
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P. Blomquist	<i>Applied Thermal Sciences, Incorporated</i>
D. D. Kautz	<i>Los Alamos National Laboratory</i>
G. R. LaFlamme	<i>PTR Precision Technologies Inc.</i>
E. D. Levert	<i>Lockheed Martin Missiles and Fire Control</i>

Advisors to the AWS C7 Committee on High-Energy Beam Welding and Cutting

P. E. Denney	<i>Connecticut Center for Advanced Technology</i>
R. D. Dixon	<i>Retired</i>
P. W. Fuerschbach	<i>Sandia National Laboratory</i>
R. W. Messler Jr.	<i>Rensselaer Polytechnic Institute</i>
J. O. Milewski	<i>Los Alamos National Laboratory</i>
T. M. Mustaleski	<i>BWXT Y-12 LLC</i>
D. E. Powers	<i>PTR – Precision Technologies, Incorporated</i>
R. C. Salo	<i>Sciaky, Incorporated</i>

AWS C7C Subcommittee on Laser Beam Welding and Cutting

P. Blomquist, Chair	<i>Applied Thermal Sciences, Incorporated</i>
P. E. Denney, Vice-Chair	<i>Connecticut Center for Advanced Technology</i>
M. Rubin, Secretary	<i>American Welding Society</i>
R. D. Bucurel	<i>WEC Welding & Machining</i>
S. L. Engel	<i>HDE Technologies, Incorporated</i>
D. F. Farson	<i>The Ohio State University</i>
A. P. Hoult	<i>IPG Photonics</i>
J. P. Hurley	<i>Cosma Power Laser</i>
D. D. Kautz	<i>Los Alamos Natcional Laboratory</i>
R. P. Martukanitz	<i>Applied Research Laboratory, Pennsylvania State University</i>
V. Merchant	<i>Electrical and Optical Solutions</i>
L. R. Migliore	<i>Coherent, Incorporated.</i>
T. Palmer	<i>Applied Research Laboratory, Pennsylvania State University</i>
G. C. Schmid	<i>Bechtel Bettis, Incorporated</i>

Advisors to the AWS C7C Subcommittee on Laser Beam Welding and Cutting

R. D. Dixon	<i>Retired</i>
P. Hochanadel, Ex-Officio	<i>Los Alamos National Laboratory</i>
S. Jensen	<i>Visotek, Incorporated</i>
T. A. Jones	<i>Ford Motor Company</i>
J. O. Milewski	<i>Los Alamos National Laboratory</i>
D. E. Powers	<i>PTR – Precision Technologies, Incorporated</i>

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Foreword

This foreword is not part of AWS C7.2M:2010, *Recommended Practices for Laser Beam Welding, Cutting, and Allied Processes*, but is included for informational purposes only.

The first practical demonstration of a laser occurred in 1960. As laser output power increased through maturing technology, the use of lasers for material processing became widespread by the early 1970s. Currently, lasers are an accepted industrial tool for traditional and nontraditional materials processing operations that benefit from the laser's unique characteristics. While the materials processing applications of lasers in industry are diverse, this document focuses on welding, cutting, drilling, and transformation hardening.

The data contained in this *Recommended Practices* has been compiled and reviewed by the C7C Laser Beam Welding and Cutting Subcommittee of the American Welding Society, which included representatives from manufacturers and users of laser beam welding, cutting, and drilling equipment.

As industrial lasers gain wider acceptance, there is a greater need for skilled process engineers and technicians. The American Welding Society is contributing in this regard, by offering these *Recommended Practices for Laser Beam Welding, Cutting, and Allied Processes*. The intended users of these *recommended practices* are engineers and technicians involved, or planning to become involved, in laser materials processing.

It should be noted that the operating and processing parameters given in this Standard may not be the only parameter combinations that can be employed for successfully processing the materials and thicknesses shown. Changes in material chemistry, dimensional tolerances, laser beam characteristics, machine calibration, and other factors can produce different results. Therefore, the procedures presented here are simply meant to provide a set-up and design guide to help users to organize and learn the process of developing and refining a particular application.

Comments and suggestions for the improvement of this standard are welcome. They should be sent to the Secretary, AWS C7 Committee on High-Energy Beam Welding and Cutting, American Welding Society, 550 N.W. LeJeune Road, Miami, FL 33126.

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Recommended Practices for Laser Beam Welding, Cutting, and Allied Processes

1. Scope

These recommended practices present a description of laser beam equipment and procedures that can be used for welding, cutting, drilling, and transformation hardening of various materials. These recommended practices stress the process basics, parameters, and applications. Practical information has been included in the form of figures, tables, and graphs which should prove useful in determining capabilities and limitations in the processing of various materials. Readers who desire additional information about lasers and laser materials processing should consult the Reference Documents shown in Annex A, as well as the various references given throughout this document.

Any specific manufacturer product depicted in any sketch, figure, table, or product description in the document, shall not be construed as an endorsement of that particular manufacturer or product by AWS.

This standard makes sole use of the International System of Units (SI).

Safety and health issues may not be fully addressed by this standard. Users of this standard should consult ANSI Z49.1, *Safety in Welding, Cutting, and Allied Processes*, applicable federal, state, and local regulations, and other relevant documents concerning safety and health issues not addressed herein. ANSI Z136.1, *Safe Use of Lasers*, is another important source for safe operation of laser equipment. Please consult Clause 4 for more information.

2. Normative References

The following standard contains provisions which, through reference in this text, constitute provisions of this AWS standard. For undated references, the latest edition of the referenced standard shall apply. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply.

AWS Documents:¹

AWS A3.0, *Standard Welding Terms and Definitions*

3. Terms and Definitions

The following terms and definitions are specific to laser beam material processing. Terms that are not part of common welding vocabulary are defined and the definitions of some standard welding terms are changed slightly to more accurately describe those terms as they apply to the laser beam process. Common terms pertaining to all welding processes that are not listed in this compilation shall be found in AWS A3.0, *Standard Welding Terms and Definitions*. Some of the Terms and Definitions have been extracted from *The Photonic Dictionary*.

For the purposes of this document, the following definitions apply:

absorption. The transfer of electromagnetic energy to an atom or a group of atoms that may be in a gas, gaseous plasma, liquid, or solid form. This energy may be released as heat (dissipative absorption) or re-emitted as electromagnetic energy. Most laser material processing involves the transfer of energy by dissipative absorption.

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absorption coefficient. In the passage of a beam through an absorptive material, the loss of intensity of the beam per unit length of the material, usually expressed in cm^{-1} .

absorptivity. A dimensionless measure of absorption which has a value of 1 for a perfect absorber. For an opaque material, absorptivity has a value of $1 - (\text{reflectance})$. For a transparent material, absorptivity has a value of $1 - (\text{reflectance}) - (\text{transmittance})$.

active medium. A substance in a laser generator in which stimulated emission of radiation, rather than absorption or spontaneous emission, will take place after pumping from an energy source has produced a population inversion.

aerodynamic window. A device used to transmit the beam from inside of the resonator to the beam delivery optics in some high-power gas lasers ($>10 \text{ kW}$). It uses a rapid flow of gas, usually air, to create a pressure gradient between laser cavity pressure and atmospheric pressure. This pressure gradient isolates the gases inside the laser cavity from the atmosphere, and prevents contamination of the laser gas.

amplitude. The magnitude of the electric field in a radiation field. The intensity of the radiation in W/cm^2 , is proportional to the square of the amplitude.

amplification. The growth of the radiation field in the laser resonator cavity. As the light wave bounces back and forth between the cavity mirrors, it is amplified by stimulated emission on each pass through the active medium.

angle of incidence. In laser materials processing, the angle between the optical axis of the incident laser beam and the normal or perpendicular to the workpiece or an optical component. A perpendicular angle is most often used.

aperture. The diameter of an opening through which light or laser radiation passes. Also, a device containing a hole through which some percentage of laser radiation passes to alter or measure beam characteristics.

aspheric lens. A lens element in which at least one face is shaped to a nonspherical surface of revolution about the lens axis.

assist gas. A gas used to blow molten metal away to form the kerf in laser beam inert gas cutting, or to blow vaporized metal away from the beam path in laser beam evaporative cutting. In some cases, the assist gas may chemically react with the laser-heated workpiece, producing additional heat which aids the laser-cutting process.

attenuate. To reduce the intensity of the laser beam. This can be accomplished by passing the beam through a partially transmitting medium or through an optical element.

autofocus. A method or device to automatically set the focusing head so that the focusing optic is maintained at a constant distance above the workpiece.

average power. The pulsed laser beam power that is the summation of all the laser pulses averaged over time. Average power (in watts or kilowatts) can be determined by multiplying pulse energy (in joules or kilojoules) times pulse frequency (in hertz).

beam alignment. Adjustment of the optical elements so that the axis of the laser beam coincides with the optical axis of the lenses, mirrors, beam tubes, etc.

beam delivery system. The use of optics, such as mirrors, lenses, tubes, and fibers arranged in such a way that a laser beam can be precisely directed to a specific location in a safe manner.

beam diameter. The diameter of a circular aperture which, if placed in the beam path, would transmit 86.5% ($1e2$ value) of the total power in the beam.

beam expander. An optical system used to increase the diameter of an optical beam. In a laser, this device also serves to collimate the beam.

beam quality. The focusability of a laser beam, commonly specified by the product of the radius of the resonator beam waist and the far field divergence angle. See M^2 .

beam splitter. An optical device used to split an optical beam into two or more optical beams at predetermined power levels.

beam waist. The narrowed region of a laser beam as produced by an optical resonator or at the focal plane of a focusing optic.

brightness. A term often used to describe laser sources, typically by describing the power delivered into the beam focus area expressed in watts per square centimeter. The term can have several meanings, however.

CAD. An acronym for computer-aided design describing a drawing created using computer drafting software, often used with drafting software linked to computer-aided engineering (CAE) software for calculating stress or thermal distributions of objects under load.

CAD/CAM. An acronym for the process of computer-aided design and computer-aided manufacturing, where computers are used both in the design and manufacture of a part.

calorimeter. A thermally sensitive device used to measure the amount of laser output power or pulsed energy.

carbon dioxide laser (CO₂). A gas laser which uses carbon dioxide as the lasing medium and which radiates at a wavelength of 10.6 micrometers (μm). Nitrogen and helium are also used within the laser medium for better excitation and efficiency.

cavity. See **resonator**.

circularly polarized light. A light beam in which the electrical vector is rotating around the axis of propagation at the frequency of the beam. A circularly polarized beam is often used to optimize performance in contour cutting.

classification of lasers. The American National Standards Institute (ANSI) has introduced a classification scheme for lasers or laser systems, based on the laser's potential to inflict injury to personnel. The system is based upon the intensity of emitted radiation from the laser or laser systems. The higher the classification number, from one to four, the greater the potential hazard.

CNC. An abbreviation for computer numerical control, a device that controls a machine tool by reading numerical data and transforming it into movement of machine axes.

coherence. A property of radiation in which the phase between any two points in the radiation field has a constant difference, or is exactly the same throughout the duration and extent of the radiation. Laser light is coherent radiation.

collimated beam. Radiation in which a ray in a given point in the cross-section of a beam is nearly parallel to every other ray, with the degree of parallelism limited by the laws of diffraction.

collimator. An optical system which creates a collimated beam.

conduction mode welding. A melting and fusing operation in which the incident beam energy is transferred to the root of the weld solely by conductive and convective heat flow in the molten metal. See **keyhole mode welding**.

continuous power. See **continuous wave**.

continuous wave (CW). A laser beam which is produced continuously rather than as a series of pulses.

contour cutting. Laser cutting involving motion of the beam relative to the workpiece either by moving the beam or by the workpiece in two or more axes.

cosmetic pass. A partial penetration weld pass made primarily to enhance surface quality and appearance.

damage threshold. The power density at which optical components such as windows, mirrors, and rods are damaged by laser radiation.

depth of focus. The distance along the direction of propagation of a beam for which the power density is greater than 90% of its peak value in the focal plane.

diffraction. The tendency of light to spread out as it passes through space due to wave nature of light. As laser light passes by an opaque edge or through an aperture, secondary weaker wavefronts are generated, apparently originating at that edge. These secondary wave fronts will interfere with the primary wave front as well as with each other to form various diffraction patterns.

diffraction limited. The property of a high quality laser beam, whereby only the effects of diffraction determine the spot size produced by an optical system.

diode laser. A type of laser in which the active medium is a semiconductor with polished end facets forming mirror surfaces. Also called semiconductor laser. Diode lasers used for alignment emit in the visible; other diode lasers emitting in the infrared are used for material processing.

disk laser. Characterized by a heat sink and laser output that are realized on opposite sides of a thin layer of active gain medium. Despite their name, disk lasers do not have to be circular; other shapes have also been tried. Disk lasers should not be confused with Laserdiscs, which are a disk-shaped optical storage medium.

divergence. The expansion angle (measured in milliradians) of an optical beam in the far field. In specifying the beam divergence, one should note whether it is the full-angle or half-angle divergence.

divergence, full-angle. The expansion angle of an optical beam measure on both sides of the optic axis.

divergence, half-angle. The expansion angle of an optical beam measured from the optic axis to the extremities of the beam (as specified by the beam diameter).

doping. The process of adding a small concentration of a lasing ion or atom to a host material. The host material supports the dopants, influences the emission of energy from the dopants, and conducts away excess heat.

dross. The melted and resolidified metal or metal oxide produced during cutting or drilling that adheres to the top or bottom edge of a cut or drilled surface.

duty cycle. The fraction of time that a repetitively pulsed laser is producing pulsed output.

effective spot diameter. See **melted spot diameter**.

energy density. Laser output energy per unit area, expressed, for example, as J/cm².

energy transfer efficiency. The ratio of the heat absorbed by the workpiece to the incident laser beam energy.

enhanced pulse. A laser pulse output containing an initial short-duration burst of power when the discharge is first energized, which subsequently decays to a lower level of output. See **leading edge spike**.

excimer laser. A laser that emits ultraviolet energy from molecules called *excimers* that are created in pulsed electrical discharges and exist only for a very short period of time, on the order of nanoseconds. Excimer lasers use combinations of a gas such as argon, xenon, or krypton with halogens such as fluorine. Wavelengths from 0.193 to 0.348 μm have been generated.

excitation. Process of transferring energy from the energy source to the active medium.

far field. Far from the laser source; a term used in describing how a laser beam propagates. Mathematically, far field occurs at a distance D such that

$$D > \frac{\pi w_o^2}{\lambda} \quad (\text{Equation 1})$$

where,

λ = laser wavelength

w_o = minimum radius of the output laser beam

fast axial flow (FAF). A laser design in which the active medium (gas) is transported at a high speed along the optical axis of the laser resonator so that it can be cooled by external heat exchangers. In industrial CO₂ lasers, where this design is common, either a Roots pump or a centrifugal compressor is used to move the laser gas through the discharge region and heat exchangers.

fiber laser. A solid-state laser design in which the active medium is a doped optical fiber. Ytterbium is the most common active element doped into the fiber.

fiber optic. A small diameter solid fiber made of a transparent material such as fused quartz (or fused silica) and coated to achieve total internal reflection of a laser beam along its path. A fiber optic beam delivery system transmits the output power of the laser to the workpiece and can be bent at a shallow radius, eliminating the use of mirrors.

flashlamp. A device that converts electrical energy into light by means of a sudden electrical discharge. Flashlamps are a source of excitation in a pulsed solid-state laser.

fluence. See **energy density**.

fluence threshold. The energy density level (measured in joules/cm²) at the surface of a material, at which there is sufficient energy to cause molecular bonds to break or some interaction to take place.

F-number. The ratio of the focal length of a lens or focusing mirror to the diameter of the beam incident on the lens or mirror. Note the definition is somewhat different than that for photographic systems.

focal length. In a lens or lens system, the distance from the principal plane, the surface at which the projections of an entering and exiting ray intersect, to the focal point. In a thick lens or system of lenses, the principal plane is often inside the lens itself; for setup purposes, operators often use the back focal length, which is the distance from the front surface of a focusing lens or mirror system to the focal point.

focal plane. A plane through the focal point at right angles to the direction of propagation of the beam where the minimum spot size occurs.

focal point. A nonstandard term for focal spot.

focal spot. A location at which the beam has the most concentrated energy and the smallest cross-sectional area.

focusing head. An assembly located near the end of the beam path that is used to converge an unfocused laser beam for processing materials. The assembly consists of one or more focusing lenses or mirrors, and may include assist- and purge-gas delivery system, a focal point adjustment mechanism, and optic protection devices.

following error. In CNC equipment, the deviation of the actual path traced by the focused beam or by a machine tool from the programmed motion. This error is most important when making abrupt turns at high speed and can be reduced by slowing the speed.

fused quartz. A glass formed by heating crystalline quartz to white heat, then cooling. It has a lower index of refraction than crystal quartz.

fused silica. Glass consisting of almost pure silicon dioxide. It is purer than fused quartz.

gallium arsenide (GaAs). A synthetically grown crystal used, among other things, in laser optics like lenses and mirrors.

gas laser. A laser in which the lasing medium is a gas. This type of laser is subdivided by medium into atomic (such as helium–neon laser), molecular (such as carbon dioxide laser), and ionic (such as argon, krypton, xenon, or helium–cadmium laser, for example). Excimer lasers are also gas lasers.

gas recirculation. A system to circulate the laser gas through the active laser region and the heat exchangers in a closed loop. The gases are cooled and re-excited continually. Commonly used in high-power lasers, a means to circulate the laser gas through the active laser region and heat exchangers in a closed loop.

Gaussian distribution. A symmetric two-dimensional equation which approximately describes the spatial power distribution of many laser beams. The equation of the Gaussian distribution is:

$$P(r) = P_o e^{\frac{-2r^2}{w^2}} \quad (\text{Equation 2})$$

where,

$P(r)$ = power density

P_o = maximum power density

r = radial distance out from the center of distribution

W = radius at which power density is 0.135 times maximum

(see **beam diameter**)

Gaussian mode. The fundamental transverse mode of a stable laser resonator (called TEM_{00} mode). A laser operating in this mode produces a beam having a Gaussian distribution.

glass laser. A laser in which the active medium is an optical glass doped with a small concentration of a lasing material, typically neodymium. Glass is easier to produce than YAG, especially in large sizes, but its thermal properties are not as good as the YAG crystal. See **YAG**.

helium-neon laser. A laser in which the active medium is a mixture of helium and neon, and which commonly has wavelengths in the visible range (400 to 700 μm). They are used widely with materials processing lasers for alignment.

hermetic. The rating of a seal that prevents the exchange of fluids (gases or liquids) between a contained volume and an exterior environment.

irradiance. See **power density**.

infrared (IR). Electromagnetic radiation possessing wavelengths between those of visible light and microwaves, i.e., approximately 0.8 μm to 1 mm.

joule. An SI unit of energy equivalent to 1 W of power lasting 1 second. Used as a unit of measure of the output of pulsed lasers.

kaleidoscope. Optical device used to integrate the transverse mode of the laser beam to be evenly distributed across the beam. Both transmission and reflective types are available.

kerf. The width of a cut produced during a cutting process.

keyhole mode welding. A technique that employs a concentrated heat source with sufficient intensity to vaporize some workpiece material. This results in the formation of a vapor hole (“keyhole”), surrounded by molten material that penetrates deeply into or through the work piece. As the concentrated heat source is advanced, molten metal flows around the walls of this vapor hole, fills in the trailing edge, and solidifies to produce a continuous weld.

kissing weld. A weld on a corner, T-, or lap joint in which the laser beam is incident at a small angle with respect to one of the surfaces being joined, and with respect to the joint to be welded.

laser. A device that produces a concentrated coherent light beam by stimulated electronic or molecular transitions to lower energy levels. Laser is an acronym for “Light Amplification by Stimulated Emission of Radiation.”

laser beam. The output radiation of a laser that can be steered and focused by mirrors, lenses, or both, to do useful work.

laser system. A machine or fabrication tool consisting of a laser, a workpiece holder, and a means of delivering the beam to the workpiece and deflecting it over the workpiece in a controlled manner. The most common type of controller is a computer numerical controller, or CNC.

leading edge spike. The initial phase of a pulse from some pulsed lasers, in which the instantaneous peak power is considerably greater than the average power during the pulse. The leading edge spike is useful in rapidly heating a workpiece to temperatures at which the absorption is greater than that at room temperature. The trailing edge of the laser pulse is used to maintain the high temperature and process the material.

lens. A transparent optical element with curved surfaces, used to converge or diverge light rays via refraction.

M. The magnification ratio of an unstable resonator (i.e., the ratio of the outer diameter to the inner diameter in an annular-shaped beam).

M^2 . A measure of beam quality that compares a laser beam with a theoretically ideal beam that is limited solely by diffraction (i.e., when $M^2 = 1$).

melted spot diameter. The diameter of a melted spot on the workpiece (also known as *effective spot diameter*).

meniscus lens. A lens having one surface convex and the other concave.

micrometer (micron). A distance of one millionth (10^{-6}) of a meter. This term is commonly used in specifying the wavelength of light and is abbreviated as μm .

mirror. An optical element which reflects nearly 100% of the laser beam.

mode. A stable condition of oscillation in a laser. There are transverse modes and longitudinal modes. Longitudinal modes occur at slightly different frequencies; most lasers operate on a large number of longitudinal modes simultaneously. Transverse modes describe the distribution of energy in a plane perpendicular to the direction of propagation. A laser can operate in one transverse mode (single mode) or in many modes simultaneously (called *multimode* or *mixed mode operation*).

monochromatic. Light which consists of single wavelength. Most lasers emit their light in a very narrow band of wavelengths around a central wavelength.

multimode. See **mode**.

near field. A term used to describe the propagation of a laser beam, referring to the beam characteristics at positions close to the laser.

Nd:glass. Neodymium-doped glass which is utilized as the lasing material in some solid-state lasers. The neodymium atoms are the active medium.

Nd:YAG. Neodymium-doped yttrium aluminum garnet (YAG) crystal which is utilized as the lasing material in a common type of solid-state laser. The neodymium atoms form the active medium. See **YAG**.

nozzle. A device projecting from the focusing head with an outlet to direct gas into the laser beam processing area.

optical axis. An imaginary line through an optical system along which the center of a laser beam is expected to follow; the line usually passes through the center point of all optical elements such as lenses, mirrors, apertures, and gain media.

optical coating. Dielectric or metallic coating on an optic with one or more thin surface layers to control surface reflection or transmission as a function of wavelength.

output coupler. A partially transmitting mirror at one end of the laser resonator which allows the extraction of laser energy from the laser.

peak power. The peak power is often approximated by dividing the energy of the pulse, or the energy contained in a leading edge spike, in joules, by the pulse duration in seconds.

percussion drilling. A process by which repeated pulses remove material and increase the depth of a hole until the workpiece is perforated. Subsequent pulses enlarge the hole and remove recast material.

photodiode. A semiconductor device in which light is directly converted to a flow of electricity which can be displayed in a time resolved fashion, for example with an oscilloscope.

photon. The quantum, or small discrete amount, of electromagnetic energy that moves at the speed of light.

plane polarized light. Light in which the oscillation of the electric field is only in a single plane (also called *linearly polarized light*). There are two possible plane polarizations, each one perpendicular (orthogonal) to the other.

plano convex. An optical element with a flat (planar) face on one side and a rounded outward (convex) face on the opposite side, which converges the light incident on the convex side.

plasma plume. See **plume**.

plume. The vapor cloud that forms above the laser material interaction zone. It can consist of excited and partially ionized assist gases and atoms of the material vaporized by the intense laser beam and can have a temperature equivalent to tens of thousands of degrees. Under certain conditions, the plume can absorb or scatter the incoming laser beam, reducing transmission of the beam, the energy absorbed by the workpiece, and weld penetration.

polarization. Limitation of the vibration direction of the propagated electromagnetic field (laser beam) to a single plane. Various forms of polarization can be found; these include random, linear, elliptical, and circular.

polarizer. An optic which transmits light of only a single polarization, or otherwise alters the polarization of radiation.

population inversion. A state in which more atoms or molecules of a lasing medium are at a higher energy level than at some lower energy level. This is necessary to promote the release of photons so that the lasing process can occur.

power. With respect to lasers, power is the rate of energy flow from the radiation source. Power is usually measured in watts (W), an energy flow of a joule per second, or kilowatts (kW).

power density. Intensity, or the power per unit area, of the output of a laser; expressed as, for example, W/cm².

power meter. A device used to measure laser beam power. See also **calorimeter**.

power ramping. A controlled change in the power level of a laser beam. Power ramping is useful for smooth completion of circular welds and for preventing depressions or fractures at the end of the weld.

pulsed laser. A laser which emits light as a pulse or a series of pulses rather than continuously.

pulse duration. The duration measured between the half-peak-power points at the front and trailing edges of a pulse.

pulse energy. The total energy contained in a laser pulse, or a series of laser pulses from a repetitively pulsed laser, usually measured in joules. It is calculated by dividing the measured average power by the pulse repetition rate.

pulse enhancement. See **enhanced pulse**.

pulse frequency. The output pulse repetition rate, in pulses per second (Hz), for a pulsed laser.

pulse length. See **pulse duration**.

pulse overlap. In spot welding with a repetitively pulsed laser, the amount (usually expressed as a percentage of the diameter of the melted zone) by which the diameter of the melted area created by one pulse overlaps that created by the preceding pulse.

pulse shape. The variation in time of the amplitude of a single laser pulse during the pulse duration.

pulse width. See **pulse duration**.

pump. An energy source used to excite the active medium and create a population inversion.

pumping. See **excitation**.

pyroelectric. A crystal which is a source of electrical current when radiation is incident on it; the current is proportional to the time rate of change of the crystal's temperature. The term also refers to laser detectors containing these crystals, which may be used to measure either the laser energy or laser power depending on crystal properties and associated circuitry.

Q-switch. A device used to produce very short duration and intense pulses from ruby or pulsed YAG lasers. A large amount of energy is stored during the off time and a burst of energy is released during the on time.

quarter-wave plate. A polarization retarder which causes light of one linear polarization to be retarded by a quarter wavelength (90 degrees) relative to the other polarization. The quarter wave plate is utilized to convert linear polarization to circular polarization, primarily for cutting applications.

recast. A layer of metal which melts and then solidifies along the walls of a hole or cut edge of a laser processed metal.

reflectance. The ratio of reflected power to incident power.

repetition rate. See **pulse frequency**.

resonator, optical. An optical system formed by two or more mirrors that reflect most light emitted by the medium back into the medium allowing light amplification to take place.

resonator, stable. A resonator in which the radiation reflected between the cavity mirrors converges on the longitudinal axis. A stable resonator can produce a beam with a Gaussian mode.

resonator, unstable. A laser resonator in which a light ray reflected between the cavity mirrors will move away from the cavity axis. The resonator is "unstable" for light propagation rather than mechanically unstable. Usually, laser energy is extracted by a mirror at a 45 degree angle to the optical axis which contains a hole which is aligned with optical axis.

RF excitation. A method of laser excitation using radio frequency waves. This allows excitation through the glass or quartz envelope of the tube, so that the electrodes are isolated from the lasing gas.

rod, laser. A cylinder of transparent lasing material with polished end faces used as the active medium in a laser.

ruby laser. A laser in which the lasing material is a single crystal of aluminum oxide doped with chromium ions. The cylindrical ruby rod is pumped by a pulsed xenon flash lamp, producing a laser output in the red region of the spectrum, at a wavelength of 0.694 μm . Ruby is the material in which laser operation was first demonstrated in 1960.

shutter. A mechanical or optical device used to block or control the transmission of laser beams.

slab laser. A solid-state laser in which the host medium is a rectangular or trapezoidal block of material, usually YAG. Formation of the light beam occurs more uniformly in the material than in a rod laser reducing the thermal gradients in the material.

slow flow. A gas laser in which the flow of gas is along the axis of the laser beam, but is relatively slow so that the extraction of waste heat from the gas is done primarily by thermal conduction through the walls of a tube to a cooling medium.

spherical aberration. The failure of a spherical surface of a lens or mirror to form a perfect image; light rays incident on the surface at different radii come to focus at a different distance from the surface along the optical axis.

spot size. The diameter of a focused laser beam. See **beam diameter**.

stability. The ability of a laser system to maintain a beam with constant output characteristics, such as power level or mode.

standoff. The distance between the focus head's beam exit aperture and the work surface. The standoff distance influences the dynamics of the assist gas interaction with the material being processed.

stimulated emission. The emission of a photon from an atom or a molecule in an excited state in response to the presence of another photon of approximately the same wavelength. The resulting photon will have the same wavelength, polarization, phase, and spatial coherence as the original one.

TEA laser. An acronym for "transversely excited, atmospheric pressure laser." The TEA laser is a gas laser for which excitation of the active medium is provided by an electric discharge transverse to the optical axis of the medium at pressures of one atmosphere or greater. This type of laser is used primarily for marking applications.

TEM₀₀. Laser radiation of the fundamental transverse electric mode. The spatial intensity has a Gaussian distribution. See **transverse mode**.

thermal diffusivity. The controlling transport property for the transient diffusion of heat into the base metal during laser materials processing.

$$\alpha = \frac{\kappa}{\rho c_p} \quad (\text{Equation 3})$$

where,

κ = thermal conductivity

ρ = density

c_p = specific heat

thermocouple. A type of sensor consisting of two electrically conducting circuit elements of different thermoelectric characteristics joined at a junction.

thermopile. An arrangement of thermocouples in series so that the voltages from individual thermocouples add. In a thermopile, the series of thermocouples are arranged such that the alternate junctions of the thermocouple are at the measuring temperature and the reference temperature.

Transverse Electromagnetic Mode (TEM). See **transverse mode**.

transverse flow. Refers to the direction of the gas lasing medium in a gas laser. Transverse flow lasers have the gases flowing at right angles to the direction of laser beam propagation.

transverse mode. The distribution of energy in a plane perpendicular to the direction of propagation. See **mode**.

transmittance. The ratio of transmitted power to incident power.

trepan. A type of drilling where a circular hole is made either by rotating the laser optics within the focusing head, or by programming a circular motion of the focusing head.

up-collimator. See **beam expander**.

wavelength (λ). The distance between two points in a periodic wave which have the same phase.

YAG (Yttrium Aluminum Garnet). A synthetic crystal used as a laser rod host material in Nd:YAG laser.

4. Safety Considerations

4.1 Introduction. The scope of this clause is to introduce users and potential users of laser beam materials processing to important safety considerations. Some of the governing bodies for these areas will be identified and a list of minimum guidelines for safe use of lasers for materials processing will be provided. It should be noted, however, that this is not an all-encompassing document by itself and that all aspects of safety should be considered in developing or implementing a laser application. Personnel involved with lasers and laser materials processing should always read, understand, and follow all of the safety guidelines provided by the laser and machine tool manufacturer, as well as all other pertinent safety standards.

4.2 General Safety. There are a wide variety of potential hazards that can be discussed under the category of general laser safety. These hazards relate to typical minimum safety requirements for any manufacturing or development facility.

The American National Standards Institute (ANSI) in association with The American Welding Society (AWS) has issued a standard which covers the potential hazards associated with welding and cutting processes, ANSI Z49.1, *Safety in Welding and Cutting*. Also, the Occupational Safety and Health Administration (OSHA) has established a range of regulations designed to protect personnel working on or around industrial equipment. As these bodies have established the general safety requirements for welding and cutting, and for industrial environments, no further detail will be provided. OSHA has published Instruction Pub. 8-1.7 on *Guidelines for Laser Safety and Hazard Assessment*. This document was developed to provide guidelines to Federal OSHA and Plant Site Officers, consultants, and employees for the assessment of laser safety. In general, this document cites the standards of the appropriate governing body (AWS, Laser Institute of America (LIA), ANSI) as the minimum acceptable safety criteria. Also, many foreign regulatory agencies have safety standards, regulations, or recommended practices that are either based on ANSI standards or are similar to them.

There are two main bodies that provide specifications on laser safety. The Food and Drug Administrations' Center for Devices and Radiological Health (part of the U.S. Department of Health and Human Services) is concerned primarily with the performance characteristics as they apply to the manufacturer and puts forth its regulations in the *Code of Federal Regulations*, Title 21, Subchapter J, Part 1040.10 on "Performance Standards for Laser Products." These specifications apply to all laser installations, whether they are new installations or modifications to existing facilities. Of primary concern to the laser user, ANSI describes the minimum safety requirements for laser users in their specification ANSI Z136.1, *Safe Use of Lasers*.

4.3 Laser Safety

4.3.1 Classification of Lasers. ANSI Z136.1 divides lasers into four broad categories based on their potential hazards. The following laser classes are derived from the ANSI definitions:

CLASS 1 LASER PRODUCT: Denotes exempt lasers or laser systems that cannot, under normal operating conditions, produce a hazard.

CLASS 2a LASER PRODUCT: Denotes lower power visible laser systems that are not intended for prolonged viewing and, under normal operating conditions, will not produce a hazard if viewed directly for periods not exceeding 1000 seconds.

CLASS 2b LASER PRODUCT: Denotes low-power visible lasers or laser systems which, because of the normal human aversion responses, do not normally present a hazard, but may present some potential for hazard if viewed directly for extended periods of time (like many conventional light sources).

CLASS 3 LASER PRODUCT: Class 3a denotes lasers or laser systems that normally would not produce a hazard if viewed for only momentary periods with the unaided eye. They may present a hazard if viewed using collecting optics.

Class 3b denotes lasers or laser systems that can produce a hazard if viewed directly. This includes intrabeam viewing of specular reflections. Except for the high-power Class 3b lasers, this class will not produce a hazardous diffuse reflection (radiation reflected over a wide angular range).

CLASS 4 LASER PRODUCT: Denotes lasers or laser systems that can produce a hazard not only from direct or specular reflections, but also from a diffuse reflection. In addition, such lasers may produce fire and skin hazards. Of these four classifications, only Class 4 lasers are incorporated into systems used for materials processing. A Class 4 laser may be part of a system designed in such a manner as to be considered a Class 1 laser system. Such a system cannot, under normal operating conditions, produce a hazard. This can be achieved using engineering controls such as enclosures, interlocks, and other mechanisms.

4.3.2 Laser Safety Officer. All facilities with materials-processing laser installations shall designate a Laser Safety Officer (LSO) per ANSI Z136.1. The ANSI standard describes the position and duties of the LSO. These include ensuring that the correct engineering controls are in place and functional. These engineering controls may include, but are not limited to, safety interlocks, signs, signals, and light-tight beam enclosures. Other duties include the implementation of the proper administrative and procedural controls, such as the posting of safety signs and equipment, and ensuring standard operating procedures are posted and followed. All laser installations are required to have a standard format sign posted in the laser operation area, which lists the type of laser, its wavelength, power level, and classification type. Figure 4.1 shows an example of a sign for a Class 4 laser system. The proper format is listed in ANSI Z136.1.

The Laser Safety Officer is also required to determine and inform the pertinent personnel of the maximum permissible exposure (MPE) for the laser system installed in the facility. The MPE is calculated using the formulas and tables in ANSI Z136.1 and limits are given for intrabeam viewing, extended source viewing, and skin exposure. It should be noted that a high-power collimated or unfocused laser beam is more dangerous over large distances than a focused beam, which diverges rapidly. Some laser materials processing operations may be extremely noisy, especially if used in enclosed areas. Proper controls should be implemented to ensure that adequate hearing protection or noise reduction techniques are used.

4.4 Electrical Hazards. The voltages used in lasers are sufficient to cause fatal injuries to personnel and account for most laser-related fatalities. All electrical equipment associated with laser beam materials processing should be installed in conformance to ANSI/NFPA 70, *National Electric Code* and ANSI/NFPA 79, *Industrial Machinery*.

All doors and access panels should be properly secured, either electrically or mechanically, to prevent access by unauthorized personnel to electrical components, especially those operating at the laser excitation potential. All personnel working on or around high-voltage components should be trained in the proper safety techniques for electrical systems, as well as in the technique of removing a victim from an electrical circuit and administering cardiopulmonary resuscitation (CPR). Personnel should be aware of and adhere to any additional electrical safety requirements of the laser system installed in their facility. Wherever access to high voltage is possible, the area should be properly posted in conformance to ANSI Z535.1, *Safety Color Code*, and ANSI Z535.5, *Accident Prevention Tags*.

4.5 Laser Radiation Hazards. There are two potential dangers associated with laser radiation: eye and skin hazards. Depending on wavelength, damage to either the cornea, the retina, or both, of the eye is possible. Exposure to radiation from a CO₂ laser (10.6 μm) typically results in corneal damage. The radiation from an Nd:YAG laser, at 1.06 μm , is much closer to the visible spectrum (0.4 to 0.7 μm) and can be transmitted by the cornea and lens. The lens will focus the laser light on the retina, causing severe and permanent damage to the retina and other intraocular material. This focusing, by the lens of the eye, can cause even low-power diffuse laser light to be focused to a sufficient power density to cause retinal damage. Low-power helium–neon (He–Ne) lasers (0.633 μm), often used for alignment purposes, may also present a hazard. Requirements for eye protection are described in ANSI Z87.1, *Practice for Occupational and Educational Eye and Face Protection*, and the Laser Institute of America's *Guide for the Selection of Laser Eye Protection*. It is important that the selected eye protection be clearly marked to ensure it is only used for the laser wavelength and power levels for which it is intended. ANSI Z136.1, and the LIA's *Laser Safety Guide* describe the proper warning signs and labels that should be employed wherever beam exposure is possible.



Figure 4.1—Sample Precautionary Sign for a Class 4 Laser System

Skin damage is restricted primarily to burns. It should be noted, however, for high-powered lasers these burns can be deep and cause severe and permanent damage. As stated above, ANSI Z136.1 defines the MPE for all laser wavelengths, including the typical industrial lasers and He–Ne alignment lasers.

4.6 Visible Radiation Hazards. Viewing of the visible radiation emitted during laser materials processing can also be harmful to eyesight. During welding, a bright plume, similar in appearance to a welding arc, is generated from the interaction between the laser beam and material being processed. The size and intensity of this plume is a function of the material being processed, the power level, and the shielding gas used. Consequently, no exact guidelines can be given. However, the radiation emitted is broadband, from the ultraviolet, which can cause skin erythema (sunburn) and photokeratitis (arc eye) through the visible to the infrared, which can contribute to the formation of cataracts.

As the plume is generally too bright for direct viewing, adequate filtering, such as welding shades, should be employed for eye protection. As a general guideline, the filter used should be of sufficient optical density to ensure the viewer's comfort at the highest level of light intensity encountered and there should be no evidence of eye irritation after exposure. The optical viewing system should provide filtering in conformance to ANSI Z87.1 and should include provisions for filtering the visible and ultraviolet radiation from the plume as well as the laser radiation. All persons involved with laser beam materials processing should be instructed in the use of proper optical filtering and should be required to use such protection.

4.7 Hazards from Fumes and Gases. Welding, cutting, drilling, and surface modification with lasers may result in the generation of fumes, dust, and gases that can be hazardous to personnel. These airborne contaminants may include metal particles and oxides, ozone, and other toxic gases. The hazards associated with welding and cutting of metals have been documented in a variety of American Welding Society publications, including *Fumes and Gases in the Welding Environment*. It should be noted that some organic materials, such as plastics, can generate fumes that are hazardous. Care should be taken to avoid the excessive buildup of laser discharge gases, shielding gases, and assist gases, especially in enclosed spaces where oxygen can be displaced, as described in ANSI Z117.1, *Safety Requirements for Confined Spaces*.

All necessary environmental engineering measures for fume and gas control (external venting, filtering, etc.) should be taken to prevent the accidental inhalation of harmful concentrations of fumes and gases by personnel working on or around laser materials processing equipment. Exhaust of these fumes may violate local or federal standards, and implications should be considered before using equipment. The possible toxicity of the workpiece and consumables (wire, powder, etc.) should be determined before laser beam materials processing begins. Adequate protection to personnel should be provided in conformance to ANSI Z49.1. Also, for all materials, the Material Safety Data Sheet (MSDS), available from the material supplier, should be consulted to determine what hazards exist.

5. Equipment Description

5.1 Description of Process. Laser is an acronym of Light Amplification by Stimulated Emission of Radiation, a process first demonstrated in 1960. The laser generates a coherent optical beam that has an essentially constant wavelength; the phase and amplitude at any particular time has a known relationship to that at another time. Laser output has been demonstrated at thousands of different wavelengths, but only a few have industrial application.

The laser consists of several major components as shown in Figure 5.1. These components include: (1) a lasing gain medium, (2) a means to excite the gain medium, (3) an optical resonator, and (4) a heat sink. The gain medium may be a solid, liquid, or gas. The optical cavity is used to provide a feedback system for the system to achieve enough amplification to overcome the losses within the system.

There are many different types of lasers available for material processing, which have significantly different kinds of outputs. Wavelengths vary from less than 0.2 to over 10 micrometers (μm); pulse durations range from below 1 nanosecond (ns) to continuous wave; peak powers can be measured in megawatts (MW); and average powers go up to several kilowatts (kW). The laser beam is sent either through the atmosphere or through fiber optics to a work station.

For most production applications, the carbon dioxide (CO_2) and the neodymium doped yttrium-aluminum-garnet (Nd:YAG) lasers are used (see Table 5.1). A brief discussion of the operation of these lasers follows.

5.2 CO_2 Lasers. The carbon dioxide (CO_2) laser is the most powerful type of industrial laser presently available. It is in general use for contour cutting and deep penetration welding. The long wavelength of CO_2 light, 10.6 μm , is absorbed by most solids. This allows CO_2 lasers to process a wide variety of materials.

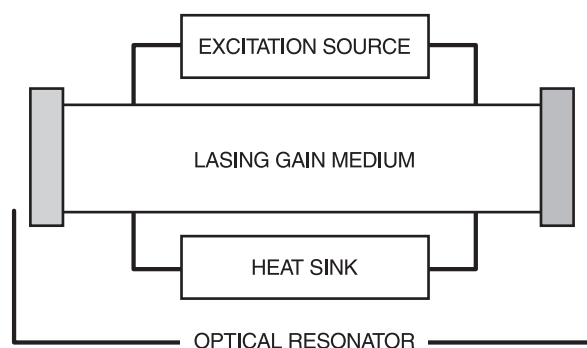


Figure 5.1—Four Major Components of a Laser

Table 5.1
Operational Comparison of CO₂ and Nd:YAG Material Processing Laser

	CO ₂	Nd:YAG
Active Medium	CO ₂ , N ₂ He Gases	Nd:YAG Crystal
Excitation	Electrical Discharge	Lamp
Wavelength (microns)	10.6	1.06
Average Power (kW)	0.1–45.0	0.1–5.5
Peak Power (kW)	0.1–50	0.1–100
Pulse Frequency (kHz)	CW—100	CW—50
Efficiency (%)	5–15	1–4
Beam Quality (M^2)	1–3	1–2 special applications 10–100 typical
Consumables	CO ₂ , N ₂ He Gases	Lamps
Transmissive Optics	ZnSe, GaAs	Quartz
Reflective Optics	Metal	Metal or Dielectric
Fiber Delivery	Not Available	Quartz
Safety Shield	Acrylic, Glass	Filters
Capital Cost (\$/Watt)	50 200	100–400

5.2.1 Principle of Operation. The CO₂ laser is a gas discharge device; it operates by sending an electric current through a gas. In industrial lasers, high efficiency is obtained by using a mixture of helium, nitrogen, and carbon dioxide. Other gases such as oxygen or carbon monoxide may be added to alter the chemical equilibrium in the laser gas. Electrical energy is coupled to the gas by establishing a glow discharge in the nitrogen. The nitrogen transmits this energy to the CO₂ molecules by resonant transfer, which puts a large percentage of the molecules in an elevated energy state. The carbon dioxide provides the population inversion required for operation as a laser. Laser emission at 10.6 μm in the infrared is produced when these molecules drop to an intermediate state. Collisions between carbon dioxide molecules and helium atoms return the CO₂ to the ground level, where the process can begin again. The helium also provides discharge stability.

The gas is typically passed through a heat exchanger where it is cooled, allowing it to be recycled. Large chillers are required for high-power CO₂ lasers. CO₂ Laser efficiencies, which are high for lasers, are still only 6% to 10%, and all the rest of the incoming power is converted to heat.

5.2.2 CO₂ Laser Resonators. Two groups of resonator configurations, stable and unstable, are used in industrial carbon dioxide lasers.

5.2.2.1 Stable Resonator. To sustain laser oscillation, optical feedback must be provided. This is usually accomplished with an optical resonator consisting of a pair of spherical mirrors facing each other (see Figure 5.2).

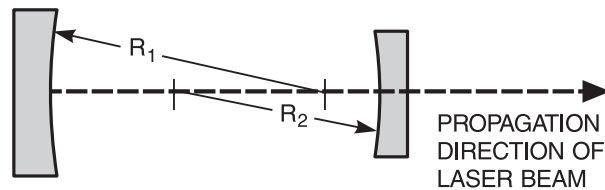


Figure 5.2—Stable Laser Resonator

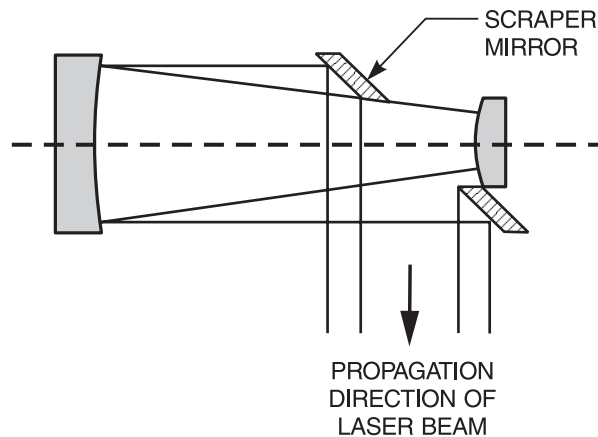


Figure 5.3—Confocal Unstable Laser Resonator

A resonator is stable if rays of light initially near the axis of the mirrors are kept confined between them. This condition is met if, for mirrors of radius R_1 and R_2 spaced a distance L apart:

$$0 < \left(1 - \frac{L}{R_1}\right) \left(1 - \frac{L}{R_2}\right) < 1 \quad (\text{Equation 4})$$

The radii, R_1 and R_2 are defined as positive for concave mirrors. Most lasers up to the 6 kW level have stable resonators. Output mirrors for this optical cavity are generally transmissive materials, with antireflective (AR) and reflective thin-film coatings. Stable resonators generally use pairs of concave mirrors, or a flat mirror and a concave mirror. Such structures can sustain oscillation of electromagnetic waves at well-defined axial resonance frequencies; these frequencies are referred to as *longitudinal modes*. The particular amplitude (or intensity) patterns of the waves in a plane transverse to the direction of propagation are referred to as the *transverse modes*.

5.2.2.2 Unstable Resonator. A laser beam can only get out of a stable resonator by transmission through one of the resonator mirrors. This requires that the mirror be partially transmitting to the wavelength of light generated in the laser, and that it be mounted so that the beam can go through it. At very high powers, absorption in the mirror can cause heating, optical distortion, and damage. To avoid these consequences, high-power systems are often designed with unstable resonators in which energy is not confined within the cavity and can be extracted using reflective optics. Instead of being transmitted through a partially transparent mirror, the transmitted beam goes around the edge of an otherwise totally reflecting mirror. Unstable resonators have modes analogous to those of stable resonators, although their mathematical form is not as simple, and they require involved numerical calculations to define them. A confocal unstable resonator, as shown in Figure 5.3, produces an output with an annular power distribution. For CO₂ lasers with output powers greater than 6 kW, a transparent front mirror cannot be used and the excitation gases are kept inside the resonator by the use of an aerodynamic window through which the laser beam exits.

The magnification ratio, M , of unstable resonators is the ratio between the outer and inner diameters of the annular power distribution and is important in establishing a balance between power and beam quality. For a particular resonator configuration, the power that can be extracted is zero at $M = 1$, increases to a maximum near $M = 2$, and then drops off slowly

as M increases further. When an unstable resonator beam is focused, there is a central power peak surrounded by diffraction rings. At low magnifications near $M = 2$, most of the power is in the diffraction rings, so the focusability and power density are low. As M increases, more of the power goes into the central spot, allowing high-power densities to be reached. For CO_2 lasers, magnification ratios of about 4, which reduce power by about 25% from the maximum, produce beams that are nearly as focusable as those from low-order stable resonators.

Note that the magnification, M , of an unstable resonator is quite different from M^2 used to indicate beam quality.

5.2.3 Output Characteristics of CO_2 Lasers

5.2.3.1 Temporal. CO_2 lasers can operate in continuous wave (CW) or in a variety of pulsed modes controlled by the power supply driving the discharge (see Figure 5.4). The pulse frequency may be as high as 100 kHz, although complete modulation of the output is seldom achieved above 2 kHz. The most common modes of pulsing are termed *gated* and *enhanced*. In a gated mode, the laser operates at a peak power level that is within its normal CW range. The output is modulated to generate a reduced duty cycle. Gated pulses can be any length that is compatible with the chosen repetition rate. Lasers that can produce enhanced pulses have peak powers that are several times their CW rating.

5.2.3.2 Spatial. The low density and high thermal diffusivity of a gaseous laser medium reduce the tendency to distort the light that goes through it. This allows even high-power CO_2 lasers to have good beam quality. Beams from many lasers with outputs of up to 1.5 kW are close approximations to the fundamental Gaussian mode TEM_{00} . These beams produce a spatial intensity distribution in a plane normal to their propagation direction that is as shown in Figure 5.5. Such beams may be focused to the limit set by the diffraction of light through an aperture (diffraction limited). A spot size of 0.1 mm is easily achieved by normal focusing lenses for CO_2 lasers with a TEM_{00} beam.

Another property of TEM_{00} beams is low divergence, which allows great flexibility in laser system design since the laser does not have to be near the focusing lens. Divergence is simply the angle at which the laser beam spreads as it propagates. The typical values are in the range of 1 milliradian.

CO_2 lasers with maximum continuous powers over 1.5 kW usually have higher order or multimode outputs. The effect of high order or multimode outputs in material processing is that such beams do not focus to as small a spot as the beam from a TEM_{00} laser although the spatial intensity distribution may still be bell-shaped and quite similar to a Gaussian distribution in appearance. These beams can be focused to a spot with a diameter M^2 times the diffraction limit, where M^2 is a measure of beam quality associated with the mode (see 5.2). It is generally not possible for higher power lasers to generate a TEM_{00} beam because output mirrors cannot handle high central power densities, and their resonators are intentionally configured to produce higher order modes. Most CO_2 lasers exceeding 6 kW in power use an unstable resonator, which produces a beam with good focusing properties without having to send high-power densities through transmissive optics.

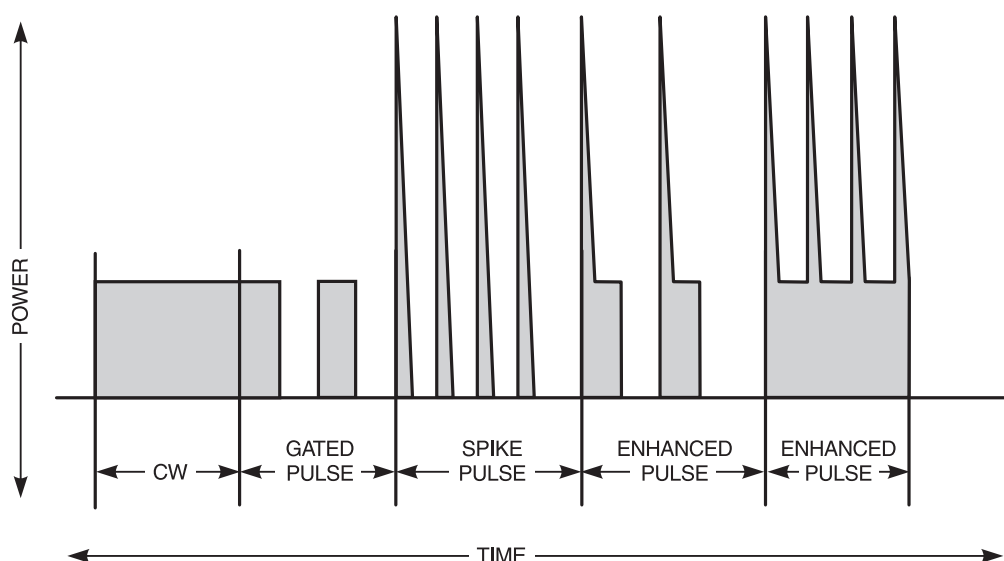


Figure 5.4—Examples of Laser Temporal Pulse Shapes

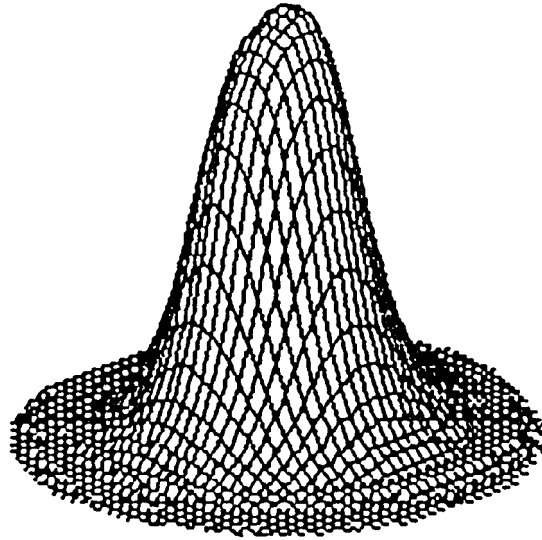


Figure 5.5—Spatial Intensity Distribution for a Near Gaussian Mode Laser

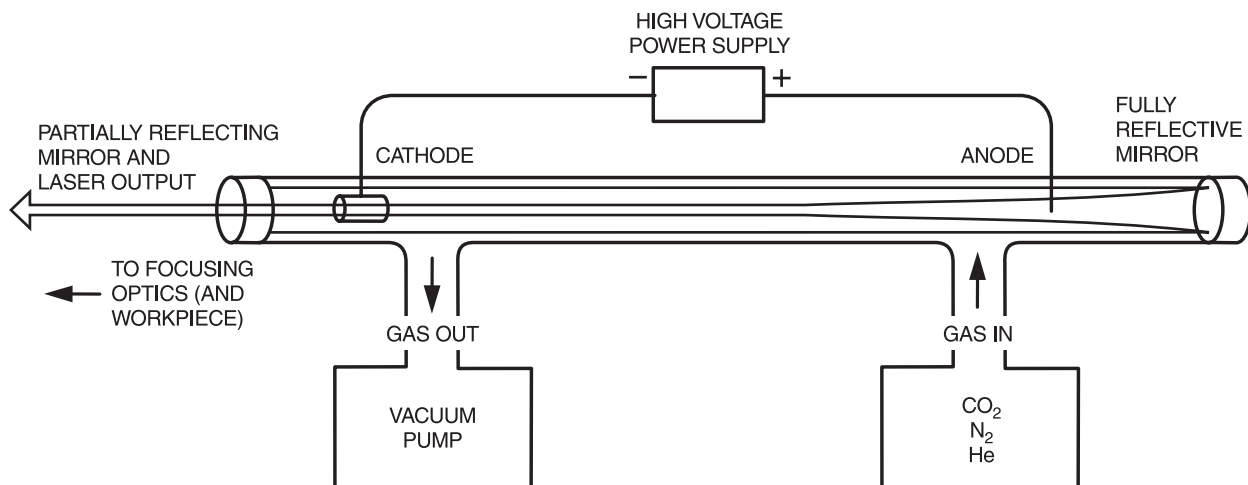


Figure 5.6—Schematic Diagram of a Slow Axial Flow Laser

5.2.4 Types in Use. The earliest industrial CO_2 lasers consisted of glass tubes with mirrors on both ends. The laser gas flowed down the tube while electricity was applied near each mirror. These devices are very simple and reliable, but are limited to about 50 W per meter of discharge length because there is no means to cool the gas. These are called slow-flow lasers (see Figure 5.6). The size of slow-flow lasers becomes impractical if more than one or two kilowatts is required. They are in use today because they can produce stable high quality outputs and because the large volume of active medium allows for massive pulse enhancement.

The transverse flow laser was developed to produce high power in a relatively small package. It does this by circulating the laser gas perpendicular through the discharge region at high speed and then cooling it with a heat exchanger so that it can be reused (see Figure 5.7). Transverse flow lasers tend to have asymmetrical modes because the gain characteristics of the discharge vary across the beam. In addition, they are hard to pulse because they operate at high discharge currents. Despite these limitations, transverse flow lasers have been extensively implemented into laser welding systems.

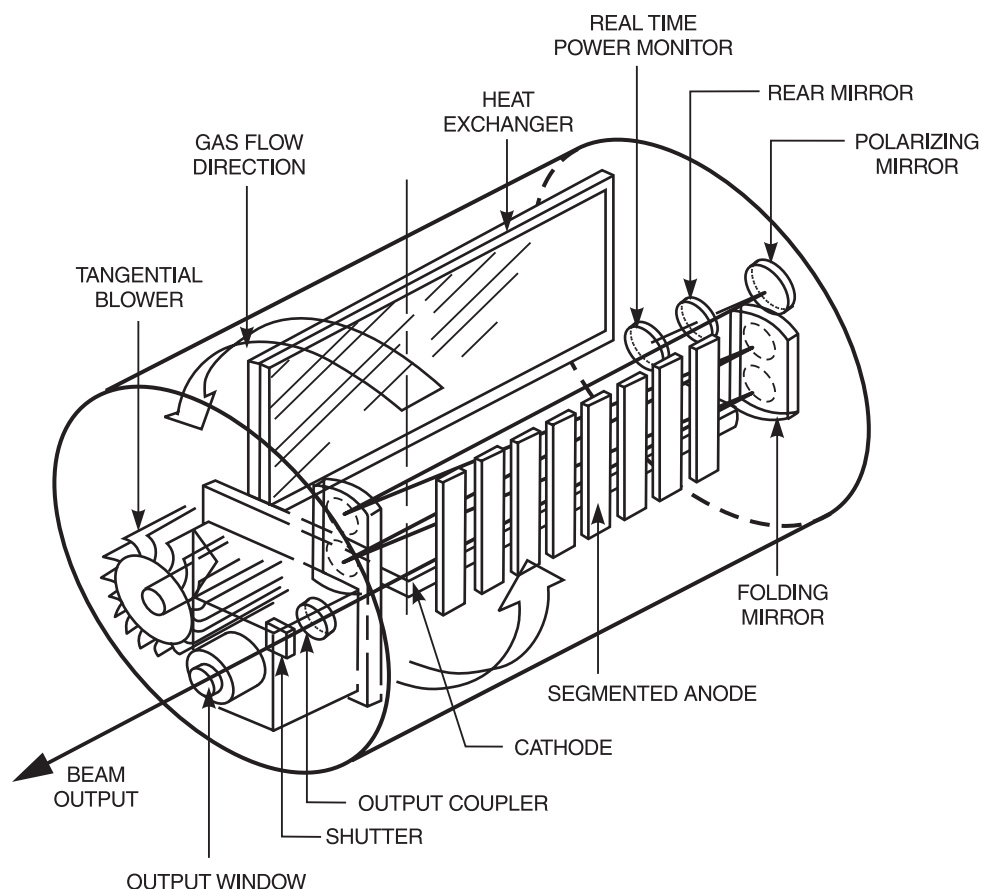


Figure 5.7—Schematic Diagram of a Transverse Flow Laser

Fast axial-flow lasers are a modification of the slow-flow laser using either a Roots or turbine pump to circulate the gas (see Figure 5.8). The high-speed gas movement has resulted in laser designs with up to 1 kW power output per meter of resonator length. Fast axial lasers are small, powerful, inexpensive to build, and can have excellent beam quality. Thus, greater power in a smaller equipment package is achieved.

5.3 Nd:YAG Lasers. A solid-state laser uses a transparent solid substance as the active medium. The most common solid-state laser in industrial applications is the neodymium doped yttrium-aluminum-garnet laser, commonly referred to as the Nd:YAG laser. Nd:YAG is used as the host crystal because it has relatively high thermal conductivity, high mechanical strength, good optical quality, and can be grown in large sizes.

Because the 1.06 μm light from the Nd:YAG is transmitted easily through flexible quartz fibers, system design can be considerably simpler than with CO₂ lasers. In addition, the Nd:YAG wavelength is absorbed more readily by metals than CO₂ laser radiation, further improving process efficiency.

5.3.1 Principle of Operation. An industrial Nd:YAG laser contains a crystalline rod surrounded by xenon or krypton lamps, or by light-emitting diodes. Energy is transferred from the lamps or diodes to the host crystal by reflectors parallel to the crystal. Light from these sources excites the neodymium atoms, which emit light at a wavelength of 1.06 μm (see Figure 5.9). In order to get higher powers, several water-cooled rods may be placed in series. Nd:YAG lasers have electrical efficiencies of about 1% to 4%, and need large chillers to maintain their optical elements at stable temperatures.

The majority of Nd:YAG lasers currently installed are pulsed; however, continuous power units are available for high-rate cutting and welding applications. Pulse durations may be as short as 0.1 milliseconds, pulse rates as high as 2000 Hz, and peak power levels are up to 100 kW. The mode structure of the majority of these lasers is multimode. Multimode Nd:YAG lasers are focusable down to a spot size of 75 μm . Resonator mirrors for this laser are fused quartz with AR and reflective thin-film coatings.

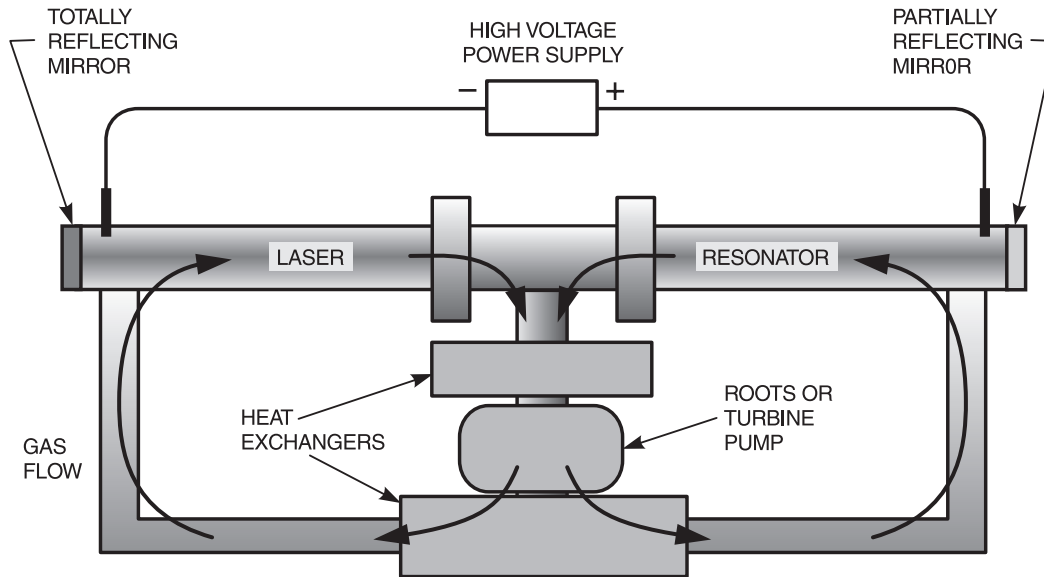


Figure 5.8—Schematic Diagram of Fast Axial Flow Laser

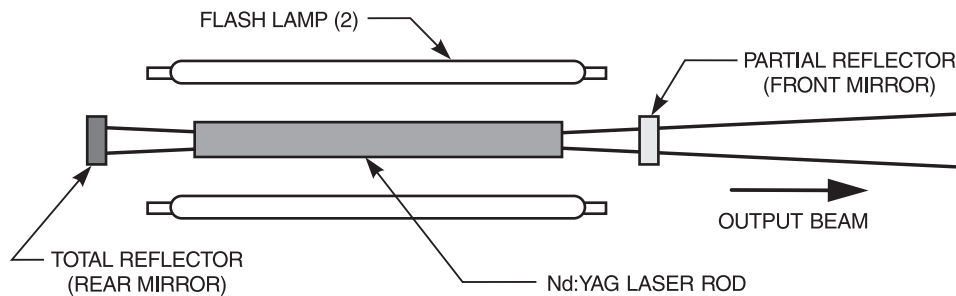


Figure 5.9—Schematic Diagram of a Solid-State Nd:YAG Rod Laser

5.4. Output Characteristics of Nd:YAG Lasers

5.4.1 Temporal. Nd:YAG lasers may be operated in either pulsed or continuous wave (CW) modes. Pulsed Nd:YAG lasers have flashlamps or diodes, while CW Nd:YAG lasers use continuous arc lamps. Nd:YAG lasers cannot be switched from pulsed to CW operation because the excitation equipment (lamps and power supplies) is distinct and significantly different for each type. Pulse repetition rates are generally below 200 Hz. Control of the power going into the lamps allows tailoring of the laser-pulse shape and duration. The solid laser medium has a high concentration of light-emitting atoms, so the peak power can be very high. Material removal is usually accomplished with short, high-power pulses, while joining is done with longer pulses of lower peak power or with a continuous beam.

5.4.2 Spatial. Laser rods accumulate heat in the center as they are cooled along their outside surface. Therefore, there will be a temperature gradient across the rod's diameter whenever substantial power is produced. This gradient induces changes in the rod's refractive index, which degrades the optical performance of the laser. High-power Nd:YAG lasers have multimode outputs with high divergence. This limits the ability of optics to focus the beam to a small spot, and requires the resonator to be near the work area.

The total internal reflection face pumped laser (TIR-FPL), also called the “slab” laser, reduces this problem by bouncing the beam from side to side within a rectangular crystal, compensating for thermal gradients in the material

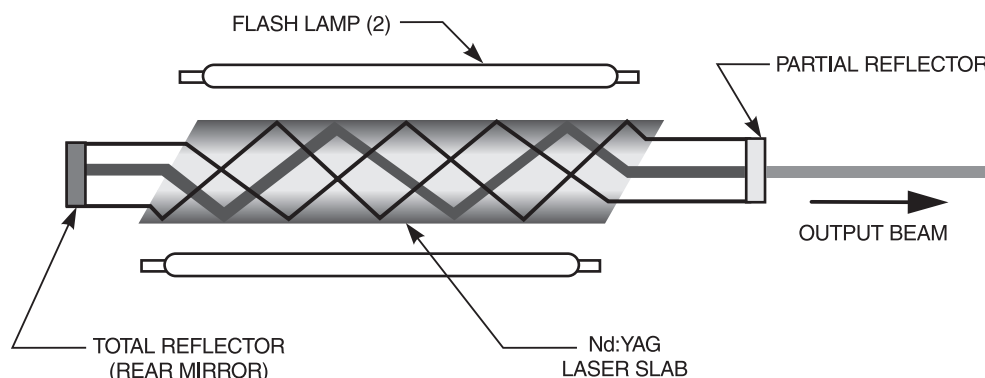


Figure 5.10—Schematic Diagram of a Total Internal Reflection-Face Pumped (TIR-FP) Slab Laser

(see Figure 5.10). The thermal stresses in the YAG medium, which distort the laser light, are canceled-out as the light crisscrosses the long axis between slab-surface reflections.

5.5 Other Types of Material Processing Lasers

5.5.1 Nd:glass. Nd:glass lasers are very similar to Nd:YAG lasers. The laser rod is made of neodymium-doped glass rather than garnet. When glass rather than YAG is used as a matrix, a higher concentration of neodymium atoms can be incorporated in the laser rod. This allows glass lasers to produce stronger pulses than Nd:YAG lasers, which makes them more appropriate for deep drilling. Because the poor thermal conductivity of glass limits the pulse frequency to about one pulse per second, this type of laser is not used for contour cutting.

5.5.2 Ruby. Ruby was the first material in which laser emission was observed. The ruby laser is a flashlamp-pumped solid-state device like the Nd:YAG and Nd:glass lasers, but emits visible light. Although largely replaced by other types, it is still suitable for drilling, with characteristics similar to Nd:glass lasers.

5.5.3 Excimer. The excimer laser is an electrically excited gas laser. The gases used vary, but are always combinations of inert gases (argon, xenon, and krypton) with halogens such as fluorine. In the discharge, excited dimmers such as KrF, and trimers such as KrF₂, can be formed. These are unstable molecular forms that emit ultraviolet light when they dissociate. The name excimer is a contraction of excited dimmer. Wavelengths from 0.193 to 0.348 μm have been generated. Because of the short lifetimes of the excited states, excimers operate only in a pulsed mode. Pulse duration is very short, in the range of 0.01 to 0.5 μsec , while peak power can be as high as 100 kW.

The UV output and high peak power of the excimer laser are very attractive for material processing. Drilling, marking, material removal, and cleaning have been done which exploit these unique characteristics.

5.5.4 Fiber Lasers. Fiber lasers and fiber laser amplifiers were originally developed for the telecommunications industry. As the power output capability increased, fiber lasers were packaged for industrial applications and are finding extensive use in cutting and welding, applications. Just as neodymium ions can be doped into YAG rods and slabs for applications in industrial Nd:YAG lasers, these and other ions can be doped into silica or other substrates that can be drawn into long thin fibers. The surface layer of the fiber, called cladding, is doped to give it a higher index of refraction so that it acts like a mirror; the laser radiation is reflected off the walls of the fiber but can be transmitted down the core of the fiber in a nearly lossless fashion. The core of the fiber is typically <20 μm in diameter; the entire fiber including the cladding is 125 μm in diameter. Outside the cabinet in which the beam is generated, the fiber is within an armored sheath which provides protection during handling.

Wavelength selective Fiber Bragg gratings act as the resonator mirrors and hence define the laser cavity in the active fiber. There are gratings, called fiber Bragg gratings, at both ends of the length of fiber that contains the active ions. The gratings consist of a sequence of short lengths of fiber in which the index of refraction has been modified by irradiation with an intense ultraviolet light. The sequence of modified regions reflects light for which the wavelength corresponds to the spacing between the modified regions. Light of other wavelengths is however transmitted through the gratings with

little effect. The length of fiber in which the grating has been imbedded act as wavelength-specific mirrors. At one end of the region containing the active ions, there is a grating that acts as a total reflector; at the other end is a weaker grating that acts as a partial reflector, allowing some of the laser light to escape from the resonator and pass down the fiber.

The ions imbedded in the fiber laser are excited by light from shorter wavelength diodes. The diode light can be injected through the cladding of the fiber or into the end of the fiber, and passes through the fiber Bragg grating which is wave-length selective; it reflects the laser light but allows the pump light to pass through. A visible alignment beam can also be injected in the end of the fiber, passes through the gain region, and comes out the active end of the fiber along with the processing beam.

The length of fiber that constitutes the fiber laser can be bonded directly to an additional length of fiber that delivers the beam to a remote worksite. The beam transmitted out of the fiber is usually of very high quality, and can be focused too small a spot-size. Fiber lasers can be either continuous or repetitively pulsed. Single-mode lasers up to 10 kW and multimode lasers up to 50 kW average power are available. These multimode lasers are made by coupling together the output of many single-mode lasers. The “wall plug” efficiency of fiber lasers (ratio of electrical power in to optical power out) is 20% or higher.

The fiber laser produces excellent beam quality for high average power industrial lasers. Single mode laser beams may be transmitted to the workpiece by a single mode fiber as small as 15 μm or by larger diameter multimode fibers to produce a more top-hat beam profile if required for welding. Fiber lasers are capable of very high speeds for cutting thin materials (<6 mm) and provide efficient, highest aspect ratio keyhole welds. Alternately, longer focal length lenses allow for less sensitive, more tolerant processing.

Q-switched fiber lasers with nanosecond pulses are now available up to 500 W average power for certain ablation type processes.

The active element doped into the fiber in most cases is ytterbium, in which case the wavelength of the output is very close to the wavelength of the Nd:YAG laser (see Figure 5.11). Alternatively, the active element may be erbium or thulium, in which case the wavelengths are in the range of 1545 and 1950 nm respectively. This wavelength is not transmitted by the cornea of the eye and hence may very occasionally be preferred for low power industrial applications.

5.5.5 Disk Lasers. The disk laser is a diode-pumped Yb:YAG (Ytterbium: Yttrium Aluminum Garnet) laser. The active laser medium is a thin disk which is excited from the front surface by diode lasers. The back surface of the disk is mounted to a cooling block, which has a highly reflective surface and acts as a mirror in the laser resonator (see Figure 5.12).

Thin-disk lasers are particularly attractive for the generation of ultrashort pulses at very high power levels. In addition to the high-power capability, the main advantages in this context are: the ease of achieving diffraction-limited operation (which is a prerequisite for mode locking), the broad gain bandwidth of Yb:YAG (the so far most suitable gain medium for thin-disk lasers), and the very small nonlinearity of a thin disk, which helps to avoid excessive nonlinear phase shifts despite the high intracavity peak intensities, and thus in many cases allows the use of much simpler techniques.

5.6 Laser Systems. In order to process material, a laser must be integrated with a way to deliver the beam and the means to handle the workpiece. All laser contour cutters and most welders are controlled by a computer. The most common type of control is one which reads numerical data and transforms it into axis commands. Such devices are called *computer numerical controls*, or *CNCs*. Additionally there are many laser processing applications implementing programmable logic control systems where multi-axis contouring is not required. The focusing head, also called a cutting head or a welding head, consisting of a lens or mirrors and provisions for assist gas, and must be maintained at the correct distance

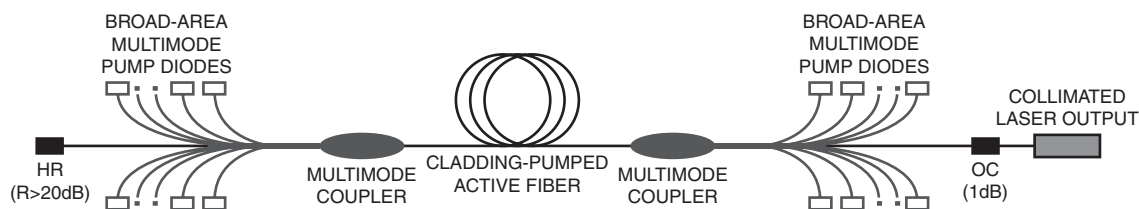


Figure 5.11—Schematic of the Basic Components of a Fiber Laser

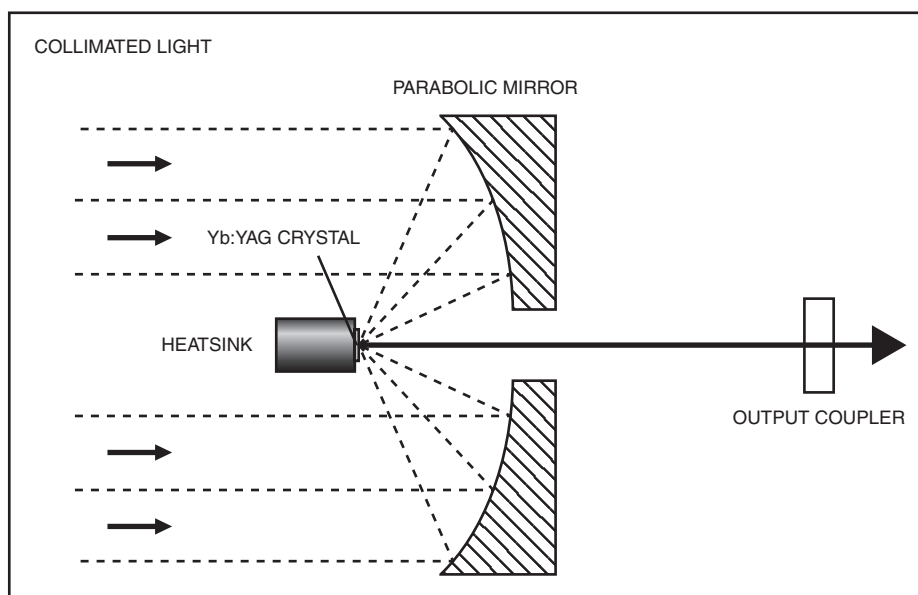


Figure 5.12—Principle of Thin Disk Laser Cavity

from the part to be processed. These components must often be enclosed to provide safety for personnel. The entire package is termed a *laser system*.

The focus distance and spot size that result when an optic focuses a laser beam are well-defined functions of the distance between the focusing optic and laser. Because of their high divergence (the beam spreads out rapidly as it leaves the resonator) Nd:YAG lasers are usually set within one meter of the focusing optic and maintained at that distance. The small size of a Nd:YAG laser resonator allows it to be set on a moving axis, so that there are no significant in-process variations in the focus. When fiber optics are used for Nd:YAG beam transmission, the resonator to focusing optic distance is not an issue.

CO₂ lasers, however, present a different challenge. Though the laser resonators are large and best kept stationary, their low divergence allows the beam to propagate 10 m or more, without significant beam expansion. Spot size variation can occur when the process parameters are set correctly for a specific laser-to-lens distance and then the distance changes, as with a moving beam system. Large changes in distance will change the beam diameter and resulting spot size, with possible loss of process quality.

Along with speed, repeatability is required from production systems. Many laser welds need beam-to-part alignments held under 0.1 mm. Part positioning using manual adjustments and viewing systems, which are common on general purpose welders, are unsuitable for high production rates. The fixturing, motion system, and control must be adequate to maintain the required alignment without manual adjustments. For example, commercially available manipulators, such as pipe rollers, may have insufficient control of rolling speed and positional accuracy for the laser process to be consistent.

There is considerable variety in the design of laser systems. Machines are available for contour cutting of sheet metal, drilling of turbine blades, slitting of sheet materials, miniature component welding, and high-speed welding on production lines.

5.6.1 Cutting Workstations

5.6.1.1 Two-Dimensional Workstations. Laser contour cutters must generate relative motion between the cutting head and the workpiece. This can be accomplished by moving the head, the work, or both. Many machines that move the work attach it to a moving table, while others slide the material over a stationary platform. Each approach has advantages and disadvantages. It is easier to put a small or odd shaped part on a table than to set it in grips, while a stationary platform allows repositioning of large sheets, does not allow the laser beam to hit the fixturing, and has great advantages in fume collection.

For optimum quality, all the optical elements in the beam delivery system should be held motionless, since any vibration or misalignment results in poor cut quality or inaccuracy. Fixed optics, however, require that the workpiece move, which is a complicated operation when cutting large sheets. The minimum floor area that a fixed beam system can have is four times the maximum sheet size, which is a problem with large workpieces. Automatic sheet feeding and part removal is difficult, as is accurate contouring with widely varying loads. Under these conditions, moving one or two optics simplifies the laser system. With two-dimensional “flying optics” systems, sheets move only when they are being loaded onto or removed from the cutting table. The axis drives always handle the same load, allowing servo response to be optimized for X and Y optic motion. Hybrid systems combining fixed and flying machine attributes move one optic for the X-axis and the sheet/table for the Y-axis, thus negating some of the disadvantages of each configuration.

There are, however, several problems that appear when the optical system has to move. These include:

(1) **Divergence.** Laser beams do not propagate unchanged through space. Their diameters and other properties vary as a function of distance from their source. Since, with a moving beam system, the focusing lens intercepts the laser beam at different locations, the focal point location and spot size will vary. The net result is that cutting conditions could vary at different locations on the table.

(2) **Alignment.** With fixed optics it is only necessary to get the laser beam through the delivery system without it clipping any apertures. For a moving beam to function properly, it must be set up so that there is no change in alignment across the entire range of axis travel. This is a far more critical constraint than that demanded of a fixed beam, made worse by the fact that there are more mirrors, that they are on mechanical slides subject to acceleration and vibration, and the beam path is generally longer.

(3) **Rigidity.** There is little penalty for making a fixed optic rigid by building a massive support structure. However, if the optic structure is moving, it must be designed and constructed to suppress vibration, resist deflection, and be low in weight to limit inertial effects generated by acceleration. Excesses in any of these areas will result in quality variations.

(4) **Beam Path Cleanliness.** All high-power laser systems are sensitive to dirt on their optical elements. Dust particles that settle on lenses and mirrors are heated by the beam, causing damage to the components. As a result, all industrial laser systems must seal the beam path against the contaminants that exist in shop environments. This is simple to do for a fixed beam, but more complex when the elements are moving. In many moving beam systems, the laser optics share enclosures with gears, motors, and other generators of contaminants, leading to short optics life.

5.6.1.2 Multi-Axis Workstations. Multi-axis machines can take the form of robotic, gantry, or portal mechanical structures. The engineering difficulties involved in making a multi-axis motion system are similar to those described above for the two-dimensional moving beam, only more severe. The ability of multi-axis equipment to cut complex contours, however, makes the effort worthwhile.

New challenges have appeared as multi-axis machinery has entered production. Sheet metal cutters are usually programmed off-line using CAD/CAM systems to generate instructions for the machine’s numerical control, allowing the laser to cut parts continuously. Programming multi-axis equipment is more difficult, since some CAD/CAM systems are incapable of generating machine code for cutting on three-dimensional contours. In addition, many contoured parts are not well specified, so that numerically generated programs fail to fit the actual workpiece. As a result, multi-axis equipment usually operates in the teach mode, where the operator leads the machine through the desired path while the computer records position data. Since this is a slow process which ties up very expensive equipment, it is desirable to implement another programming method. An optical device that replaces the cutting head has been used to read an indicator line on the workpiece. This is much faster than manual teaching, but still stops production during teaching and reattachment/realignment of the cutting head. Alternatively, a separate measuring machine can simulate the multi-axis machinery in teach mode, allowing programming to be accomplished without interfering with production work.

As CAD/CAM capabilities grow, downloading of three-dimensional cutter path data to the multi-axis system will become the most effective and efficient programming process.

5.6.2 Welding Work Stations. It is possible to weld with many laser systems, even those designed for cutting. In many cases, a system comprising a laser, positioning tables, and CNC can be used for short-run welding along with drilling and cutting work merely by changing the laser settings and cutting down the flow of assist gas. At the other extreme are systems designed and built to weld specific assemblies on production lines. Such dedicated systems can have very high production rates; for example, 1600 laser welds per minute are performed on razor blade cartridges.



Figure 5.13—Laser Beam Welding Equipment

The most effective general-purpose laser welding systems have multi-axis motion control. Welding workstations can be constructed similar to the cutting systems described in 5.6.1. A common welding configuration utilizes a two-axis table motion and a vertically mounted laser focusing head (see Figure 5.13). The table moves in X- and Y-directions, while the optics move in the Z-direction. Flexibility is enhanced with tilting and rotary axes hardware mounted to the table, which provide angular and rotary motion for welding parts. Such machines have been built with lasers ranging from low-power Nd:YAG to multi-kilowatt CO₂, and with work envelopes of several centimeters to a meter or more.

5.5.3 Laser Equipment Accessories

5.6.3.1 Enclosures. Enclosures vary greatly to suit the intended use of the systems. Large systems are often unenclosed Class 4 devices requiring operators and bystanders to wear laser safety glasses. Smaller systems usually incorporate enclosures with interlocked doors for safe operation in any surroundings. Systems used for hermetic welding of electronic devices are often enclosed in glove boxes so that the packages contain a detectable inert gas after welding. Company policy, local, state, and federal regulations should be examined to determine the enclosure requirements for a laser system installation (see Clause 4, *Safety Considerations*).

5.6.3.2 Optics. The optical elements available for laser systems vary considerably depending on the (1) laser resonator type, wavelength, power, and manufacturer model, (2) processing characteristics required, and (3) service environment. A recommended practice for all beam delivery systems requires that the number of optical surfaces be kept to the minimum number needed for motion/process function. Additionally, all of the following items need to be considered in implementing a beam delivery system:

- (1) Transmissive or reflective focus element
- (2) Water or air cooling required for the laser power transmitted
- (3) Focal length and physical configuration of the focus element (plano convex, meniscus, aspheric, parabolic, spherical, 90 degrees, 45 degrees)
- (4) Gas shielding system
- (5) Beam diameter compensation required (i.e., collimator) if divergence is severe and/or beam path is dynamic and lengthy
- (6) Optical element substrates and coatings needed to accommodate or influence the required beam characteristics and yield adequate service life

Coaxial viewing optics, often seen on Nd:YAG laser focusing modules, are of great benefit in setting up a welding job on a work station. The most critical part of laser welding is often fixturing and aligning the beam to the weld joint, and direct observation of the laser's path on the workpiece is the easiest way to ensure good results. Coaxial viewing optics are not common on CO₂ laser systems; implementation is difficult because of the large difference in wavelength between visible

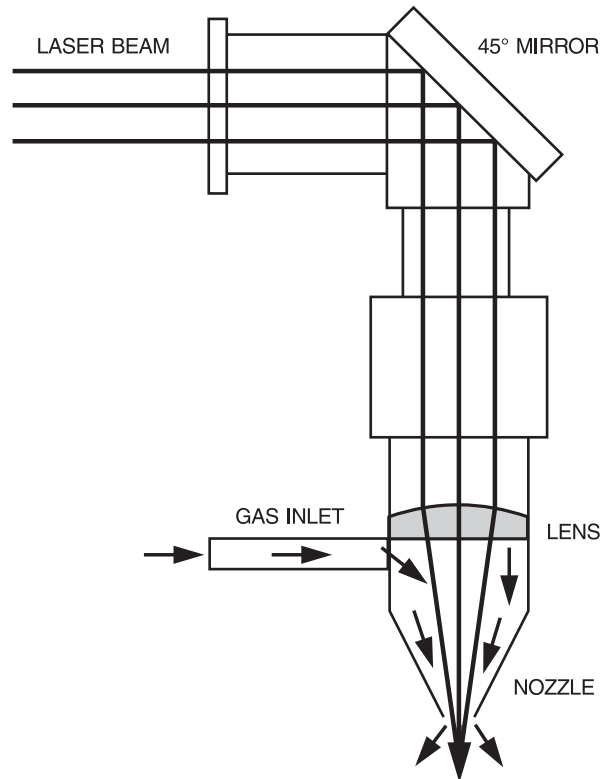


Figure 5.14—Focusing Head

and laser light. Viewing systems applicable to Nd:YAG lasers with fiber optic beam delivery systems are located after the beam emerges from the fiber.

5.6.3.3 Focusing Head. A focusing head consists of a lens or mirror to concentrate the beam on the workpiece, appropriate mounting devices (air or water cooled), and gas delivery, which may be a coaxial cutting assist gas, various configurations of weld shielding gas, or a plasma suppression gas. The head may also contain manual or electronic devices to monitor and control the distance between the head and the workpiece.

Nd:YAG and low-power CO₂ laser beams are typically focused with a lens as shown in Figure 5.14. Properly configured mirrors have performance equivalent to lenses. Water-cooling will provide process performance stability and enhance the optic's life expectancy.

Most laser systems move the final optical element to focus the laser energy on the work. This movement is usually obtained by a CNC controlled drive motor attached to the focusing head. This motion can be from less than 1 mm to many meters. The relationship between the surface of the workpiece and the focal point of the lens is one of the most important processing variables, so control is essential to maintaining process consistency. The depth of focus for CO₂ systems can range from ± 0.1 mm up to ± 2.5 mm, depending on the focal length of the optic used. In many cases, part variation is greater than this. It is important for the system to provide some way to maintain the focus condition when processing such materials. CNC programming of the focusing head movement, based on measurements of the part variation, is one method of maintaining consistent standoff distance.

Machines that cut flat sheets often have heads that ride on the surface of the work with ball bearings. This approach works well for unfinished parts of a regular shape such as tubes or flat sheets, but is unsuitable for contoured material, and the ball bearings can mar highly finished parts. A more sophisticated approach is to attach a drive motor to the focusing mechanism and control it with a sensor. Capacitive probes work well in all orientations and do not protrude from the focusing head, but are restricted to conductive workpieces. Contact probes, consisting of a fork or cup around the nozzle, work on any material, but function best in the vertical direction.

5.6.3.4 Optic Protection. During laser materials processing, material ejected from the interaction point can strike the lens and damage it. Molten and vaporized debris can be ejected at nearly the speed of sound, and a small amount of this material can reach the lens, especially one with a short focal length. Lens damage from spatter can be controlled by using expendable cover shields. This is less practical with CO₂ lasers because optical-quality materials transparent to 10.6 µm light are nearly as expensive as the lenses themselves, reducing the savings.

To obtain adequate lens life, focal lengths of 200 mm or more are typical for CO₂ welders. As power increases, even this distance will be insufficient to ensure adequate lens life. An inexpensive salt window is sometimes used with low-power CO₂ lasers to protect the focusing optic from debris, but the lower peak power of these lasers greatly reduces the velocity of the ejected material, so that it is much less of a problem. An air jet blowing across the beam between the lens and the weld can be used to deflect ejected particles. Gas jets are usually sufficient to protect the CO₂ optics from ejected material. With Nd:YAG lasers, a coaxial gas assist and a cover slide are usually employed to protect the lens from debris. The cover shield is an inexpensive glass slide or a plastic film that is transparent to the beam. As the cover slide gathers debris, it absorbs some of the beam energy, and performance is degraded. Generally, the cover slide is replaced, or the plastic tape is indexed, at intervals to minimize energy loss.

Another method to protect optics is to use an aperture-disk spinning between the focusing lens and the material. Laser pulsing is synchronized with the spinning of the disk, so that the pulse is delivered just as the aperture is positioned directly under the lens; the lens is protected from the ejected debris by the solid section of the disk as the aperture is spun out from under the lens.

5.6.3.5 Fiber Optics. Optical fibers for laser beam delivery are solid strands of transparent materials. Fused quartz is the preferred fiber optic material. The long, slender, defect-free construction provides excellent flexibility and allows light to pass through long sections with very low transmission losses. At present, fiber optics are mainly used for Nd:YAG and Ytterbium fiber disk lasers.

The fibers used with Nd:YAG lasers are of “step index” design. These fibers have a core (the diameter is generally 0.4 to 1.0 mm) with a high refractive index surrounded by a cladding with a lower refractive index. Transmission of light occurs by total internal reflection at the interface between the core and cladding. For total internal reflection to occur, the light must strike the interface at a low angle of incidence (ϕ). This means that light must enter the fiber within an angle of the transmitting fiber axis. The sine of the angle is called the *numerical aperture* of the fiber and the cone described by rotating around the fiber axis is its *acceptance cone* (see Figure 5.15).

High-power capacity fibers use quartz for both core and cladding. The cladding is doped to alter its index of refraction. Quartz–quartz fibers have an acceptance angle of about 12 degrees. To get the laser light into the fiber, a lens is used to focus the beam to a spot smaller than the fiber diameter. The lens must also have a focal length long enough to keep all the light within the acceptance cone of the fiber.

A 2.4 kW average power Nd:YAG laser beam can be sent through a 600 µm diameter fiber. Power losses range between 6% and 10% and occur almost entirely at the input and output ends of the fiber. Transmission losses are on the order of 0.1% per meter. Sharp bending, torsion, or both, of the fiber causes losses because of the altered transmission path. A bend radius of 200 mm is the approximate limit for thick industrial fibers.

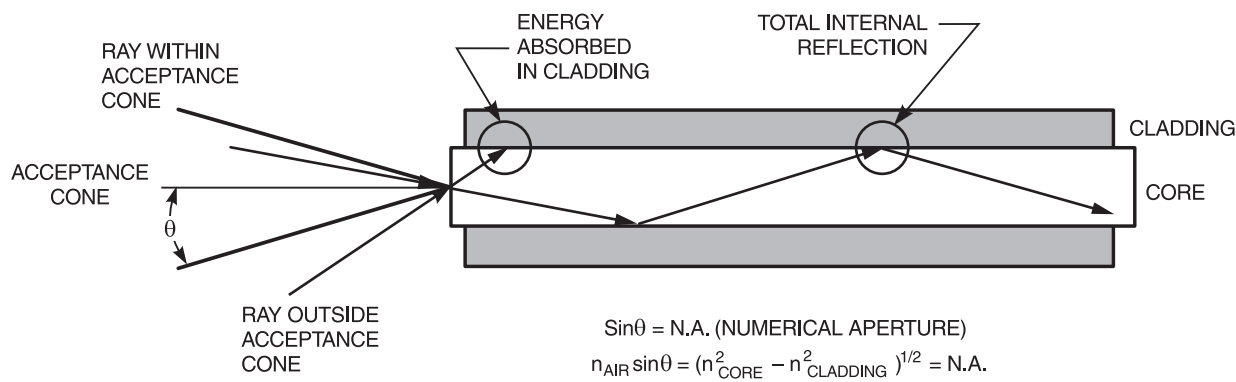


Figure 5.15—Transmission of Laser Beam Through a Fiber Optic

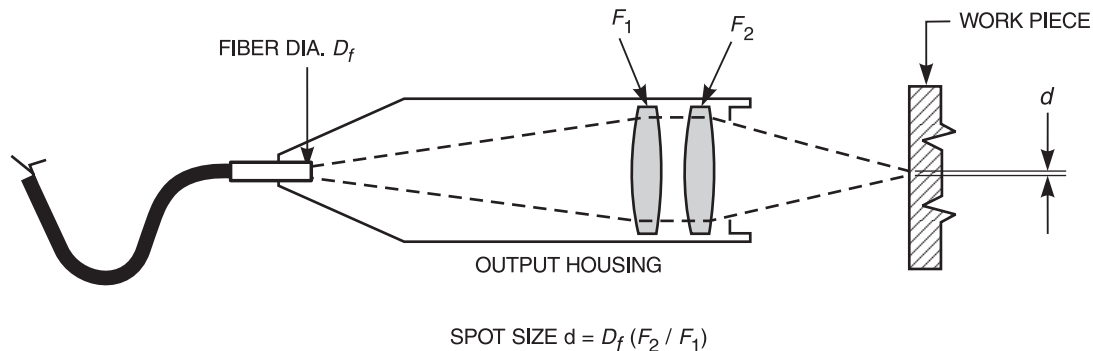


Figure 5.16—Schematic of Fiber-Optic Focusing System

Once the beam is in the fiber, the mode structure is lost. The energy comes out of the fiber with a near uniform power density across the fiber diameter and diverges at the angle φ . To handle this output, a focusing device similar to the input collector is used to form an image of the fiber end on the workpiece. Magnification ratios of 1.0 to 0.5 of the fiber diameter are possible. Figure 5.16 shows a typical focusing head for fiber optic beam delivery.

5.6.3.6 Chiller. Operating the laser system components (resonator and optics) at their optimum temperature is critical to maintaining consistency and function. Typically, the laser temperature is required to be much lower than that which is needed for the optics. If a single-loop chiller is implemented, the optics must run at a temperature dictated by the laser. This situation can cause condensation on the optics if the laser cooling temperature is low and if the dew point of the laser station's work area is not strictly controlled. A dual-circuit chiller is recommended to provide separately controlled cooling loops for the laser resonator and for the optical elements and to avoid condensation problems. Laser optics handling average powers less than 500 W do not require cooling.

5.6.3.7 Exhaust. The high-power density characteristics of laser processing, specifically material removal, often produce airborne particles that are unlike the fumes of other mechanical or thermal processes. The airborne particles could contribute to employee health problems, environmental concerns, and long-term degradation of the laser system's components. It is recommended that the compatibility of the processed material with the exhaust system be considered. For adequate fume removal, the system and filter media substrate must be properly sized and configured (see 4.7).

5.7 Fixturing

5.7.1 General Aspects of Fixturing. Fixturing is required to ensure that the workpiece is located in a defined position with respect to the laser spot. The fixture may also serve to protect the workpiece from spatter, and must restrain the workpiece from shifting due to (1) relaxation of residual stress, (2) heat input of the process, (3) force exerted by assist gases, or (4) motion inertia. Fixture construction materials should be resistant to spatter and nonflammable.

5.7.2 Design of Fixtures. Depending upon the particular application of the laser cutting or welding process, fixturing can be as simple as a manual clamping device or as complex as an automatic chucking device. For simple, low production-rate applications, manual holding devices are appropriate if designed in a fashion to accommodate good part-to-part fit-up. Sophisticated holding devices are widely used in high-production automated applications. A production fixture should be designed with the following desirable features:

- (1) Cut lines or weld joints must be accessible to the beam.
- (2) The fixture must be more rigid than the assembly.
- (3) Hold-downs, clamps, and threads of bolts and nuts should be protected from cutting, drilling, and weld spatter.
- (4) The fixture should allow inspection of the processed workpiece.

5.7.3 Fixtures for Cutting. Fixtures for cutting are almost always fabricated so that the beam is incident normally to the workpiece. Since welding forces due to thermal expansion of material are absent in the cutting operation, fixtures for cutting can be less robust than for welding.

5.7.3.1 Fabrication of Fixtures. In CNC equipment, it is often possible to fabricate the fixture using a CNC program, and modify the same CNC program to perform the cutting operation.

5.7.3.2 Assist Gas. Laser beam cutting is always done with an assist gas. The workpiece must be designed or installed to minimize hot metal spatter onto vulnerable components (clamps, chucks, components of the motion system, etc.) or coming into contact with low melting point material (e.g., nonmetallics when cutting metals). High-pressure/high-flow assist gas applications, such as nonferrous material cutting, will require fixture and clamping rigidity to resist the force of the gas jet.

5.7.3.3 Transmitted Beam. When cutting, not all of the beam energy is absorbed by the workpiece, and some fraction of the energy of the beam is transmitted through the workpiece. Correct procedures will minimize this beam loss. If this transmitted energy could cosmetically or otherwise damage another part of the workpiece, then a beam dump or other protective measures must be designed into the workpiece or cutting setup (see 5.6.5 and 5.6.6).

5.7.3.4 Reflected Beam. When cutting low melting point materials, such as plastics, or materials that char (e.g., wood or paper) the portion of the beam that passes through the workpiece should be absorbed or deflected in some manner so that it does not reflect from the mounting devices. Even a diffuse beam can cause surface melting or charring of the workpiece, damaging the cosmetic appearance of the components.

5.7.4 Fixtures for Welding

5.7.4.1 Features of Welding Fixtures. A fixture for welding should have the following features:

- (1) It must be designed to give the intimate part-to-part contact required for laser welding.
- (2) It must allow precision alignment of the beam with the joint.
- (3) It must allow upper bead weld shielding nozzles.
- (4) In many cases, the fixture itself will incorporate a root bead gas shield.
- (5) Consideration should also be given to fixturing the part in a fashion so as to not allow a full penetration weld to penetrate into the fixturing itself.
- (6) Tooling and fixturing should be designed so as to not allow confinement of smoke and welding fumes from the weld. These may result in partial absorption of the optical energy of the beam and contamination of laser focusing optics.

5.7.4.2 Thermal Considerations. Heat may be dissipated into any fixturing which is directly beneath and in contact with the parts being welded. In other words, the fixture can act as a heat sink. Caution should be taken to avoid build-up of heat in the fixture that may result in distortion which can affect part positioning. Production fixtures often use water cooling, especially those with close tolerance moving parts.

Note that though the heat input during laser welding is minimal, some clamping is still recommended to retain the pieces in position while being welded. For example, in performing butt welds between two lengths of pipe, heat input while welding on one side of the pipe may cause sufficient expansion so that a gap occurs on the other side of the pipe. As a consequence of this thermal expansion, there may be significant mechanical forces, and fixtures should be sufficiently robust to maintain the alignment of the beam with the joint throughout the welding process.

5.7.5 Spatter-Masking Materials. Spatter occurs in laser processing operations such as cutting, drilling, and welding due to the violent ejection of material from the laser interaction area. Spatter-masking and beam-stopping methods are required when adjacent surfaces require protection from adherent spatter.

Adherent spatter may be unacceptable due to cosmetic or surface finish requirements, and may result in costly processing to remove. Unacceptable spatter adherence can occur during laser drilling, cutting, or welding and may not be avoidable by parameter selection alone. There are several conventional and unconventional products that can be applied to material surfaces to prevent spatter adherence. Any spatter-masking product should be tested to assure chemical and metallurgical acceptance for the desired application. Any fumes or gases produced by the addition of a spatter masking material must be tested for environmental, health, and safety concerns. Proper ventilation must always be used. Table 5.2 lists several products that may be used as spatter-masking materials. Brazing stop-off compounds may also be used, but will be difficult to remove if heated by direct laser absorption or by heat conducted through the workpiece.

Good candidates for spatter-masking should be easily applied prior to, and easily removed after, laser processing. Materials that readily evaporate when heated will not offer long-term protection in typical multiple hole laser drilling. The base material to be processed will dictate the spatter-masking chemistry. Titanium alloys will not tolerate any compounds that decompose to produce oxygen or vaporous hydrocarbons. On the other hand, low-strength carbon steel alloys may tolerate vegetable oil.

Spatter-masking materials should be applied sparingly. In the case of laser beam welding, the faying and immediate adjacent surfaces should be free of any spatter-masking materials.

Table 5.2
Spatter Masking Materials for Laser Processing

Material	Usage
GMAW Spatter Sprays	LBD, LBC, and LBW
Magnesium Hydroxide	LBD, LBC, and LBW
Boron Nitride	LBD, LBC, and LBW
Soybean Oil	Carbon Steel
Diatomaceous Earth	High Temperature Applications

5.7.6 Beam Stopping Materials. Beam-stopping materials are used in laser beam cutting and drilling of hollow cavities. Film air-cooling holes are often laser drilled in gas turbine blades; holes are drilled through the outer wall of the part, and it is undesirable to damage or drill through the opposite cavity wall. Beam-stopping material is typically inserted or injected into the internal cavities to prevent this from occurring. It should be noted that beam-stopping materials are usable only if the drilling duration or number of shots are precisely controlled. Unlimited drill time will eventually penetrate through most beam stopping materials. Care should be taken when using highly reflective materials, such as copper, for beam stops. The reflection is often enough to cause internal damage to a part. Some beam-stopping materials can cause deleterious metallurgical reactions if they are in intimate contact with the back side of the workpiece being drilled.

The most common beam-stopping material is wax or plastic. Hot wax or plastic is easily injected into the internal cavities. The wax captures the breakthrough spatter and prevents damage to the opposite cavity wall. After processing, the wax or plastic material can be removed from the part by heating in a furnace and allowing the hot liquid material to drain. Copper strip is also effective as a beam-stopping material if the cavity is accessible for insertion and removal of the strip. In situations where reflection from the copper may cause damage or personnel hazard, graphite may be a more suitable beam-stopping material.

6. Process Control and Monitoring

6.1 Introduction. Because laser materials processing is primarily an automated process and is used in the manufacture of high-value-added products, the requirements for process control are often more difficult than for other traditional fusion welding processes. This section will describe a variety of methods, ranging from simple to complex, which can be employed to manage laser materials processing. The monitoring methods to be used and the level of process control required will depend on the individual needs.

6.2 Laser Beam Quality. The most critical process control task in laser materials processing is the control of incident laser power density via focusing of the laser beam. Focusing of industrial lasers is the process of imaging the beam waist of the laser cavity. Where this waist is located depends on the type of laser and its construction details, but all laser beams will diverge from a minimum waist radius at an angle (see Figure 6.1) which will determine the focusing properties of the laser beam at all other subsequent optical components.¹ The product of this cavity waist radius (T) and the far field divergence half angle (2) is a measure of the laser's beam quality or its focusability. It is a fundamental property of an industrial laser that cannot be improved upon by the introduction of other optical components outside the laser cavity. Low-power scientific lasers and some high-power gas lasers have excellent beam quality since they can be operated in the diffraction-limited mode and will have a minimum $w\phi$ product of:

$$w_o \phi_l = \frac{\lambda}{\pi} \quad \text{(Equation 5)}$$

where

λ = the wavelength of the laser

High-power industrial solid-state lasers and some high-power gas lasers will be operated in multimode and therefore have $w\phi$ products many times greater than the diffraction-limited value shown above. A useful way to compare the beam quality of lasers is to divide the actual $w\phi$ product for a given laser at its rated power by the diffraction-limited value:

¹ Ifflander, R., 1986, Focusing of Multimode Laser Beams with Variable Beam Parameters, *Optica Acta*, 33(8):1083–1090.

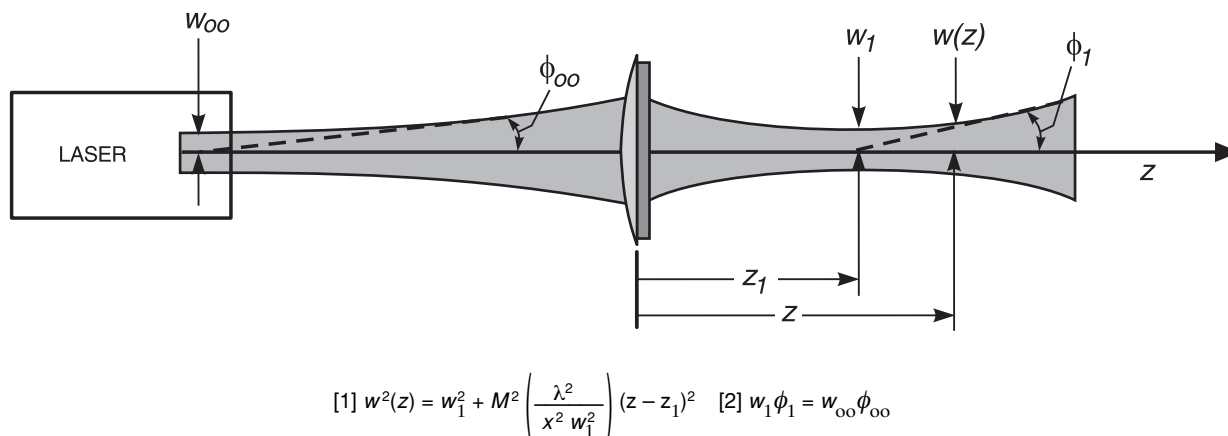


Figure 6.1—The Equations for Propagation of Multi-Mode Laser Beam Through a Focusing Lens

$$M^2 = \frac{w\phi}{w_o \phi_o} \quad (\text{Equation 6})$$

The product $w_o \phi_o$ is as given in Equation 5 above. This parameter, M^2 , is measure of beam quality, which indicates how close the output of a laser beam is to the ideal diffraction-limited output and thus helps to quantify laser beam quality (as does the numerically equivalent description for laser output “times-diffraction-limited”).

6.3 Power Density Control

6.3.1 Optic Selection. It is instructive to consider this $w\phi$ product when specifying the focusing optics to be used in a given welding application. It is apparent from Figure 6.2 that the angle of the laser beam exiting a focusing optic, ϕ , depends on the focal length of the optic and the diameter of the beam, D_B , entering the optic. Since the product $w\phi$ is the same at all optical elements, the focused spot size is determined by the focal length of the lens, f , and the diameter of the beam entering the optic. The spot size gets smaller as the entering beam diameter increases and as the focal length of the optic decreases. The effective F number (F#) of the optic is:

$$F\# = \frac{f}{D_B} \quad (\text{Equation 7})$$

Spot size is directly proportional to F number; optics with small effective F numbers produce small spot sizes. Typically, the diameter of the focusing optics for a particular industrial laser welder is fixed and increasing the size of the beam entering the optic in a controlled manner is not practical; the easiest way to decrease the spot size is to decrease the focal length of the focusing optic. With many industrial lasers, the diameter of the laser beam is not fixed and varies with the laser output power, as a result, the effective F number and spot size will change accordingly.

Whether using a lens or a mirror, the beam passes the focusing optic and converges until it reaches a minimum diameter. The beam remains close to this diameter for some distance. The distance over which the diameter remains relatively constant, such that the peak power density is greater than 90% of its peak value at the focus, is called the depth of focus. Beyond this region, the beam diverges considerably. The focal plane of the optic exists within the depth of focus region and represents the smallest beam spot size. When the part to be welded is located with its surface in the depth of focus region, the part is said to be “in focus”, and when the part is welded with its surface outside the depth of focus region, it is said to be “partially defocused.”

Generally, the longest focal-length optics practical are used for laser materials processing. Longer focal length optics have a greater depth of focus; in addition, their greater standoff distance helps prevent material particulates and vapors from being deposited on the focusing optics or the protective cover. Short focal length optics (lower F numbers) are selected when either a high-power density or a very small spot size is required. Careful consideration should be given to select an optic that will provide the proper power density required for the processing application.

6.3.2 Effect of Beam Quality on Focusing. Small weld widths and higher power densities can also be obtained by reducing the $w\theta$ product of the laser beam by changing the output mode of the laser beam. Some CO₂ lasers can be operated in several different modes and some modes will have lower $w\theta$ products and therefore smaller spot sizes.