Photonics-Enabled Technologies

Laser Welding and Surface Treatment

OP-TEC

Optics and Photonics Series

Laser Welding and Surface Treatment

Photonics-Enabled Technologies: Manufacturing

OPTICS AND PHOTONICS SERIES

STEP (Scientific and Technological Education
in Photonics), an NSF ATE Project

OP-TEC
National Center for Optics and Photonics Education

This document was developed by OP-TEC: The National Center for Optics and Photonics Education, an initiative of the Advanced Technological Education (ATE) program of the National Science Foundation.

Published and distributed by
OP-TEC
University of Central Florida
http://www.op-tec.org

ISBN 1-57837-395-6

PREFACE

This module is one of four pertaining to manufacturing as a photonics-enabled technology. The combined series on photonics-enabled technologies (comprising both STEP and OP-TEC materials) consists of modules in the areas of manufacturing, biomedicine, forensic science and homeland security, environmental monitoring, and optoelectronics, as listed below. (This list will expand as the OP-TEC series grows. For the most up-to-date list of modules, visit http://www.op-tec.org.)

Manufacturing

Laser Welding and Surface Treatment
Laser Material Removal: Drilling, Cutting, and Marking
Lasers in Testing and Measurement: Alignment Profiling and Position Sensing
Lasers in Testing and Measurement: Interferometric Methods and Nondestructive Testing

Environmental Monitoring

Basics of Spectroscopy
Spectroscopy and Remote Sensing
Spectroscopy and Pollution Monitoring

Biomedicine

Lasers in Medicine and Surgery
Therapeutic Applications of Lasers
Diagnostic Applications of Lasers

Forensic Science and Homeland Security

Lasers in Forensic Science and Homeland Security
Infrared Systems for Homeland Security
Imaging System Performance for Homeland Security Applications

Optoelectronics

Photonics in Nanotechnology

The modules pertaining to each technology can be used as a unit or independently, as long as prerequisites have been met.

For students who may need assistance with or review of relevant mathematics concepts, a review and study guide entitled *Mathematics for Photonics Education* (available from CORD) is highly recommended.

The original manuscript of this document was prepared by Jack Ready (consultant) and edited by Leno Pedrotti (CORD). Formatting and artwork were provided by Mark Whitney and Kathy Kral (CORD).

CONTENTS

Laser Welding and Surface Treatment

INTRODUCTION

High-power laser beams focused to small areas can deliver enough power per unit area (irradiance) to melt metals. This capability is useful for many manufacturing applications, such as welding, hardening and surface treatment involving many *metals* and *alloys*.

In laser welding applications, the beam power must be controlled carefully. Too much power will produce vaporization of the surface. Too little power will not produce sufficient melting. For this reason, only a few types of lasers are suitable for welding. The high-power CW types such as CO_2 lasers and Nd:YAG lasers are most suitable for seam welding, whereas high-power pulsed lasers can be used for spot welding.

Laser beams are capable of producing strong welds and can satisfy many practical applications in manufacturing. CW lasers with modest power can weld thin metals at reasonably high rates. Multikilowatt CO_2 and Nd:YAG lasers can weld thicker metal samples, more than an inch thick.

Most laser welding applications require a complete welding system. The system includes the laser, the focusing optics, fixturing to hold and move the workpiece, often a computer to control the motion, power monitoring equipment, appropriate safety devices and the workpiece, with its known properties of reflectivity and thermal diffusivity.

In a closely related type of application, lasers are used to modify the properties of surfaces, sometimes even without melting. Laser surface treatment can lead to hardened layers of material at the surface of the workpiece. This increases hardness and improves wear resistance of the manufactured part.

This chapter will introduce the applications of laser welding and laser-based surface treatment, covering mostly metals and alloys, but touching also on plastics.

PREREQUISITES

Course 1: *Fundamentals of Light and Lasers*

Module 1-1: *Nature and Properties of Light*
Module 1-3: *Optical Handling and Positioning*
Module 1-4: *Light Sources and Laser Safety*
Module 1-5: *Basic Physical Optics*

Module 1-6: *Principles of Lasers*

Course 2: *Elements of Photonics*
Module 2-1: *Operational Characteristics of Lasers*
Module 2-2: *Specific Laser Types*
Module 2-3: *Optical Detectors and Human Vision*

OBJECTIVES

Upon completion of this chapter, you should be able to do the following:

- List the elements of a laser welding system.
- List five advantages and three limitations of laser welding.
- Describe the importance of thermal diffusivity and reflectivity of the workpiece in a laser welding operation.
- Given two metals, state which is better suited to laser welding and state why.
- Given two laser types and a specific metal, state which laser would be better suited for welding that metal, and state why.
- Given a laser pulse duration and thermal diffusivity of a metal, calculate the penetration depth of heat into the metal correctly to two significant figures.
- Given the properties of a laser and the focusing apparatus, calculate the focal diameter for a welding operation correctly to two significant figures.
- In terms similar to those used in the text, describe the difference between conduction welding and deep penetration welding.
- In terms similar to those used in the text, describe the process of laser hardening of carbon steel.
- In terms similar to those used in the text, describe the processes of laser alloying and laser cladding.
- Given a pulsed laser and the necessary associated equipment, set up the equipment properly for a spot welding operation.
- Use the equipment in the previous objective to weld wires together. After the wires have been bonded, show that vaporization occurs at sufficiently high output from the laser.
- List the main benefits of using lasers to weld plastics.
- Identify the lasers used to weld plastics and provide their wavelength, maximum power, wall plug efficiency, minimum spot size on target, and typical interaction with plastics.
- Weld plastic sheets with a CO_2 laser.
- Plot penetration depth in the plastic as a function of increasing laser power.

SCENARIO

Anna Maria, a graduate of a photonics training program, works in an industrial company that uses laser welding equipment. She operates equipment for welding cans containing lithium batteries. She works under the direction of a senior engineer but in her daily activities is relatively independent. She is responsible for the safety practices of the battery welding process. She loads previously prepared battery cells into magazines of 16, along with covers for the batteries. She then loads the magazine into the automated welding station, which uses a 475-watt, repetitively pulsed CO_2 laser. Anna Maria actuates the system, which moves a battery into position under the laser beam, activates the laser, and rotates the battery under the beam, welding the cover onto the battery case, forming a hermetic seal. After one battery is welded, the next battery is moved into place and the operation is repeated, until the entire magazine has been welded. Anna Maria monitors the laser power to ensure that the welding conditions are correct. After the welding is complete, she visually inspects the battery cases and rejects any with defects. Anna Maria is also responsible for routine maintenance of the laser, monitoring the output over time, inspecting the mirrors and electrodes, and replacing components as necessary.

BASIC CONCEPTS

Laser Welding

Lasers can melt and weld metals if sufficiently high irradiance (power per unit area) can be delivered to small areas on the workpiece surface. Consider an ordinary small pulsed laser which emits 10 joules of energy in a pulse with a duration of 1 millisecond. With simple optics it is possible to collect and focus the beam to an area less than 0.01 cm in diameter. This leads to an irradiance greater than 10^8 watts/cm^2 at the target surface—an extremely high value. It is much higher than what can be delivered by any conventional light source. It is also considerably higher than that delivered by almost all other welding sources. For example, an oxyacetylene torch delivers about 10^4 watts/cm^2. Only an electron beam machine, which is very large and requires a vacuum system, can compare to lasers in the ability to deliver such high values of power per unit area.

Lasers for welding

Only a few of the many types of lasers that have been developed are useful for welding applications. The main requirement is that the laser be able to produce sufficiently high levels of radiant power to melt the material to be welded.

Properties of the laser must be carefully chosen to fit a specific welding application. These include:

1. The wavelength of the laser light should be absorbed well by the workpiece.
2. The power available must be high enough to produce melting.

3. The pulse duration for pulsed lasers must be long enough to permit penetration of heat into the material.
4. The pulse repetition rate for pulsed lasers must be high enough to weld a seam if seam welding is required.

Table 1 lists some of the available lasers that have been used for welding. The table also gives some of the typical values of important parameters that influence the welding. The values given in the table are an indication of those commercially available, not necessarily the highest values ever attained.

Table 1. Typical Lasers Suitable for Welding

Laser	Mode of Operation	Wavelength (μm)	Power (watts)	Pulse duration (ms)	Typical use
CO_2	Continuous	10.6	Up to 20,000	—	Seam welds
CO_2	Repetitively pulsed	10.6	Up to 20,000 (average)	1	Seam and spot welds
Nd:YAG	Continuous	1.06	Up to 5400	—	Seam welds
Nd:YAG	Pulsed	1.06	10^6 (peak)	0.5–10	Spot welds
Ruby	Pulsed	0.694	10^6 (peak)	0.2–5	Spot welds
Yb glass and disc	Continuous	1.1	Up to 6000	—	Seam welds
Diode	Continuous	8.1–9.8	Up to 3000	—	Seam welds

CO_2 lasers—The CO_2 laser, listed twice in Table 1 to include both its continuous and repetitively pulsed modes of operation, is the most commonly used laser for welding. It is used for welding thin materials at power levels of a few hundreds of watts, and for thicker materials at levels of kilowatts. Although models with powers up to 20 kilowatts are available, the beam quality at these levels is poorer than at lower powers. The maximum irradiance can be delivered to a workpiece at powers around 5000 watts where the beam quality and focusing are better.

Nd:YAG lasers—Nd:YAG lasers are also used for welding in both continuous and pulsed modes of operation. They have become well established in industrial welding and are second to the CO_2 laser in total applications. The CO_2 laser reached the capability of multikilowatt operation earlier than the Nd:YAG laser and thus dominated the early applications that required that level of power. Now, because of their shorter wavelength, which leads to better focusing, Nd:YAG lasers are replacing CO_2 lasers in some industrial applications.

Ruby and Nd:glass lasers—These lasers are among the earliest lasers developed. They have relatively low pulse repetition rates and thus are useful only for spot welding. They were used for many welding operations in the early history of laser technology, but have been mostly replaced by the other laser types in modern times.

Yb glass and disc lasers—The element ytterbium (Yb) can be incorporated into glass fibers or into YAG discs. Such lasers can have excellent beam quality. In the early years of the first decade of the 2000s, these lasers were developing rapidly, capable of kilowatt outputs. They have not yet replaced the well-established CO_2 and Nd:YAG lasers on a widespread basis for welding operations, but they are beginning to be accepted for industrial welding.

Diode lasers—Diode lasers have recently reached the level of kilowatt emission and are beginning to be considered for industrial welding operations, although they have not yet supplanted the CO_2 and Nd:YAG lasers in widespread applications. Because of the relatively poorer beam quality, they will probably be used most in applications where very small focal spots are not required.

Principles of laser welding

This section discusses the conduction and penetration types of laser welding and some of the factors that affect laser welding and the results that may be obtained.

Conduction welding—For relatively low values of laser power, less than about one kilowatt, the power per unit area (irradiance) striking the surface of the workpiece is limited. The laser energy is absorbed at the surface of the workpiece and heats it. As the temperature rises to the melting temperature, a *fusion front* (a boundary between liquid and solid material) is formed. Thermal conduction carries heat into the interior of the workpiece and the fusion front moves into the material. Because the process is driven by thermal conduction of heat from the surface of the material, this process is called *conduction welding*.

For good welding, one generally desires that the fusion front penetrate all the way through the workpiece and reach the back surface. But the conduction of heat through a thick sample requires time. This time may limit the depth to which the fusion front can penetrate and thus can limit the welding depth. Conduction welding has been widely used in industry for welding of relatively thin materials.

Figure 1 shows the time dependence of the penetration of the fusion front into a massive nickel sample for an absorbed irradiance of 10^5 w/cm^2. After about 4 milliseconds, the surface begins to vaporize. The depth of penetration without surface vaporization is limited in this case to a few thousands of an inch. To obtain greater depth, one can tailor the laser parameters to some extent. Generally, one lowers the irradiance and increases the exposure time. This control is very sensitive. Careful adjustments are required to achieve optimum penetration without vaporization.

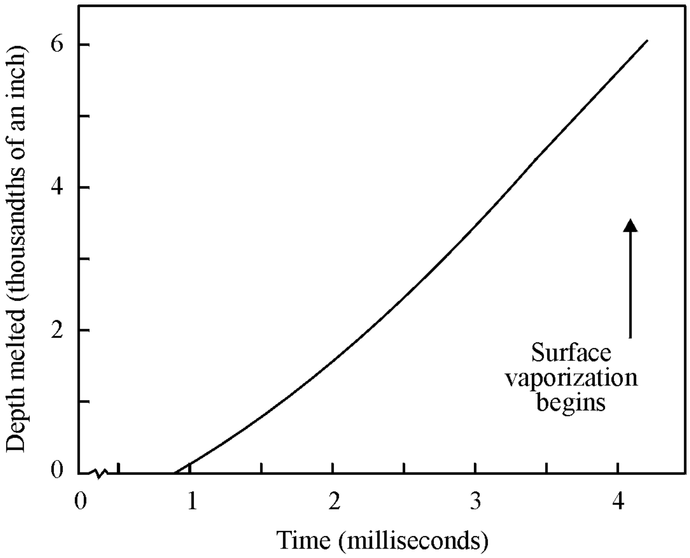

Figure 1 *Penetration of the fusion front into nickel, for absorbed laser power density of 10^5 w/cm^2*

For conduction welding, one usually wants to weld without surface vaporization. Melting without vaporization is produced only within a narrow range of parameters. If the irradiance is too high, the surface begins to vaporize before a significant depth of molten material is produced. This means that there is a maximum value of laser power that can be used.

Alternatively, for a given total energy in a laser pulse, it may be desirable to increase the pulse duration to allow time for penetration of the fusion front through the workpiece.

Penetration welding—The relatively slow process of conduction welding, in which laser energy is absorbed at the surface and is conducted into the interior of the workpiece by thermal conduction, limits the depth which can be melted effectively and hence limits the weld penetration.

At higher values of laser power, a hole may be formed in the material. Then the laser energy penetrates into the hole and the energy is deposited deeper in the workpiece, rather than at the original surface. This allows welds of greater depth to be produced. This process is called *penetration welding,* or sometimes deep-penetration welding.

The penetration welding process is illustrated in Figure 2. The figure shows the formation of the hole, which is often called a *keyhole*. The laser beam is scanned across the surface and vaporizes material. The keyhole moves through the material surrounded by molten metal, forming a tear-drop-like shape. Molten metal flows around the keyhole and rapidly resolidifies. This leaves a seam weld as the beam moves across the surface.

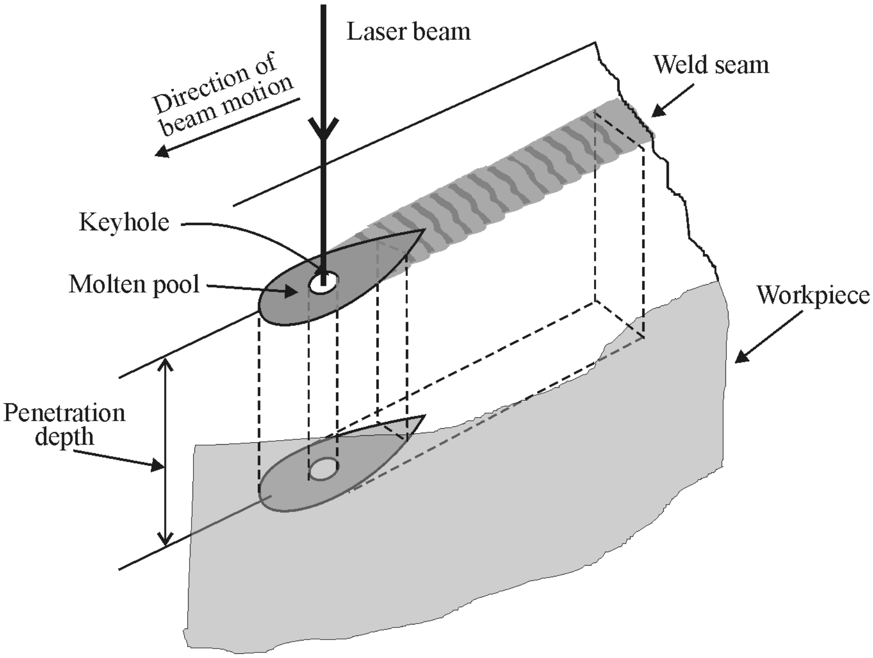

Figure 2 *Schematic diagram of the process of keyhole formation and deep penetration welding*

In penetration welding, some vaporization of the material, enough to form the keyhole, is necessary, in contrast to conduction welding, wherein one usually wants to avoid vaporization.

For constant laser beam motion, the penetration depth increases with laser power. Figure 3 shows schematically how weld penetration increases with laser power. The figure does not show exact data for any particular combination of laser and material, but rather shows the general shape of the functional relation between penetration depth and laser power.

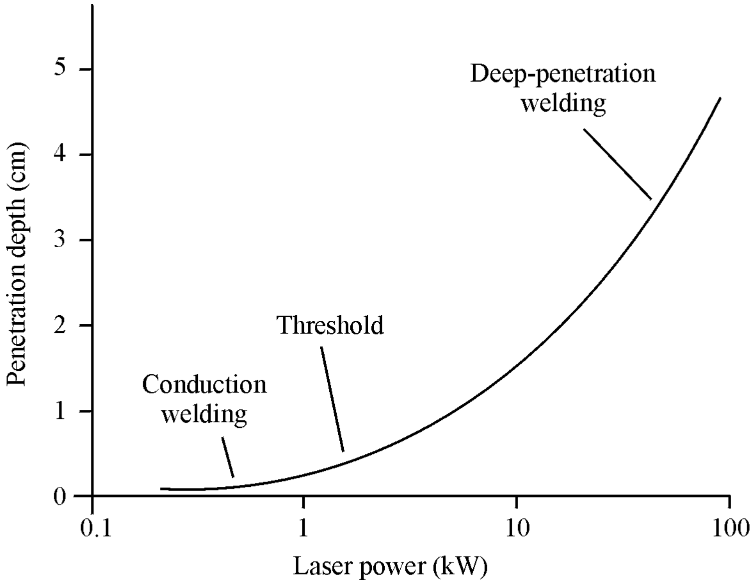

Figure 3 *Weld penetration as a function of laser power*

At levels below 1000 watts, the welding is conduction welding. The penetration increases relatively slowly with power and the penetration depth is limited. Around 1000 watts, one reaches the threshold for penetration welding and the slope of the curve increases. The threshold is often in the 1–1.5 kW region, but the exact value depends on many factors, including wavelength, beam quality, focusing, and workpiece material. Under optimum conditions, it may occur at powers as low as a few hundred watts. An irradiance around 10^6 w/cm^2 is needed to form a keyhole. At an irradiance above 10^7 w/cm^2, there often will be excessive vaporization. Thus, one usually performs penetration welding in the range of irradiance between 10^6 and 10^7 w/cm^2.

Penetration welding allows the production of much deeper welds than conduction welding. For example, it is possible to achieve welds about 5-cm deep in steel near the 100-kilowatt level.

Deep penetration laser welding has usually been performed mostly with multikilowatt CO_2 and Nd:YAG lasers. An Nd:YAG laser can perform penetration welding at lower levels of power than a CO_2 laser, because its shorter wavelength and better focusability allows a higher value of irradiance to be delivered to the surface of the workpiece. Until fairly recently there had been no well-developed multikilowatt diode lasers. Now this has changed and reliable, stable multikilowatt diode lasers are beginning to be used for penetration welding.

Effect of material properties—In welding operations, the flow of heat energy deposited by the laser is important. Heat flow is dependent on the thermal conductivity, denoted as K and having units of watts/cm-degree. But thermal conductivity is not the only factor that influences the heat flow. The rate of change of temperature also depends on the specific heat, c, of the material, which has units of joules/gm-degree. The combination of factors that is most important for heat flow is, in fact, $K/\rho c$, where ρ is the density of the material, with units of gm/cm^3. This factor $K/\rho c$ has the dimensions of cm^2/sec, characteristic of a diffusion coefficient. It has therefore been given the descriptive name *thermal diffusivity* to emphasize the fact that it represents the diffusion coefficient for heat energy. It is generally denoted as k.

The term $k = K/\rho c$ is involved in all non-steady-state heat flow problems. The significance of the thermal diffusivity is that it determines how rapidly a material will accept and conduct heat energy. Thus for welding, high thermal diffusivity means deeper penetration of the heat energy and thus deeper melting.

Table 2 lists the values of thermal diffusivity for several metals and alloys. We note that the thermal diffusivity of an alloy is generally lower than of its base metal—the major component of the alloy. *Stainless steel* and the nickel alloy *inconel* have an especially low thermal diffusivity. A low thermal diffusivity will limit the penetration of heat in conduction welding and may reduce the laser weldability.

Table 2. Thermal Diffusivity

Metal	Thermal Diffusivity (cm^2/sec)
Aluminum	0.91
Aluminum alloy 6061	0.64
Brass (70/30)	0.38
Bronze (5% tin)	0.21
Copper	1.14
Gold	1.18
Inconel (76% Ni, 16 % Cr, 8% Fe)	0.039
Iron	0.21
Magnesium	0.93
Nickel	0.24
Stainless steel 304	0.041
Titanium (99%)	0.082
Tungsten	0.62

The *depth of penetration of heat energy* into a material in time t is given approximately by Equation 1.

$$D = (4kt)^{1/2} \tag{1}$$

where D = the depth of penetration of the heat and k = thermal diffusivity of the material.

While low values of thermal diffusivity mean that heat does not penetrate well into the material, a high value of thermal diffusivity can result in rapid removal of heat from the surface. This can reduce the amount of melting. To balance these effects, one should adjust the laser parameters for optimum melting of different metals. For example, to weld copper, one should use relatively higher laser power and a shorter pulse duration to overcome losses due to the high thermal diffusivity. To weld stainless steel, one should use a relatively lower laser power and a longer pulse duration to achieve good penetration of the heat energy.

The pulse duration (or exposure time for a continuous laser) should be long enough to allow penetration of heat energy through the thickness of the sample, at least in conduction welding.

Example 1: Penetration of heat

Given: A metal with thermal diffusivity of 0.25 cm^2/sec

Find: a. Depth of penetration during a 90-nanosecond Q-switched laser pulse
b. Depth of penetration during a 100-microsecond normal laser pulse

Solution

a. Using Equation 1, for the Q-switched laser pulse, the depth of penetration is:

$$D = (4kt)^{1/2}$$

$$D = (4 \times 0.25\ \text{cm}^2/\text{sec} \times 90 \times 10^{-9}\ \text{sec})^{1/2}$$

$$D = (9 \times 10^{-8}\ \text{cm}^2)^{1/2} = 3 \times 10^{-4}\ \text{cm}$$

b. For the normal laser pulse the depth of penetration is :

$$D = (4kt)^{1/2} = (4 \times 0.25\ \text{cm}^2/\text{sec} \times 100 \times 10^{-6}\ \text{sec})^{1/2}$$

$$D = (10^{-4}\ \text{cm}^2)^{1/2} = 0.01\ \text{cm}$$

This example shows that Q-switched laser pulses are not well suited for welding because the depth of penetration will be too small for most welding applications.

The *reflectivity* of a metal surface is another important parameter. It determines how much of the laser energy that falls on a surface is reflected and, therefore, how much remains to be absorbed for heating and melting. The reflectivity is defined as the ratio of the radiant power reflected from the surface to the radiant power incident on the surface. Thus the reflectivity is a dimensionless number between zero and unity. The reflectivity is also expressed sometimes as a percentage.

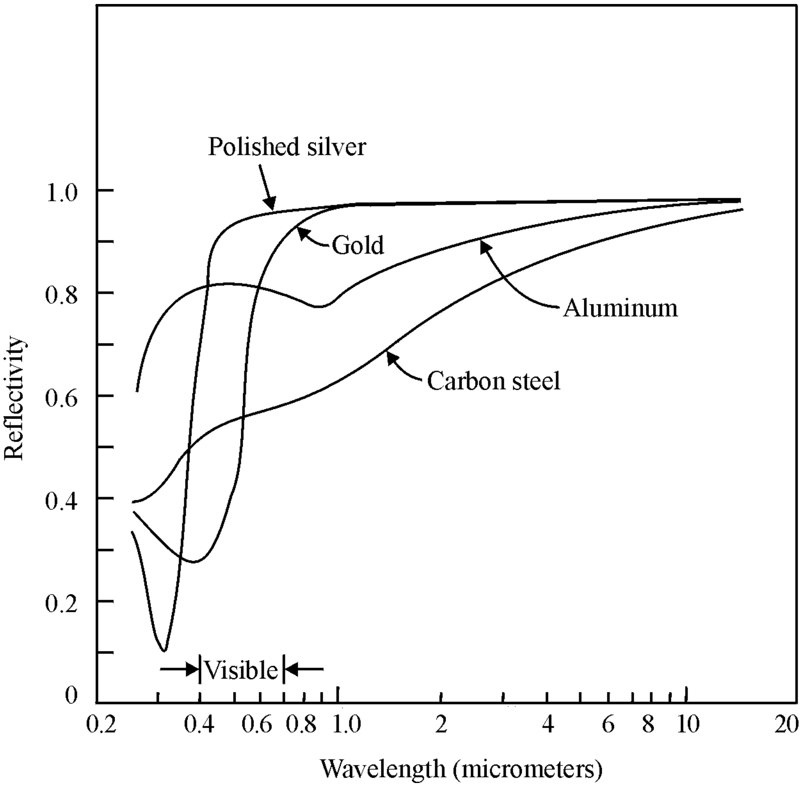

Figure 4 *Reflectivity of several metals as a function of wavelength*

The reflectivity of several metals as a function of wavelength is shown in Figure 4. These curves are characteristic of typical smooth surfaces of the metals. The exact value of reflectivity is dependent on many variables, including surface finish and the degree of oxidation. Thus the values in the figure cannot be interpreted as being exact. Still, the figure does show some important general features.

A metal like gold has a reflectivity that is low in the blue portion of the visible spectrum and high in the red and infrared portions. This accounts for the color of gold metal. Metals like aluminum and silver have high reflectivity throughout the visible spectrum. This accounts for the whitish appearance of these metals. Ferrous metals (steels and nickel alloys) typically have lower reflectivity throughout the entire spectrum. Thus they appear more dull than metals like silver.

Generally, the reflectivity of all metals increases with wavelength. This is apparent in the figure. For wavelengths longer that five micrometers, almost all metals have a reflectivity greater than 0.9. At wavelengths greater than five micrometers, the reflectivity is correlated with electrical conductivity. Metals with high electrical conductivity have the highest values of reflectivity in the infrared region. Thus the reflectivity of gold is higher than that of aluminum, which in turn is higher than that of steel.

The fraction of the light that is absorbed by the workpiece and available for heating is equal to one minus the reflectivity $(1 - R)$, where R is the reflectivity. At shorter wavelengths, the factor $(1 - R)$ is much larger than that at the CO_2 laser wavelength (10.6 μm). For example, for steel, at 1.06 μm, the value of $(1 - R)$ is near 0.35, about seven times as large as at 10.6 μm. This means that, at least initially, seven times as much light would be absorbed from a Nd:YAG laser (1.06 μm) than from a CO_2 laser for equal incident irradiances. This fact makes it easier in many cases to carry out welding operations with a shorter wavelength laser.

The high-reflectivity at long infrared wavelengths has sometimes been a barrier to the application of CO_2 lasers to welding of metals with a high reflectivity, such as copper and aluminum. Ferrous metals, such as steel, that have a lower reflectivity at 10.6 μm, are better candidates for CO_2 laser welding.

As the target surface is physically changed by the laser irradiation, the initial reflectivity may drop. This means that the laser energy can be coupled more effectively into the target, since the average reflectivity over the entire irradiation will be lower than the initial reflectivity.

The reduction of reflectivity during the laser pulse is especially helpful for CO_2 laser welding. Because of the reduction in reflectivity that occurs when a high-power CO_2 laser beam is focused on a surface, CO_2 lasers do have many practical uses for welding.

Plasma shielding—If the irradiance at the workpiece becomes too high, some of the material may become vaporized and begin to interact with the laser beam. The vaporized material may be slightly thermally ionized. This ionized material may absorb some of the laser light. This heats the vapor more and this in turn increases the degree of ionization. In a feedback process this increases the absorption further. The result is that the vaporized material may become highly ionized, that is, become a *plasma*. The plasma will be very opaque to the laser light and will absorb most or all of the *energy,* preventing it from reaching the workpiece. This effect is called *plasma shielding*.

Figure 5 shows this process schematically. The top portion shows the laser light striking the surface, melting it and causing a liquid interface to move into the material. The center part of Figure 5 shows the surface beginning to vaporize. The vaporized material remains mostly un-ionized and transparent so that the light can still reach the surface. The bottom drawing shows the vaporized material having become ionized and opaque, so that the surface is shielded from the light by the plasma formed there.

The plasma shielding obviously can have undesirable consequences for a welding operation. It keeps the laser energy from reaching its intended target and can strongly reduce the amount of welding that can be performed. It is especially troublesome in penetration welding, in which multikilowatt lasers are used and a keyhole is produced by intentionally vaporizing some of the material.

Fortunately it is relatively easy to counteract the effects of plasma shielding. One can limit the power in the laser beam and keep it below the level at which the plasma is kindled. Also, one can sweep the plasma away with a high velocity shielding gas. This will be described in the section *Welding Procedures*.

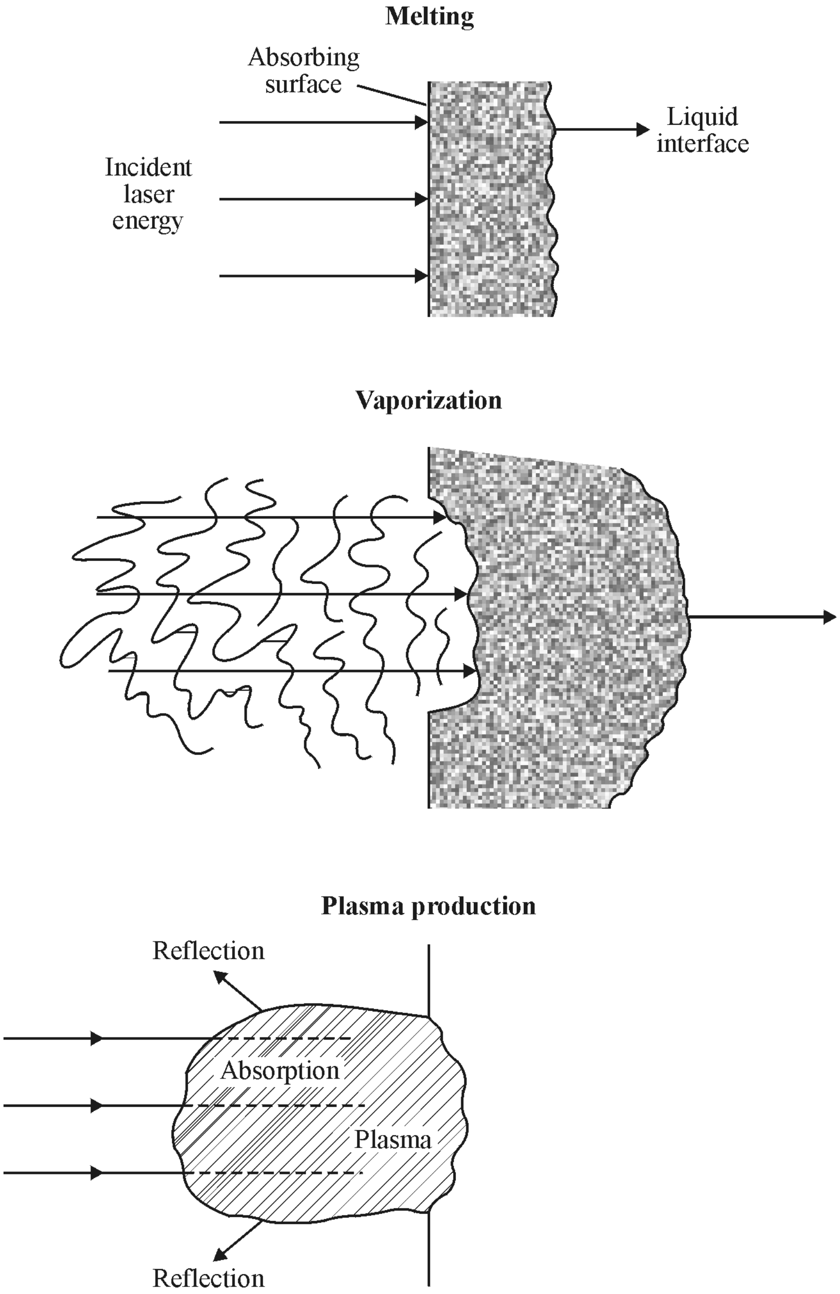

Figure 5 *Physical processes occurring when a high-power laser beam strikes an absorbing surface*

Beam delivery

It is necessary to provide some method of delivering the laser beam power from the laser to the workpiece and to focus the beam to yield a small beam size at the workpiece.

Optics—Conventional beam-delivery systems commonly use a lens to collect the beam and focus it onto the surface of the workpiece.

The next subsection shows that lenses with short focal length are desirable for producing a small focal area. But as the focal length of a lens becomes smaller, spherical aberration increases, thereby degrading the performance of the optical system. Spherical aberration causes light rays entering the lens at different distances from the center of the lens to be unfocused at a point. As a result, the laser beam will be focused to a blurred circle, rather than to a point. The effect of spherical aberration increases as the focal length decreases. This sets a lower bound on the focal length that can be used.

The effects of spherical aberration can be minimized by either of two techniques. The first is the use of *aspherical lenses* with specially ground surfaces. The second is the us of spherical lenses with shapes chosen (*best-form*) to minimize spherical aberration. Aspherical lenses are expensive and offer no great advantage over best-form spherical lenses. Therefore, one usually chooses a best-form spherical lens.

As a reasonable practical choice for visible and near infrared lasers, a “best-form” plano-convex glass lens, with the convex side toward the laser, results in minimum spherical aberration. For CO_2 lasers, a germanium lens with index of refraction equal to 4 is commonly used. In this case, minimum spherical aberration occurs for a “best-form” meniscus (convex-concave) lens, with the convex side toward the beam.

In many cases, beam bending systems are used to deliver the beam from the laser to a remote workpiece. *Beam bending* (or beam steering) systems may have one or more mirrors mounted in a supporting structure, with adjustable mirror-mounting plates to steer the beam. Fine-pitch adjustment screws are used to tilt the mirrors, so as to adjust the beam direction. The mirror or mirrors are adjusted until the position of the beam at the workpiece is as desired. The mirrors may be glass, silicon, or metal, depending on the wavelength of the laser and on its power. Such beam-benders are commercially available from a number of manufacturers.

Focusing—The unfocused, “raw” laser beam generally does not provide enough power per unit area to raise the temperature of most materials to their melting points. Also the diameter of the unfocused beam, typically a few millimeters, is too large for applications that require small heat-affected zones. For these reasons, the laser beam must be focused for most welding applications.

If one focuses the laser beam with a lens, the diameter, d, of the focal spot is given approximately by Equation 2.

$$d = f\theta \qquad (2)$$

where f is the focal length of the lens and θ is the divergence angle of the laser beam (in radians) incident on the lens. The value of d will be in the same units as the focal length f.

For many laser welding operations, the focal spot has a diameter of a few hundredths of a centimeter. To provide the smallest focal spot, a lens with a short focal length must be used. However, this may prove undesirable on a production line because of a limited depth of focus.

A sufficiently large depth of focus allows for some vibration that may be present and for some lack of accuracy in positioning the workpiece along the direction of the beam. Since the depth of focus increases with the square of the spot size, a very small focal area means that the workpiece must be positioned very accurately along the direction of beam propagation. This necessitates an optical system that provides a reasonable compromise between a large depth of focus and a small focal area.

Example 2: Focusing

Given: A pulsed Nd:YAG laser emits pulses with a peak power of 50,000 watts and a beam divergence angle of 10 milliradians. The beam is focused with a lens of focal length 2 cm.

Find: The diameter of the focal area and the peak irradiance (power per unit area) at the focal spot

Solution

From Equation 2:

$d = f\theta = 2\text{ cm} \times 0.01\text{ radians}$

$d = 0.02$ cm is the diameter of the focal spot.

The area of the focal spot is:

$\pi d^2/4 = \pi \times (0.02)^2/4 = 3.14 \times 10^{-4}\text{ cm}^2$

The peak irradiance E_{peak} is:

$E_{\text{peak}} = 50{,}000\text{ watts}/3.14 \times 10^{-4}\text{ cm}^2 = 1.59 \times 10^8\text{ watts/cm}^2$

Fibers—Optical fibers can be used to deliver laser beams to a workpiece. They have the advantage of being able to flex. Fibers made from pure silica are transmissive in the wavelength range from 400 to 1200 nm. Fiber optic beam delivery for welding is most often used with Nd:YAG lasers. At the Nd:YAG laser wavelength, the transmission of a fiber of reasonable length (up to tens of meters) may be 99%.

The advantage of fiber optic beam delivery is the ability to transmit the beam around curves to remote workstations. The end of the fiber can easily be moved so that the beam may be directed to different positions.

For a fiber of a given core diameter, there are limitations on the power that can be transmitted and on the minimum bend radius. Table 3 presents the maximum power and the minimum bend radius versus the fiber core diameter.

Table 3. Maximum transmitted power and minimum bend radius versus fiber core diameter

Core diameter (μm)	Maximum transmitted laser power (W)	Minimum bend radius (mm)
200	20	25–60
400	50	100–120
600	100	150–180
800	200	200–240
1000	400	250–300

Welding procedures

We now consider some of the practical aspects of laser welding, including common workpiece configurations, fixturing, shield gases and power monitoring.

Workpiece configurations—There are several common workpiece configurations for laser welding. Some are shown in Figure 6.

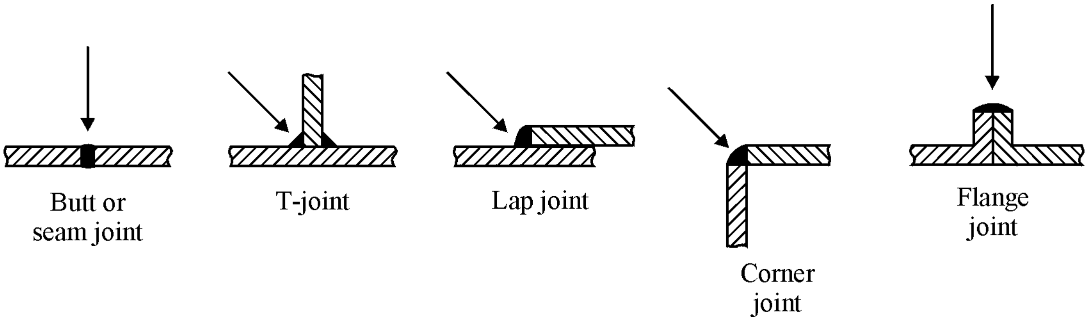

Figure 6 *Configurations for different weld joints. Arrows show the direction of the laser beam.*

Butt welds are very commonly used, especially with ferrous metals. The other types of weld configurations are usually dictated by the requirements of the shape of the component being welded. This is especially true for T-joints and corner joints. Lap joints allow the largest tolerance for beam position, but require rather high heat input because the top component must be melted before the bottom component begins to melt. Flange joints are most often used for small components.

Because of the small area of the focused laser spot, the *fit-up tolerances* are usually fairly tight. To achieve good welding, the two pieces mist be fitted closely together, so that the melted material from each piece can flow and intermix. Generally the beam should be delivered approximately equally to each piece. Table 4 presents considerations about how well the pieces to be welded should fit together.

Table 4. Fit-up Tolerances

Weld type	Gap tolerance	Beam/seam alignment
Butt	< 0.05 material thickness	< 0.5 focal spot diameter
T-joint	< 0.05 thickness of horizontal plate	< 0.5 focal spot diameter
Lap joint	< 0.05 thickness of thinner member	Relatively insensitive
Corner joint	< 0.05 thickness of horizontal plate	< 0.5 focal spot diameter
Flange joint	< 0.05 thickness of thinner member	< 0.5 focal spot diameter

Fixturing—The workpiece must be positioned and held properly. This operation is called *fixturing*. The types of fixturing vary widely, depending on the exact size and shape of the workpiece. For example, to weld a top to a can, the top must be held in place and the two pieces must be rotated together under the beam that is focused at the interface between the top and the can. If two flat pieces of metal are to be welded, they must be positioned and held tightly together and then moved so that the interface between the two pieces passes under the focus of the beam. It is impossible to describe all the various types of fixturing. Suffice it to say that proper fixturing is essential for the success of a welding operation.

Gases—During laser welding a molten pool of metal is produced. Frequently a gas is blown around the position of the weld to shield the molten metal. In many welding operations, the nozzle is coaxial with the focusing optics. A variety of nozzle types are available commercially.

One purpose of the shield gas can be to prevent plasma formation. (See the section *Principles of Laser Welding*.) The shielding gas, delivered at relatively high velocity (tens of liters per minute), removes the plasma and allows the laser beam to reach the target surface. For this case, gases with *high ionization potential*—that is, a high voltage is required to ionize the gas—are preferred. Helium and argon are commonly used, with argon often preferred because it is less expensive.

A second purpose of shielding gases is to prevent atmospheric gases from being absorbed in the molten material. Gases such as nitrogen, oxygen and carbon dioxide can be absorbed and incorporated into the weld nugget. This is often undesirable. Some steels, for example, can be embrittled and the weld joint weakened if nitrogen is absorbed. The shielding gas should be chemically nonreactive. Again, helium and argon are commonly used.

Power monitoring—In most laser-welding systems, the laser power is monitored continuously to ensure that it remains within proper limits. In setting up a weld schedule, the optimum power output of the laser is determined experimentally. Then, during the welding operation, a portion of the beam is monitored using a beam splitter. Most of the beam passes through the beam splitter and goes on to the workpiece. A small fraction is reflected and sent to a detector that has previously been calibrated to monitor the laser output. If the output changes from the desired value, the output of the detector may be fed directly back to the laser power supply to restore proper operation.

Advantages and limitations—Welding has reached production status in many practical applications. Laser welding competes with many established techniques, including arc welding, resistance welding, and electron-beam welding. In many cases, laser welding offers some advantages that are important for the particular application. Among the advantages of laser welding are the following:

a. The heat-affected zone is very small. This is especially important in cases where the weld must be made near a heat-sensitive element, like a glass-to-metal seal. This fact also reduces potential distortion of the welded part.

b. No material contacts the workpiece, so there is no contamination.

c. Laser welding can be performed in the atmosphere, or with a shield gas. This is in contrast to electron beam welding, which must be done in a vacuum.

d. Welding can be performed in otherwise inaccessible areas, for example, for repairs inside an enclosed vacuum tube.

e. The laser weld quality can be excellent, probably better than the quality of welds made with most other techniques.

Laser welding will not be expected to replace all the existing technologies. Laser welding does have some limitations, including the following:

a. Laser energy is relatively expensive, especially in comparison to arc welding and resistance welding.

b. In the conduction mode of laser welding, penetration depth is limited.

c. The weld joint fit-up requirements are tighter than for many other welding techniques.

Results

Weld depth versus speed—Results for a welding process are frequently expressed in terms of a plot showing the depth of penetration for a weld joint as a function of welding speed. This representation may be for a single value of laser power, or may contain several curves, each for a different value of laser power. It will usually refer to a single specified material. Such a plot will supply valuable information about the capabilities of a laser for a particular welding application. It will allow the user to determine whether the laser has sufficient power to weld to the desired depth at the speed, or for a given laser power, what weld speed may be obtained for a specified weld depth.

An example of such a plot of penetration depth versus weld speed for butt welding of steel with a 375-watt continuous wave CO_2 laser is shown in Figure 7. The penetration depth is representative of what may be obtained with lasers emitting a few hundred watts. At these levels, the welding is conduction welding and the weld depths are limited by thermal conduction and are fairly small. Still, the combinations of penetration depth and weld speed shown in this figure may be useful for many practical applications.

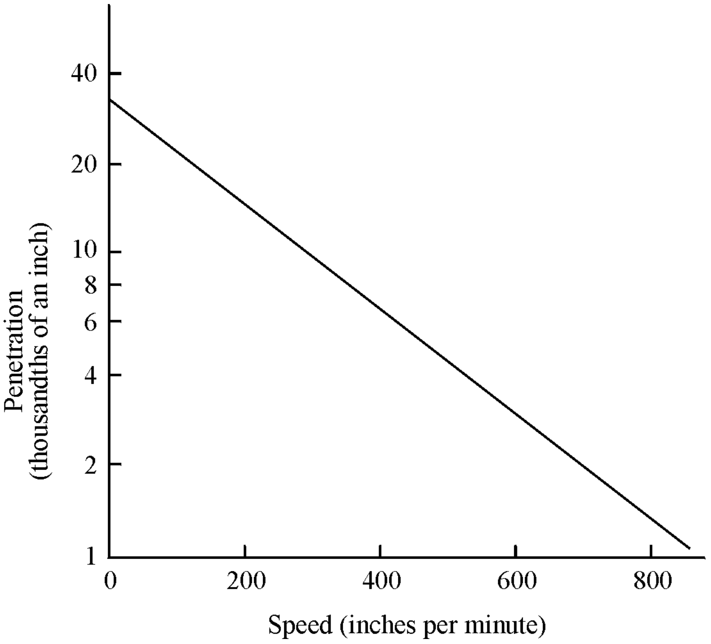

Figure 7 *Penetration depth as a function of welding speed for butt welding of steel by a 375-watt continuous wave CO_2 laser*

Figure 8 shows capabilities for multikilowatt CO_2 laser welding of stainless steel. The figure presents penetration depth versus laser power. The numbers for each curve give the rate at which the weld seam is produced. This figure is relevant to deep penetration welding, in which the limitations imposed by thermal conduction no longer apply. At multikilowatt levels, lasers can weld relatively thick metals at rates high enough to be of economic interest.

The plots shown in Figures 7 and 8 are intended to be representative, showing approximate ranges of welding results for a given laser power. Such plots may be useful for preliminary evaluation of a welding operation. The exact results for a particular welding operation will depend on the exact conditions—including

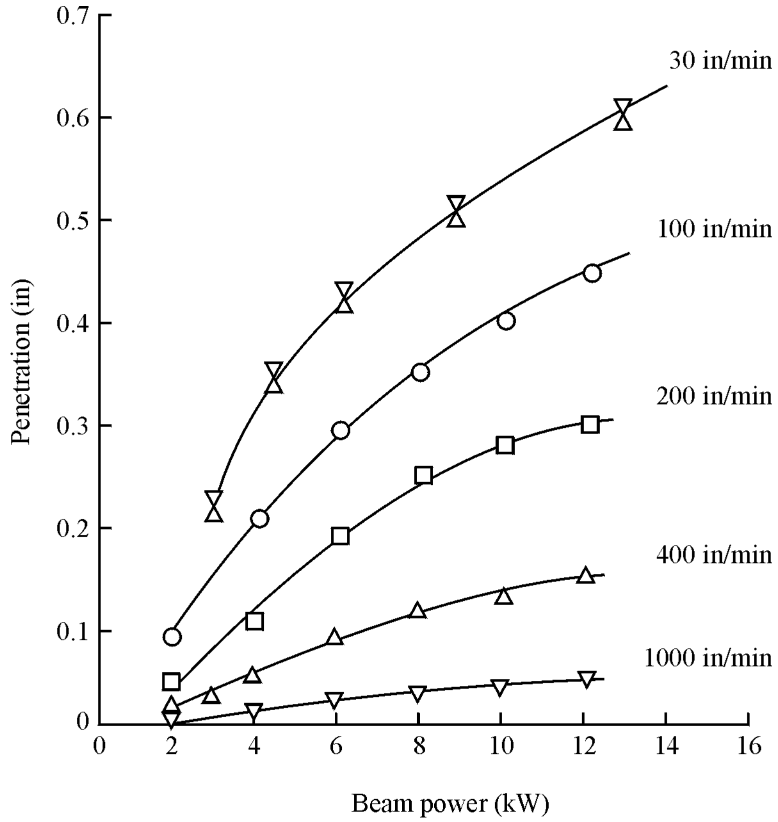

Figure 8 *Penetration depth versus laser beam power for multikilowatt CO_2 laser welding of stainless steel. The numbers for each curve refer to the speed at which the weld is made. (Data from Avco-Everett)*

beam quality, focusing, and workpiece surface condition. Thus for evaluation of the capabilities of a particular laser for a specific welding application, the user must determine the effects of the laser under the exact conditions in which it will be used.

Example 3: Multikilowatt welding

Given: The data from Figure 8

Find: The weld speed that can be obtained for a 12 kilowatt CO_2 laser with a penetration depth of 0.3 inches

Solution

Using Figure 8, and reading upward from a power of 12 kilowatts and to the right for a penetration depth of 0.3 in, one obtains an intersection near the 200 in/min curve. Thus the weld speed can be about 200 inches per minute.

Weldability of different metals—Experience has shown that certain metals and alloys are suitable for laser welding. The welding behavior of metals is governed by their metallurgical properties. Table 5 shows a comparison of the laser weldability of various metals. A value of 10 represents excellent weldability and a value of 0 represents very poor weldability. Some metals that have a metal constituent with a low boiling point (such as brass) have weldability problems because the low temperature component tends to boil off rapidly. This behavior may lead to porosity and poor-quality welds.

Table 5. Laser Weldability

Metal	Laser Weldability (10 = excellent; 0 = very poor)	Comments
304 stainless steel	10	Excellent metallurgy
Low-carbon steel	9	Good metallurgy
Nickel	8	Needs clean surface
Inconel 625 (nickel alloy)	8	Porosity in deep welds
Titanium	8	Needs low oxygen and nitrogen
410 stainless steel	7	May crack
High-carbon steel	6	Cracking at high carbon content
Aluminum	6	High reflectivity
440C stainless steel	3	Needs heat treatment to reduce cracking
6061 aluminum alloy	2	Magnesium may boil off
Brass	2	Zinc boiloff causes porosity
Galvanized steel	1	Zinc boiloff causes porosity
Copper	1	Excessive reflectivity, especially for CO_2 lasers
Gold	0	Excessive reflectivity

Hybrid welding—Hybrid welding refers to the use of a laser combined with an electrical arc in the welding process. Both the laser and the arc supply energy to the weld region. The result is a process with increased weld speed and increased weld depth, as compared to either process used separately.

The combination of arc welding and laser welding in a hybrid process has been known for many years. It is only fairly recently that workers have united the two welding technologies for practical applications.

The energy in a laser beam is fairly expensive, whereas the energy in an electrical arc is inexpensive. The energy from the arc can be used to preheat the workpiece. Then the laser beam can be used in its deep penetration mode to produce a keyhole weld. This preserves the advantages of the narrow, deep laser weld, while providing some of the total energy from the lower-cost arc. With the arc supplying some of the energy, the speed of laser welding can be increased up to 50%.

Hybrid welding has usually employed multikilowatt lasers, either CO_2 or Nd:YAG.

The hybrid welding process has been especially useful in automotive applications, where it has become common for welding the frames of automobiles.

Welding of plastic

In general, one thinks of laser welding as being applied to metals and alloys. But even though off to a slow start, laser welding of plastic parts is beginning to show up in the plastic market. The clear advantages of using lasers to weld plastics include their flexibility in the workpiece and the high quality of the weld achieved. These advantages make them superior to conventional techniques such as ultrasonic or vibration welding of plastics. On the down side, one usually has to redesign the plastic workpiece to make it suitable for the welding process, and in addition, adapt the material itself.

Table 6 provides a quick summary of the candidate lasers and the characteristics that make them suitable for welding plastic parts.

Table 6. Lasers and Their Characteristics for Plastic Welding

	Laser characteristics				
Laser type	**Wavelength (μm)**	**Maximum power (kW)**	**Maximum spot size (mm)**	**Wall plug efficiency**	**Notable effects**
CO_2	10.6	30	≃ 0.2	10%	CO_2 10.6 μm radiation is completely absorbed at the surface at depths ≤ 0.5 mm
Nd:YAG	1.06	6	≃ 0.1	3%	Generally useful in transmission and bulk heating of plastic for thicknesses from 0.1 mm to 10 mm
Diode	0.8–1.0	6	≃ 0.4 × 0.4	30%	Generally useful in transmission and bulk heating of plastic for thicknesses from 0.1 mm to 10 mm
Fiber	1.0–2.0	10	≃ 0.02	20%	Generally useful in transmission and bulk heating of plastic for thicknesses from 0.1 mm to 10 mm

CO_2 laser welding—As Table 6 indicates, CO_2 radiation at 10.6 μm is highly absorbed in surface depths less than 0.5 mm. Disadvantages of CO_2 radiation include a limited penetration of workpieces (due to the high absorption) and an inability to be transmitted down a silicia optical fiber for ease in focusing. Manipulation is achieved with *articulated arms*—involving multiple mirrors in complex geometries and overhead gantries.

Transmission laser welding—*Transmission laser* welding—with Nd:YAG and diode lasers—is used when one plastic substance is positioned over another. The top plastic substance is transparent to the Nd:YAG and diode laser radiation, thereby transmitting the radiation through and onto the lower plastic substance, which is highly absorptive of the laser radiation. The radiation transmitted by the top layer significantly heats up the lower (highly absorbing) layer. This heat is transferred by conduction back to the bottom of the upper layer, causing the two molten plastic substances to merge and form a single weld.

As shown in Figure 9, proper selection of the two plastic materials and proper orientation directly affects the ease and efficiency of the welding process. The process is simpler with clear over opaque (clear/opaque) materials than with clear/clear materials, as indicated qualitatively in the figure. The more transparent the top layer and the more opaque the bottom layer, the easier the transmission weld.

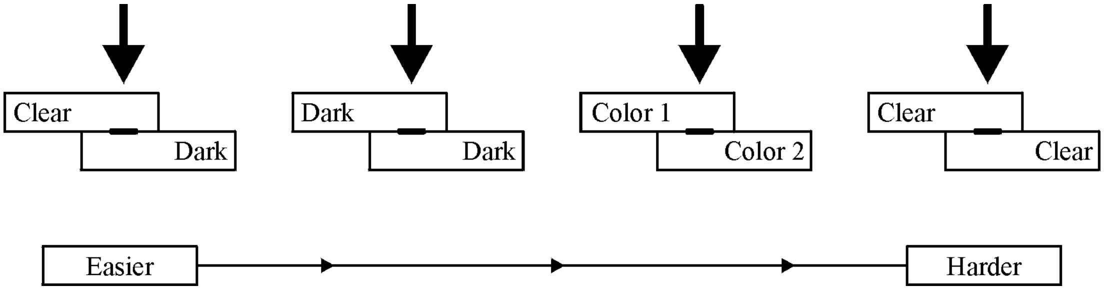

Figure 9 *Transmission laser welding involves two plastic layers. The optical absorption coefficients of the two layers have a direct effect on the ease of the welding process. For example, transmission layer welding of plastic with a transparent (clear) material over an opaque (dark) substance is easier to carry out than a clear-over-clear substance.*

Nd:YAG laser use—The Nd:YAG laser at 1.06 μm is used to heat plastics to a depth of several millimeters. The laser can heat metals or plastics doped with suitable additives (to increase the absorption coefficient) through the transmissive plastic layer in transmission laser welding. In addition, the Nd:YAG laser beam can be directed along a silica optical fiber, thereby increasing its flexibility in use. The fiber optic can be used either with robot or gantry manipulation processes.

Diode laser use—The diode laser—as seen in Table 6—is a worthy alternative to the Nd:YAG laser. Diode laser systems with laser powers up to 6 kW are on the market. They have a wall-plug efficiency (30%) ten times that of the YAG laser and are competitively priced. The output beam of a diode laser is *rectangular* in shape (0.4 mm × 0.4 mm) and therefore cannot be focused on target to a spot as small as can a YAG laser. But if small spot focus ability is not an issue, the diode laser competes well with the YAG laser. Like the YAG laser, the diode laser can be adapted for use in gantry or robotic delivery.

Benefits of laser welding of plastics—Laser welding of plastics offers significant advantages over the ultrasonic or vibrational conventional welding techniques. Some of the advantages are:

- Welding seam joints are flexible and weld quality is consistent and reproducible, with a minimum reject/failure rate.
- A perfect weld surface is attainable and minimal thermal and mechanical power is required.
- Controllable beam power lowers the risk of workpiece damage or disfiguration.
- The welds are as strong as conventional ultrasonic plastic welds.
- One can achieve excellent welding seams near to heat-sensitive components on small, detailed physical structures.
- No melt ejecta or microparticula are created—important for the medical community.
- The nonphysical contact process in the formation of the weld is hygienic and clean.
- Precise focusing—especially with the Nd:YAG laser—enables one to form highly accurate joints and welds.

Examples of laser plastic welding—Figure 10 shows the results when a 20 μm polycarbonate film was welded onto a 1.2-mm-thick clear disk of microstructured polycarbonate at 200 mm/mm. The shallow features of the substrate microstructure are clearly retained.

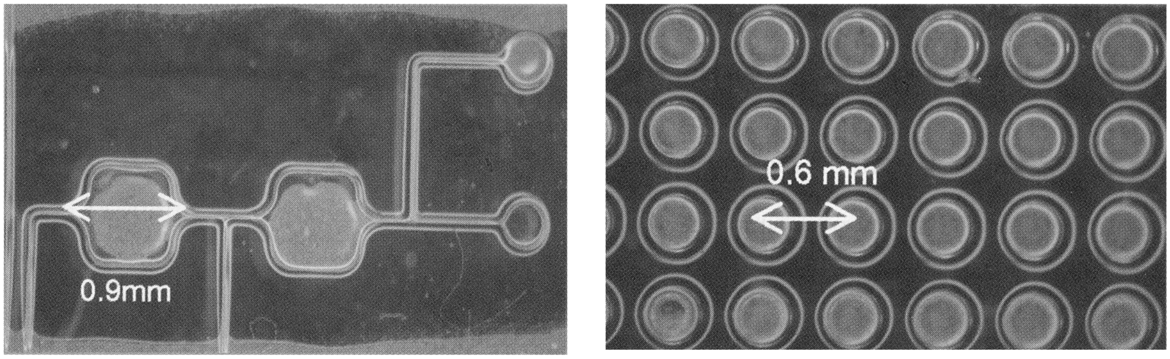

Figure 10 *An example of successful laser welding in the microstructure domain (Courtesy of Coherent, Inc.)*

In Figure 11, the “magic” of laser welding is shown, an achievement impossible without the technique of laser welding. A microphone cap is welded onto a car-seat belt. The challenge was to achieve a strong weld between the microphone button and the belt fabric, without damaging either the microphone electronics or the fabric in the belt.

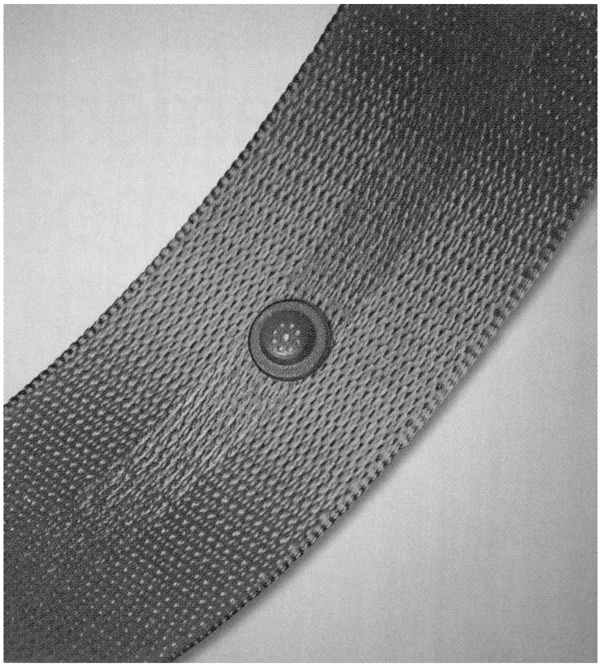

Figure 11 *Laser welding of a microphone "button" to an automobile seat belt without damage to either (Adapted from Rofin, Europe)*

Applications

Laser welding, both conduction welding and penetration welding, has been widely accepted for industrial applications for manufacturing a wide variety of products. Most such applications have used Nd:YAG lasers and CO_2 lasers, but some applications using diode lasers or Yb lasers are beginning.

Thin sheet welding—By thin sheet welding, we mean welding of material with thickness less than 0.5 mm. Both Nd:YAG lasers and CO_2 lasers have been employed. For material of this thickness, conduction welding has been used more than deep penetration welding, but some penetration welding has been done.

Lap welding is most often used for thin sheet material, because butt welding may lead to blow holes in the weld.

Table 7 gives some examples of thin sheet welding.

Table 7. Thin Sheet Welding

Material	Thickness (mm)	Laser	Power (W)	Weld type	Weld speed (meters/min)
Stainless steel (304)	0.1 5	CO_2	700	Butt	25
Stainless steel	0.03	CO_2	125	Lap	7.5
Stainless steel	—	Nd:YAG	400	Spot	Not applicable
Aluminum	0.35	CO_2	1500	Butt	40

The weld speeds are sufficiently high to allow efficient use of the welding for industrial applications. Examples of applications of welding of thin sheet material that have reached production include welding of razor blades and welding of battery cases.

Sheet welding—The welding of thicker sheets of material with thickness in the range from 0.5 to 3 mm is usually performed in the deep penetration mode using multikilowatt lasers, both CO_2 and Nd:YAG. Such welding is most often performed in the butt configuration, because the material is thick enough that blow holes are not a problem.

Table 8 presents some examples of welding of materials in this thickness range.

Table 8. Sheet Welding (0.5–3 mm thick)

Material	Thickness (mm)	Laser	Power (W)	Weld type	Weld speed (meters/min)
Stainless steel (409)	1	CO_2	6000	Butt	6
Cold-rolled steel	1.8	CO_2	6000	Butt	5
Aluminum (6082)	1	Nd:YAG	2800	Butt	4
Aluminum (6016)	1.2	CO_2	3500	Butt	2.5

Welding of such sheet material has become widely used in the automotive industry, particularly for welding of auto body parts. It has been used in the shipbuilding industry, where it has offered the capability to fabricate novel designs and to achieve weight reductions.

Plate welding—Still thicker plates of material, with thickness greater than 4 mm, may be welded with multikilowatt lasers. Such material requires at least 4000 watts to allow a reasonable combination of weld speed and penetration depth. Material with thickness up to 50 mm has been welded. Table 9 presents some examples.

Table 9. Plate Welding (> 4 mm thick)

Material	Thickness (mm)	Laser	Power (W)	Weld type	Weld speed (meters/min)
Carbon steel	12	CO_2	9000	Butt	0.8
Carbon steel	6	CO_2	25,000	Butt	10
Carbon steel	9	Nd:YAG	4000	Butt	0.3
Carbon steel	5	CO_2	4000	Butt	0.6

Such welding has most often been used for structural materials, like carbon steel. It has been widely used for pipe welding and in the shipbuilding industry for welding of primary panels.

Tailored blank welding—*Tailored blank welding* involves butt welding of two metal sheets to form a single flat sheet. The two original sheets may be identical, may be of different materials, may have different thicknesses and may have different structural strengths. The resulting sheet will have properties that allow it to be used in a manufacturing operation for which a single uniform sheet would not be suitable.

Tailored blank welding began in 1983 when a sheet metal supplier could not supply a large enough sheet for a new automobile design. Two sheets were laser-welded together to supply a sheet of sufficient size. By the early 2000s, tailored blank welding had become very important in the automotive industry.

Tailored blank welding most often involves welding of steel or aluminum alloys with thickness in the 1–2 mm range. The process usually uses CO_2 lasers with power in the 6000–8000 Watt range or Nd:YAG lasers with power in the 4000–5000 Watt range.

Usually the tailored blanks are stamped to form a sheet that may have different properties (mechanical strength, thickness) on the opposite sides of the weld. This gives design engineers the capability to design parts with different characteristics at the locations where they are needed.

Laser tailored blank welding is a demanding process. The welds must be very accurate dimensionally and must be capable of surviving, without fracture, later stressful operations, like stamping out shaped parts from them. Laser welding of tailored blanks has proved to be superior to other competing technologies for producing them.

Automotive industry applications—Laser welding has become widely used in the automotive industry, where it offers the capability of making high quality seams economically. Laser welding has become common for welding of the frames for auto bodies For example, a German manufacturer uses laser welding to weld the rear fender section to the car roof with an invisible seam.

The lasers used for welding auto frames are usually multikilowatt lasers, either CO_2 or Nd:YAG.

Laser welding has also been used for a diversity of other applications, such as welding clutch housings to prevent oil loss and welding steering shaft pinions to reduce microcracking in the carbon steel material.

Laser welding in automotive applications offers the advantages of low heat distortion of the welded parts, of very clean weld seams and of requiring very little post-weld cleanup, an economic advantage.

Perhaps the most significant application of laser welding in the automotive industry has been the production of tailored blanks, which has increased rapidly in the last 20 years. Tailored blanks can form the shape required for later metal forming operations, usually metal stamping. This gives design engineers the capability to tailor performance characteristics on an auto body. As an example, a sheet from a tailored blank could be used to provide galvanized steel in an area where corrosion resistance is required and to provide thicker material in places where greater strength is needed.

Now laser-welded tailored blanks are utilized in most passenger car and sport utility vehicle designs produced throughout the world. The availability of tailored blanks allows engineers improved capability to design body structures with attractive curves, good-looking wide tailgate sections, and items such as narrow strong pillars and lightweight door assemblies. It is estimated that in 2004 more than 180 million laser-welded tailored blanks will be used in automobile manufacturing.

Surface Heat Treatment

High-power lasers are used in a number of ways to heat and modify surfaces, especially to increase their wear resistance.

Transformation hardening

The most important laser surface treating process is transformation hardening.

Principles—*Transformation hardening* involves laser heating of ferrous metals followed by rapid cooling. This leads to a transformation of the crystalline structure of the metal that leads in turn to hardening of the metal. If one heats steel or other iron-containing metals to a red heat and then rapidly cools the metal, the result is a hardening transformation.

The process has been known for many centuries. It is essentially the same process used by blacksmiths to harden horseshoes. The blacksmith heats the horseshoe in a furnace and then plunges it into a tub of water. In laser transformation hardening, the heat source is a laser, instead of a furnace.

A high-power laser beam passing across a surface heats a thin layer of material to a high temperature, above 1000 degrees Kelvin, but below the melting point. Then, as the beam moves on, the thin heated layer cools rapidly by conduction of the heat energy into the interior. The result is a very fast quenching and hardening of the surface layer.

This method of hardening applies only to certain ferrous metals that can undergo a desirable transformation in the structure of the metal. A number of important structural metals, such as carbon steel and cast iron, can be hardened in this way.

Austenite to martensite transformation—The temperature-time history of the transformation process for carbon steel is illustrated in Figure 12. The sample is heated to a temperature above 1000 K and undergoes a transformation to a crystalline phase called *austenite.* Then, if the metal cools rapidly, within about one second, it will transform to a crystalline structure called *martensite*, which is very hard. If the cooling is too slow, the metal will transform to other softer crystalline phases (*pearlite* or *bainite*). This shows the importance of rapid cooling for transformation hardening.

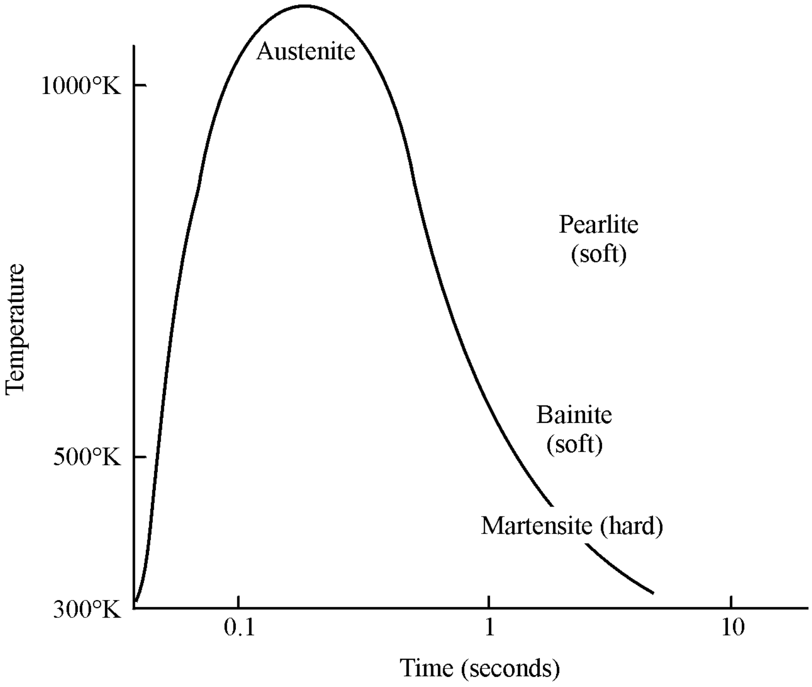

Figure 12 *Temperature-versus-time profile in a hardening transformation*

Example 4: Temperature-time transformation

Given: The data in Figure 12

Find: The result of a process in which a carbon steel surface is heated above 1000 degrees K and allowed to cool to 300 degrees K over a time of 10 seconds

Solution

Using Figure 12, one sees that the cooling curve will pass through the soft bainite phase. The result of the processing will thus not produce hardening of the steel.

Lasers used in surface hardening—The CO_2 laser is the laser that has been most often used for such surface hardening. It operates at power levels of at least one kilowatt continuously. This is needed to produce surface coverage at a rate high enough to be economically attractive. Because the coverage in a hardening operation is usually over an extended area and one does not need a fine focus, the advantage that a shorter wavelength Nd:YAG laser might have over a CO_2 laser in a welding operation is not important.

Transformation hardening with Nd:YAG lasers and diode lasers has also been demonstrated, but these lasers have been less often used for this operation.

Because one usually desires to harden the surface of a part with extended dimensions, the laser beam generally does not have to be focused. Rather, one wants a uniform beam to provide coverage over the whole part. Beam shaping optics may be used to spread the beam into a line, which is then scanned across the part.

Results—Figure 13 shows some results for the hardness as a function of depth in a sample of carbon steel that was hardened by the passage of a CO_2 laser beam across its surface. The units of hardness are expressed as the so-called "Rockwell C" or R_C hardness. This refers to a standard test method for hardness of metals.

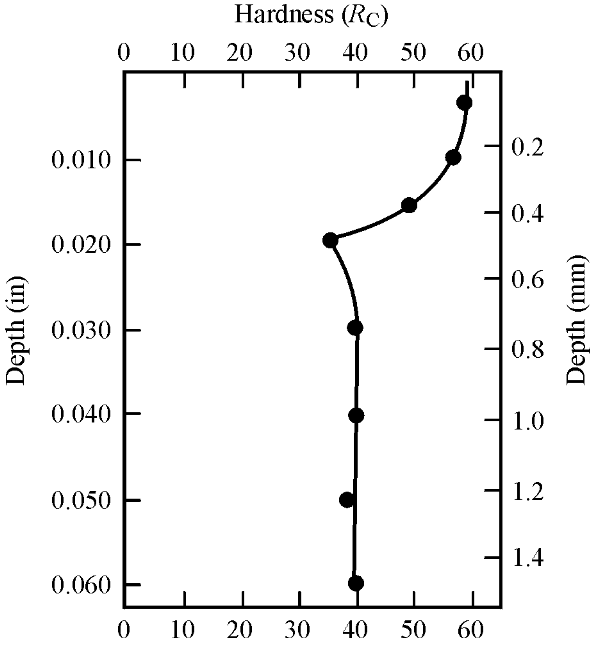

Figure 13 *Results from treating a carbon steel surface with a multikilowatt CO_2 laser (From E. V. Locke and R. A. Hella, IEEE Journal of Quantum Electronics QE-10, 179 [1974])*

Rockwell hardness is a measure of resistance to surface penetration (indentation) by a specified indentor under a stated load. The Rockwell hardness tester measures the depth of surface penetration by a steel ball or a diamond cone. The hardness is expressed by a number obtained by subtracting the penetration depth from an arbitrary constant. Because several different loads and indentors are used to provide optimum results in different ranges of hardness, a suffix such as B or C is used to specify which standard combination of load and indentor was used. The Rockwell C test uses a conical diamond indentor and a load of 150 kg. It is often used for measurements on steel.

As the figure shows, the original metal had a Rockwell C hardness equal to 40. After laser treatment of the outer layer to a depth of 0.2 mm, the surface was hardened to a Rockwell C value of nearly 60. This represents a significant and desirable increase in surface hardness. The hardened outer layer will provide increased resistance to wear and abrasion.

The ability of the laser to provide coverage of a surface may be derived from curves such as shown in Figure 14. This shows the combinations of laser power and scan speed necessary to obtain a specified hardened depth, in this case 0.056 cm, for carbon steel. The beam diameter is the parameter for the different curves. For a different hardened depth or a different material there would be a different set of curves. Diagrams like Figure 14 allow the user to determine the parameters required to obtain a specified result. They may also be used to derive coverage rates, by multiplying the spot size by the speed at a given point.

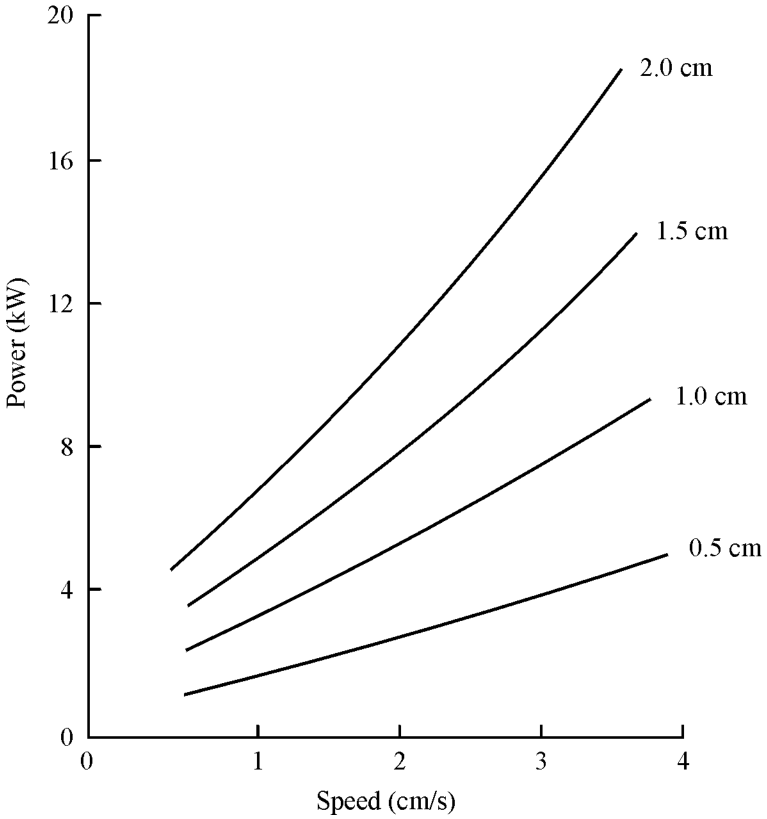

Figure 14 *Laser power versus scan speed required to produce a hardened depth of 0.056 cm in carbon steel. The different curves were obtained with the indicated values of laser beam diameter. (Based on data from V. Gregson)*

Example 5: Coverage rate for hardening

Given: The data in Figure 14

Find: The coverage rate (the area hardened per unit time) for hardening to a depth of 0.056 cm in carbon steel with a laser power of 10 kW at a speed of 2 cm/sec

Solution

Using Figure 14, reading to the right from a laser power of 10 kW and upward from a speed of 2 cm/sec, the intersection is near the curve for a spot size of 2 cm. The coverage rate is 2 cm/sec × 2 cm or 4 cm^2/sec.

Applications—Laser-induced transformation hardening has become widely used in industry to harden surfaces to improve the resistance of manufactured parts to wear. This hardening process has been adopted especially in the automotive industry, where it is used to harden items like steering gear assemblies and diesel engine cylinder liners, so as to increase their lifetime.

In another important example, transformation hardening has been used to harden turbine blades. Turbine blades in steam turbines are eroded by water droplets that hit the blades. Transformation hardening with a 6-kilowatt CO_2 laser has been used to harden the blades and substantially increase their lifetime.

Surface alloying

Laser surface alloying is an alternative method of modifying surface properties. For laser alloying, one melts the top layer of a surface, together with some material added to the surface. During the melting, the added material mixes with the top molten layer of the surface. The surface layer has its composition changed because of the added material mixed into the surface. The process produces a localized region of alloyed material with composition and properties different from those of the original material.

In surface alloying, one can add elements such as boron, carbon, chromium and nickel to the surface of a metal part. The result can be increased hardness or corrosion resistance for the surface.

The purpose of surface alloying is to produce a surface layer with desirable properties, like increased wear resistance, on a relatively inexpensive substrate. For example, on a carbon steel part, one can produce a stainless steel surface layer by alloying chromium and nickel into the surface.

Often a multikilowatt CO_2 laser is used for surface alloying. High power is needed to produce an economically attractive rate of surface coverage. In comparison to transformation hardening, the technique is applicable to a wider range of materials, but the power required is higher, because the surface must be melted, whereas in transformation hardening, no melting is needed.

The material to be added may be present on the surface before the laser irradiation begins, or may be blown onto the surface in a gas jet during the irradiation. In the first case, the material may be present in a paint on the surface or it may simply be deposited as a powder.

Table 10 presents some working conditions and results for the alloying of chromium into steel, using a CO_2 laser, a process that increases the corrosion resistance of the steel. The results in the table indicate the values of alloyed depth and alloying concentration that may be obtained in this process.

Table 10. Working conditions and results for surface alloying of steel with chromium, using a CO_2 laser

Laser power (watts)	Precoated thickness (μm)	Alloyed depth (μm)	Working speed (meters/min)	Chromium concentration (atomic %)
3000	100	600	0.5	10
4500	100	700	1.0	11
3000	200	450	0.5	25
4500	200	400	1.0	40
3000	300	100–200	0.5	30–34
4500	300	200–350	1.0	17–33

Surface cladding

Laser cladding involves welding of material to the surface of a workpiece. In contrast to the process of laser alloying described above, in laser cladding the cladding material does not mix extensively with the substrate material. Rather it forms a separate layer attached to the surface. The material added to the surface can be supplied as powder, wire or strip. Powder is used most often because it is relatively easy to control the process.

In laser cladding, the laser beam melts the surface of the workpiece. Powder is continuously injected into the melt pool to form the cladding. Usually the powder is transported by a carrier gas. Shield gas protects the molten material from the atmosphere. Figure 15 shows a typical configuration with the powder being supplied from the side.

Laser cladding is performed with little mixing of the cladding and base materials. At the surface of the base material, 2% or less of the cladding material is mixed into the base material. This is in contrast to the results of a laser alloying operation, as indicated in Table 10, which shows much higher concentrations of the alloying material.

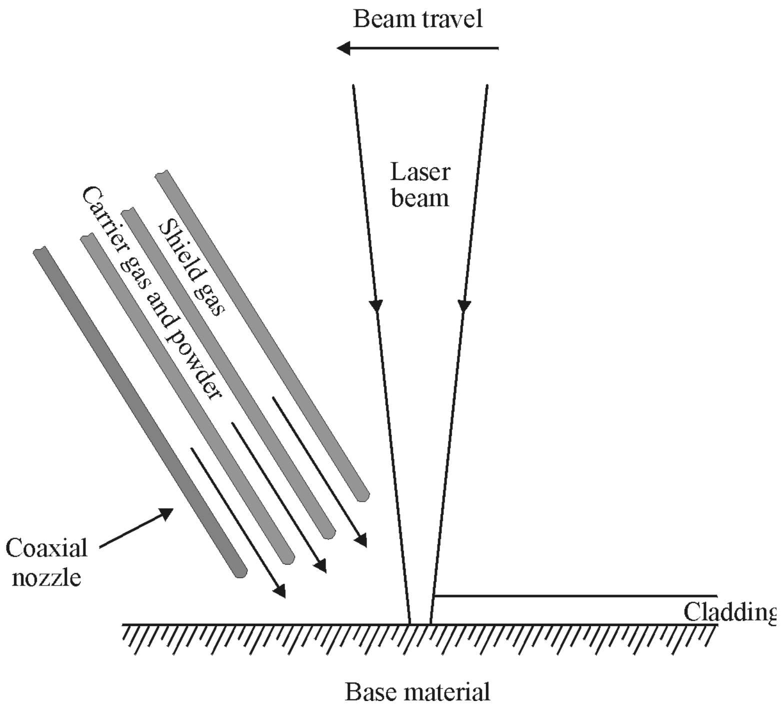

Figure 15 *Laser cladding with powder feed from the side*

Because cladding is essentially a welding process, the base material and the cladding material should have good welding characteristics. Cladding materials used to increase surface hardness and wear resistance are often cobalt-based alloys or nickel-based alloys. Laser cladding has been used to provide improved wear resistance for components such as turbine blades, valves and bearings.

The lasers usually used for cladding are multikilowatt CO_2 and Nd:YAG lasers.

Table 11 presents typical parameters used for laser cladding.

Table 11. Typical processing parameters for laser cladding

Laser	Power (watts)	Speed (meters/min)	Cladding material feed rate (gram/min)	Cladding layer thickness (mm)
CO_2	1000	0.5	8	0.5
Nd:YAG	2000	15	15	0.5
CO_2	10,000	0.6	30	0.8
CO_2	20,000	1.2	120	1.5

EXERCISES

1. List the elements of a laser welding system.
2. List five advantages and three limitations of laser welding.
3. Describe the importance of thermal diffusivity and reflectivity of the workpiece in a laser welding operation.
4. Is copper or stainless steel better suited for laser welding? Why?
5. Would a Nd:YAG laser or a CO_2 laser be better suited for welding aluminum? Why?
6. For a metal with thermal diffusivity equal to 0.5 cm^2/sec and for a laser pulse duration of 800 nanoseconds, to what depth will heat penetrate into the material during the laser pulse?
7. For a CO_2 laser beam with a beam divergence of 0.005 radians focused by a lens with a focal length of 7.5 inches, what will be the diameter of the focal spot?
8. Describe the difference between transmission laser welding and welding with a CO_2 laser. Why can CO_2 lasers NOT be used in transmission laser welding of plastics?
9. Compare the use of CO_2, Nd:YAG, and diode lasers in laser plastic welding and indicate where each is most often used.
10. In terms similar to those used in the text, describe the difference between conduction welding and deep-penetration welding.
11. In terms similar to those used in the text, describe the process of laser hardening of carbon steel.
12. In terms similar to those used in the text, describe the processes of laser alloying and laser cladding.

LABORATORY

Materials

Continuous CO_2 laser with output of 20 watts
Germanium lens with 1.5-inch focal length
Lens mount with translation capability
Power meter for CO_2 laser
Solid-state laser (ruby or Nd:YAG) with millisecond duration pulses and output of a few joules per pulse
Energy meter for solid-state laser
Optical bench
Translation stage
Motor drive for translation stage
Glass lens (1–2-inch focal length)

Stopwatch
Diamond wheel
Measuring microscope
Samples of copper wire
Assembly for holding copper wires
Samples of lucite
Carbon block
Flat copper plate

Procedures

A. Spot welding copper wires together

1. In the first portion of this experiment, you will make a spot weld between two pieces of copper wire. For this operation the solid-state laser (ruby or Nd:YAG) will be used. Observe the safety precautions relevant to the laser that is used and wear safety goggles appropriate for the laser output.

   The experimental setup is shown in Figure 16. The copper wires will be held stationary and the motorized drive for the workpiece will not be used.

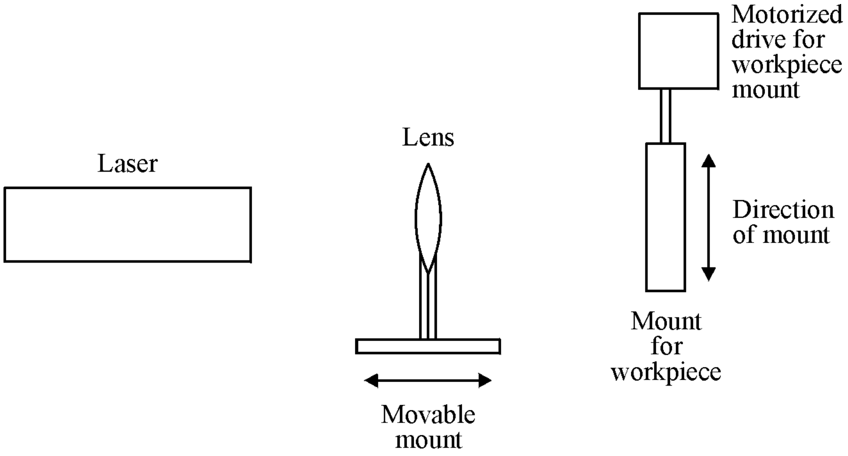

Figure 16 *Experimental arrangement for welding. (The motorized drive for moving the workpiece is used only for the welding of lucite with the* CO_2 *laser as described in Procedure B below.)*

2. The glass lens will be held in the lens mount so that it can be moved to obtain the best focus. The first step involves determination of the optimum focal position. For this a flat copper plate is employed. Insert the copper plate on the workpiece mount. Move the lens to a position so that the distance between the lens and the surface of the plate is less than the focal length of the lens. Fire one pulse from the laser, so that it is focused by the lens and strikes the surface of the plate. It will make a small mark or hole on the surface.

   Then move the lens one millimeter further from the plate. Also, move the copper plate so that a fresh area is behind the lens and fire the laser again. Repeat this operation a number of times until the lens has been moved to a position several millimeters farther from the plate than the focal length of the lens.

Measure the diameters of the holes or marks produced in this way using the measuring microscope. Make a plot of the hole diameter as a function of lens position. It should have the general form shown in Figure 17. The position marked by the arrow is the minimum hole size and indicates the optimum focal position of the lens. For the remainder of this portion of the experiment, keep the distance between the workpiece and the lens equal to this distance.

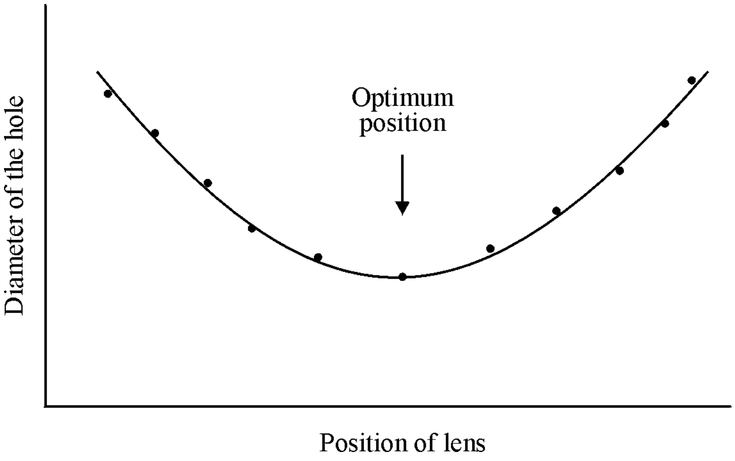

Figure 17 *Hole diameter as a function of position of focusing lens. This is a generalized plot meant only to show the shape of the curve, so dimensions are not specified.*

3. To make the weld, position the wires at the focus of the lens. The configuration of the wires should be as shown in Figure 18. The wires should be side by side in close contact. You may need several trials to position the wires correctly. The dotted circle in the figure shows where the beam should hit.

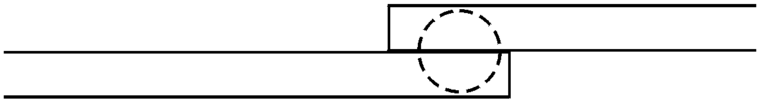

Figure 18 *Configuration of wires for welding. The dotted circle shows where the beam should strike.*

4. When the optimum position has been determined, hold the two wires still, fire the solid-state laser, and make a weld between the two wires. Repeat this operation with fresh wires at a number of different values of the solid-state laser output. Use the energy meter to measure the laser energy output for each setting of the laser power supply at which the laser is fired.

   At relatively low output energy, the melting will be incomplete and the welds will not be satisfactory. As the laser energy increases, the fusion becomes more complete and a stronger weld should be observed.

   As the laser energy is increased still further, vaporization begins and the wire material will begin to be evaporated excessively. Once again, the weld will not be satisfactory. This indicates that there will be an optimum value for the output of the solid-state laser for welding the wires. Observe the weld obtained as a function of the laser output energy and compare your observations with the comments made above.

B. Penetrating and welding Lucite with a CO_2 laser

1. The next operation involves welding of pieces of lucite with the CO_2 laser. The lucite is highly absorptive of the CO_2 laser wavelength of 10.6 μm.

   During this operation, follow all safety procedures appropriate to operation of the CO_2 laser, including wearing of safety goggles opaque to the wavelength of the CO_2 laser.

   The setup is similar to that of Figure 16, but the solid-state laser is replaced by the CO_2 laser and the glass lens is replaced by the germanium lens. For this portion of the experiment, the motorized drive for the workpiece will be used.

2. The first step is to find the optimum position for the germanium lens. This is done by moving the lens to obtain maximum effect on the lucite. Turn on the CO_2 laser and align the beam, the lens, and the lucite so that the beam is centered on the lens and is focused on the lucite. Remember, the CO_2 laser beam output at 10.6 μm is NOT visible to the eye. Therefore, an auxiliary spotting laser used with the CO_2 laser will be needed to determine the position of the CO_2 laser spot. Next, block the beam with the carbon block. Then move the lens mount so that the lens is further away from the position where the beam is focused on the lucite surface. Start the motor that moves the holder for the lucite. The lucite will be driven across the beam. The lucite should be capable of several inches of clear travel before the lucite moves out of the beam. When the lucite is moving, remove the carbon block and allow the laser beam to score a small line in the surface of the lucite. Then reinsert the carbon block and stop the motion of the lucite.

3. Move the lens to a new position and reposition the lucite sample so that the lucite moves in a direction perpendicular to the previous direction of travel. Repeat this operation several times until the lens has been moved through the position of optimum focus. For each lens position, a small line should be scored on the surface of the lucite. For each operation, record the position of the lens relative to the lucite surface.

4. When a number of lines have been scored in the surface of the lucite, measure the width of each line with the measuring microscope. Plot the *width of the line* as a function of *lens position*. This plot shows how the diameter of the laser spot on the lucite varies with the position of the lens. At the optimum focal position, the width of the line will be minimum and the depth of the scored line will be maximum. The curve for the line width should have the general shape shown in Figure 17, with line width plotted along the *y*-axis and lens position along the *x*-axis. The position of the arrow indicates the optimum lens position. Keep the lens in this position for the rest of the experiment.

5. The next step involves measuring the *depth of penetration of the fusion zone* into the material *as a function of time* for a constant power on a stationary piece of lucite.

   With the lens at the optimum position determined above, and with the carbon block in the beam, insert a fresh piece of lucite. This piece of lucite will not be moved during the exposure. Make sure the beam will hit a clear area on the surface of the lucite. Remove the carbon block for a short time and allow the beam to strike the target. Reinsert the carbon block. Measure the length of time over which the beam struck the lucite with a stopwatch and record the time. Move the lucite so that the beam will strike a fresh location and repeat the operation for a different length of time.

6. Repeat this operation for a number of different times of exposure of the lucite to the beam. Then cut a cross section through each spot with the diamond wheel. Measure the depth of penetration of the melted zone into the lucite with the measuring microscope. Plot the results as a function of the square root of the exposure time. The results should form approximately a straight line, as indicated by the equation $D = (4kt)^{1/2}$ for penetration depth D, time t, and thermal diffusivity k.
7. Now try welding two pieces of lucite together. Place the two pieces side by side and in close contact on the translation mound: The edges of the lucite should be flat and smooth to ensure good contact. The geometry should be that of the butt or seam mount shown in Figure 6. Adjust them so that the laser beam will strike a point on the interface of the two pieces. The motion of the translation stage should be in a direction that allows the intersection of the two pieces to move through the beam. Several trials may be needed to achieve good alignment. When you complete the alignment satisfactorily so that the two pieces move accurately through the beam focus, re-insert the carbon block into the beam.

   Move the lucite pieces to a fresh region along the intersection between the two pieces, that is, to a region that has not been struck by the laser beam. Start the motor so that the lucite pieces move, remove the carbon block and allow the pieces of lucite to be welded together along a short region. Repeat this operation at several different levels of laser power. For each value, measure the laser power with the power meter. Increase the laser power until a weld zone is obtained that penetrates all the way through the lucite.
10. When you have made several welds, use the diamond wheel to cut the weld perpendicular to the welding line. The general appearance of the weld should look like Figure 1-19. This figure shows examples of both complete and incomplete penetration.

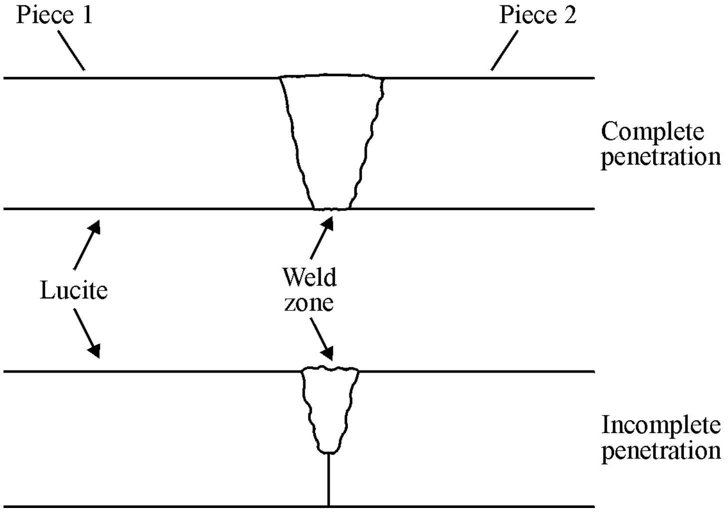

Figure 19 *Appearance of weld zones for a butt weld between two thin sheets*

11. Measure the depth of penetration of the weld zone for each value of laser power. Plot the *depth of penetration* versus the laser power. This gives a plot of weld depth as a function of power for constant speed. From the data in the plot, determine which combination of power, speed, and thickness produces welding with full penetration.

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