LASER BEAM MACHINING

Laser beam machining involves the practical harnessing and manipulating of laser radiation to have some effect on a material. The advantage of the laser over other light sources is that the light is produced in a well-defined beam which is easily manipulated and focused to produce the high intensities required to machine materials. The first laser was operated in 1960 by Maiman (1) and for a little while, at least, the cliché that it was an invention looking for an application had some truth to it. However, it was soon realized that the properly developed laser could be used in a wide range of scientific and industrial applications. It is ironic that in these early days before dedicated power and energy meters had been developed, the unit of measure of "power" of the laser was the number of razor blades drilled with a single pulse. Today, one large application of lasers is spot welding the flexible blades of a modern "high tech" razor blade to its support.

Throughout the ages, humankind has advanced by using its intelligence to harness and manipulate energy. Early civilizations developed tools, first made of stone but later of metal. These tools were used to direct their energies in a more efficient way. More recently we have mastered chemical, electrical, and nuclear energy. As our mastery of these energy forms has advanced, so has our technology, and this is reflected in the precision to which we can manufacture components and our ability to miniaturize them. Examples of this are abundant. The computing power which once occupied several large rooms is now built into a device the size of a wrist watch through the replacement of valve technology with transistors and then integrated circuits (ICs). Automobile body panels, once made to a tolerance of a millimeter or so, are now manufactured to within a few tens of microns. The fuel injection orifices in a diesel engine are drilled to within a few microns.

Lasers have contributed greatly to our ability to manufacture and miniaturize and continue to do so. By 1966 the first commercial 100 W power carbon dioxide (CO_2) laser was commercially available. Since then the power available has increased a hundredfold and there are many laser types available offering a choice of power, wavelength, and pulse format. This proliferation has widened the scope of laser applications which today range from heavy industry, such as welding in shipyards, to microelectronics, where the laser photolithographic process is used to manufacture ICs and memory chips. A laser beam for welding has a number of advantages over conventional techniques. A laser beam is an almost parallel beam of light. It is focused to a small diameter, it is easily directed via optical components, and its power is accurately controlled. This allows the user to exert precise control over the position and extent of the weld which, in turn, improves the quality of the weld and reduces thermal damage to the component.

GENERALIZED LASER BEAM MACHINING

Laser beam machining is the interaction of the laser beam with a material resulting in some change to the material. This is in the form of material removal (drilling and cutting), material addition (alloying and cladding), chemical changes (marking), structural changes (hardening or annealing), or joining (welding and soldering). The interaction results from

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*. Copyright © 1999 John Wiley & Sons, Inc.

the absorption of laser radiation by the workpiece. A certain fraction of the incident laser power is absorbed over the absorption depth and the remainder is reflected. Transmission of the beam occurs only when the absorption depth is greater than the material thickness but this is not the case for most materials of interest. Generally the absorbed energy or power is converted into heat in the material. Then the nature of the induced effect depends on the amount of energy absorbed, the time over which it is absorbed, and the thermal transport and thermodynamic properties of the material (2,3,4). In some cases, the energy of individual laser photons is important because, when high enough, it breaks chemical bonds which change the chemical nature of the material or even removes individual atoms or molecules from the structure. This is often called "cold ablation" because there is little or no thermal input to the material.

The absorption of the incident light intensity I_0, is given by the following equation:

$$I(x) = I_0 e^{-\alpha x} \tag{1}$$

where $I(x)$ is the intensity at depth x and α is the absorption coefficient. The absorption coefficient is a material property that also depends on the wavelength of the light and its intensity (at high intensities nonlinear effects occur). Light is an electromagnetic wave which, as it passes through a medium, interacts with the electrons of the medium whether they are bound or free. The electric field forces the electron to vibrate at the frequency of the wave. As the electron vibrates, it reradiates (transmits light), or, if it is restrained by lattice forces, it couples energy into the lattice via phonons. The phonons cause the lattice to vibrate which is manifested as heat. If sufficient heat is absorbed, then the material melts or is vaporized. Figure 1 shows the sequence of events as the absorbed power increases.

Beyond heating the material, the process in Fig. 1 assumes that the flow of heat away from the irradiated zone is less than the absorbed power. However, in some cases, a point is reached where the heat loss equals the absorbed power, and, therefore, the process may reach only the melting stage, for example. Heat flow in a material is proportional to its thermal conductivity k and the rate of change of temperature depends upon the specific heat C. The heating rate is inversely proportional to the specific heat per unit volume, which is equal to ρC, where ρ is the density. A thermal diffusivity κ may therefore be defined as $k/\rho C$ which is the change in temperature produced in a unit volume by the quantity of heat which flows in unit time through a unit area of a layer of unit thickness with a unit temperature difference between its faces. Thermal diffusivity is involved in all nonsteady-state heat flow processes and is therefore of great significance for pulsed-laser machining. The depth of heat penetration D over time t is given in Eq. 2 (see 2,3,4):

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

Typical values of κ for metals range from 0.05 to 1.0 cm^2s^{-1}. Taking carbon steel as an example ($\kappa = 0.12\ cm^2s^{-1}$), the penetration depths for laser-pulse durations of 10 ns, 100 μs and 10 ms are 0.7, 70, and 700 μm, respectively. A short laser pulse (10 ns) ablates material and so the heat penetration depth characterizes the extent of the heat damage to the remaining material, and submicron values are typically observed. Medium-length laser pulses (100 μs) are often used in laser drilling applications, and the heat penetration depth is typical of the drill depth per pulse. A long-pulse laser (10 ms) is often used for welding sections approximately 1 mm thick. Thus an appreciation of the laser beam energy, pulse duration, material absorption coefficient (which is wavelength-dependent) and the thermal diffusivity give a good indication of the type of interaction and effects possible.

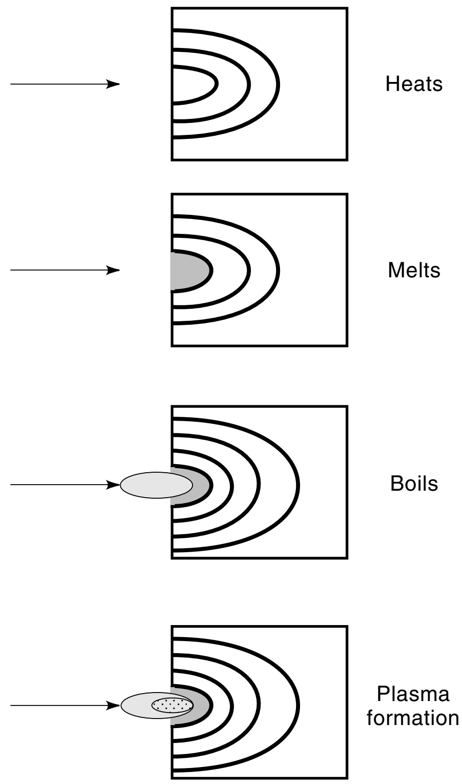

Figure 1. The sequence of events as the absorbed power increases. First the material is heated, then it melts, increasing power absorbed boils the melt, and finally very high absorbed power leads to plasma formation.

LASER MICROMACHINING

Laser micromachining is the use of lasers to produce features or components with micron precision and is widely used in the electronics, automotive, and precision engineering industries (5). Typical applications include drilling blind and via holes in printed circuit boards (6), dicing chemical vapor deposition (CVD) diamond wafers into miniature heat spreaders for high-power semiconductor devices (7), drilling precision fluid orifices for fuel injection (8) and aerosol components, etching silicon in the photolithographic process (9,10), manufacture of micro sensors and micro devices for surgical use, drilling orifice plates for inkjet printer heads (11), and manufacturing micromolds (12). For the feature size and precision required in micromachining, low- to medium-power lasers are used which control material removal more accurately. In addition the laser beam must produce small, well-defined, irradiation zones on the workpiece to make the hole or pattern desired. The material removal must be precise and must not produce significant amounts of debris or heat damage or induce mechanical stress in the component. These results are usually most easily achieved with a short-pulse laser operating in the visible or ultraviolet part of the spectrum where absorption is greater. Lasers which fall into these categories are the copper vapor laser, the Q-switched Nd:YAG laser, and the excimer laser.

LASER BEAM CHARACTERISTICS AND MANIPULATION

Laser Beam Characteristics

A laser beam is characterized by describing its spatial properties (beam profile and divergence), spectral properties (the range of wavelengths which it contains) and temporal properties (pulse duration and pulse repetition frequency). An excellent review of these subjects is in (13,14). A detailed treatise on these subjects and lasers in general can be found in Ref. 14a.

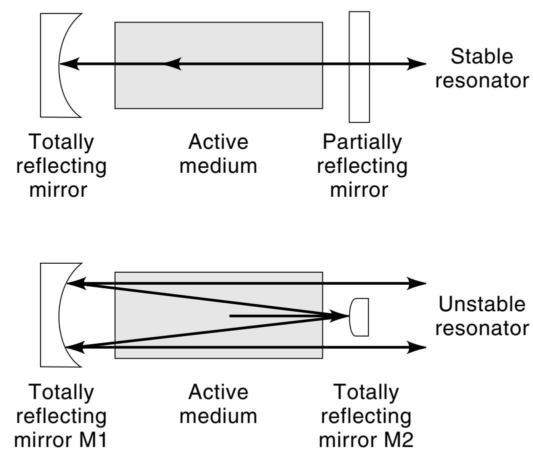

Figure 2. Diagram of a stable resonator showing the containment of the paraxial ray and output coupling via a partially reflecting mirror. The lower diagram shows an unstable resonator illustrating the output coupling by geometrical loss.

Laser Beam Divergence and Profile. Laser beam divergence is the spreading of the beam as it propagates by diffraction. It should not be confused with the spread or convergence of a beam caused by a lens or some such device which may be canceled by using an appropriate optical element. The divergence θ of the beam determines the minimum diameter w to which the beam is focused by a lens of focal length f and is given approximately by Eq. (3) [see (13), (14)].

$$w = f\theta \tag{3}$$

The beam profile is the spatial distribution of cross-sectional intensity at a given point along the axis of beam propagation. The "near-field beam profile" (near the output of the laser) and "far-field beam profile" (at a great distance from the laser or at the focus of the beam) are the profiles most often quoted. The beam divergence and profiles are determined by the laser resonator of which there are two principal types known, somewhat misleadingly, as stable and unstable resonators. Their descriptive names do not refer to the power or beam stability of the laser but rather to the type of output coupling. A stable resonator has mirrors which contain the paraxial rays over multiple reflections within the resonator. The beam is coupled out of the resonator by making one of the mirrors partially reflecting. In an unstable resonator, paraxial rays leave the resonator after a few reflections by being coupled past the perimeter of one of the mirrors. These resonators are illustrated in Fig. 2. The beam profile of the stable resonator is Gaussian or Gaussian-like in both the near and far field. The beam profile of the unstable resonator is more complex; it is annular in the near field, and forms a central disc with lower intensity rings outside it in the far field. When the magnification of the resonator (defined as the ratio of the radius of curvature of mirror M1 to M2) is high, the near field is a plane wave and, in the far field, 84% of the power defines the central disc. The far-field intensity distribution is described mathematically by the Airy pattern.

From Eq. (3) it can be seen that, for applications requiring a very small focused beam diameter, the beam divergence should be as small as possible tending to zero. Unfortunately diffraction presents a limit to minimum divergence. This minimum divergence (often called diffraction-limited) is realized only with certain lasers and when conditions are optimum. The diffraction-limited divergence, which also depends on the near-field beam profile, is given in Eq. (4) for a Gaussian beam and in Eq. (5) for a plane wave (as produced by an unstable resonator with high magnification):

$$\theta_{\mathrm{DL}} = 4\lambda/\pi d = 1.27\lambda/d \tag{4}$$

$$\theta_{\mathrm{DL}} = 2.44\lambda/d \tag{5}$$

where θ_{DL} is the full-angle, diffraction-limited divergence, λ is the radiation wavelength and d is the near-field beam diameter. These equations show that the divergence is inversely proportional to the beam diameter. Therefore, it is meaningless to compare beam divergences without stating the near-field beam diameter or the ratio of the divergence relative to the diffraction limit. Using Eqs. (3), (4), and (5), the minimum focused beam diameter for a diffraction-limited beam is calculated by the expression

$$w = f\theta_{\mathrm{DL}} = f\beta\lambda/d = (f\#)\beta\lambda \tag{6}$$

where β is 1.27 for a Gaussian beam and 2.44 for a plane wave, and $f\#$ is the f-number of the focusing system used, that is, the focal length divided by the beam diameter at the lens. For a copper vapor laser, $\lambda = 511$ nm and with $f1$ focusing the minimum spot size is 1.24 μm. The spot size for a Gaussian beam is defined as that diameter which contains 86.5% of the power, and, for an unstable resonator, it is the diameter which contains 84% of the power.

Although the laser spot size is a good indicator of the minimum size feature, such as a hole, that can be produced, it is possible to produce features larger and smaller than the spot size. For example, if the intensity of the beam at the spot diameter is in excess of the ablation or machining threshold intensity, then the feature size will be larger than the beam spot. Likewise, if the machining threshold is much higher than the intensity of the beam at the spot diameter, then the feature size will be smaller than the spot. This is illustrated in Fig. 3.

The optical quality of the laser beam differentiates it from any other light source and significantly affects the machining process in many complex ways. The laser beams described in this section are those that are achieved under ideal conditions. In practice these ideal conditions are not always achievable, titled and it is not possible to describe the interaction of the laser beam with the material by simple algebraic equations. However, some qualitative observations can be made.

As described in this section and the section titled "Focusing," the focused laser spot size is proportional to the divergence of the laser beam. Therefore a low divergence laser beam enables the beam to be focused to a smaller spot size, which permits the drilling of smaller holes, the cutting of narrower kerfs and welding, soldering, or heat treating smaller areas. A smaller focused spot size also increases the focused intensity of the laser beam. Higher intensities generally produce higher temperatures in the workpiece and therefore tend to increase or change the machining effect (for example, increasing the evaporation rate of the material or change the machining effect from melting to evaporation).

The depth of focus (DOF) of a laser beam is given in Eq. (6a) and is defined as the distance over which the laser beam is within a factor of $\sqrt{2}$ of its minimum diameter. For a given beam diameter and required focused spot size, a lower divergence beam enables a longer focal length lens to be used which increases the depth of focus. Therefore a lower divergence beam (closer to the diffraction limit) can enable deeper holes or cuts to be made or can be used to relax the tolerance to which the lens position has to be held relative to the workpiece.

$$\mathrm{DOF} = 2\pi w^2/\lambda = 2\pi f^2\theta^2/\lambda = 2\pi(f\#)^2\beta^2\lambda \tag{6a}$$

While the divergence of the beam plays an important part in the machining process, so does the intensity distribution of the laser beam at the workpiece. For example, most hole drilling applications require round holes and a nonround intensity distribution at focus can produce nonround holes. Uniform intensity distribution is very important when the laser beam is used to illuminate a mask which is then imaged onto the workpiece.

For further details and examples of how the optical quality of the laser beam affects the machining process the reader is referred to Refs. 14b, 14c, 14d in the bibliography.

Laser Beam Spectral Bandwidth. The laser spectral bandwidth is the range of wavelengths or frequencies emitted by the laser. The bandwidth or spread of wavelengths depends on the type of laser and how it is configured. Some lasers, such as dye lasers, have large bandwidths of 20 THz (approximately equivalent to a 20 nm spread at a central wavelength of 600 nm) whereas others, such as the frequency-stabilized HeNe laser, are essentially monochromatic with bandwidths of 1 MHz. The gross bandwidth is determined by the bandwidth of the atomic or molecular transition that produces the laser photons. The laser cavity itself has resonant modes (14) whose width and bandwidth are determined by the cavity length and mirror reflectivity. Resonant longitudinal modes occur when a laser photon has the same phase after one complete transit through the laser cavity. Equation (7) gives the frequency separation $\Delta\nu$ of the longitudinal modes where c is the speed of light and $2L$ is the complete round-trip distance.

$$\Delta\nu = c/2L \tag{7}$$

The bandwidth $\delta\nu$ of each mode depends on the reflectivity of the cavity mirrors and is given by Eq. (8).

$$\delta\nu = \{c[1-(R_1)^{1/2}]\}/[2L\pi(R_1)^{1/2}] \tag{8}$$

In this equation it is assumed that the reflectivity of one mirror is R_1 and the second mirror has 100% reflectivity as in Fig. 2. The bandwidth of a longitudinal mode is typically a few megahertz. Therefore the spectral output of the laser is made up of a series of longitudinal modes, each with a very narrow spectral bandwidth and whose intensity envelope follows the gain profile of the laser. The practical bandwidth of the laser is reduced by configuring the laser cavity so that optical losses are incurred over all but part of the bandwidth. These losses reduce the effective gain over most of the bandwidth to levels below the threshold required for laser action. Consequently laser action then occurs at longitudinal modes which fall within the part of the bandwidth above threshold.

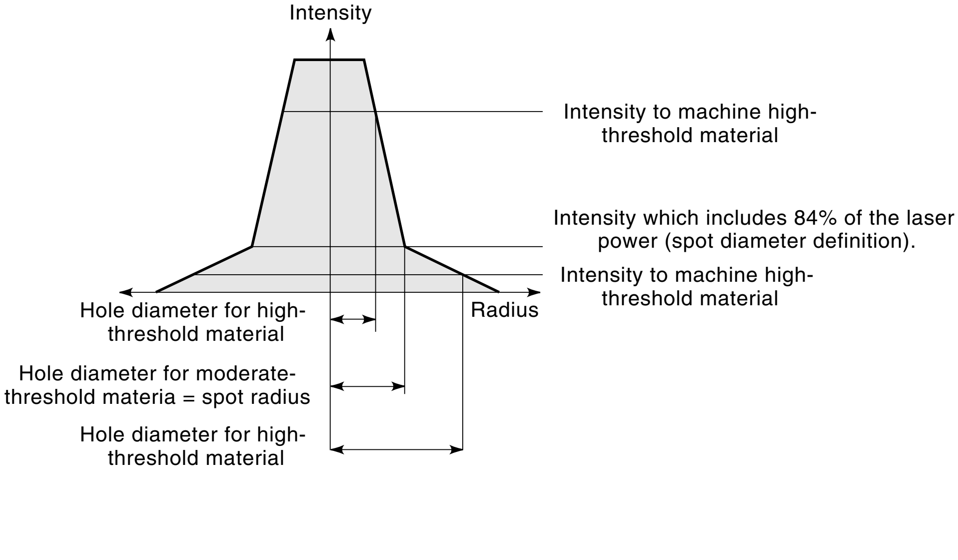

Figure 3. Laser beam with a simple beam profile, illustrating how the feature size depends on the machining threshold relative to the laser intensity.

This technique is used to narrow the bandwidth and is also used to tune the laser frequency.

In most machining applications, the laser wavelength significantly affects the machining process because of the wavelength-dependent nature of the workpiece material's absorption coefficient. However the bandwidth does not greatly affect the process because the absorption bands in most materials are relatively broad. Spectral bandwidth is important when the ultimate performance is required and when focusing or imaging a laser beam and chromatic aberrations must be minimized. The focal length of a simple singlet lens depends on the curvature of its surfaces and its refractive index. Because the refractive index is wavelength-dependent, the lens focal length is also wavelength-dependent. Photolithographic production of integrated circuits employs excimer lasers because their ultraviolet wavelengths permit higher resolution imaging. To attain the highest resolution, however, the laser bandwidth is narrowed from typically 1 nm down to a few picometers.

Laser Beam Temporal Characteristics. Lasers produce continuous output or pulsed output. The pulse widths range from milliseconds to femtoseconds although usually a given laser or configuration is limited to a much narrower range of pulse widths. A laser is operated in one of four basic ways: continuous wave (CW), pump-pulsed or quasi-CW, Q-switched, or mode-locked (14). CW operation is possible with most but not all lasers. CW operation requires that the lifetime of the lower level of the laser transition is shorter than the lifetime of the upper laser level. If this is so, then electrons are quickly recycled to the upper laser level to maintain output with continuous energizing or pumping of the laser. Quasi-CW operation occurs when the laser is capable of CW operation but the pumping of the laser is pulsed. Typically this produces pulses of millisecond or microsecond length. The pulse repetition rate for such a device is usually in the range 1 Hz to 1000 Hz.

Q-switching employs an intracavity shutter (often an electro-optic or acousto-optic device, rather than a mechanical device) to produce nanosecond length pulses. The laser is either pump-pulsed or continuously pumped. Initially the shutter is closed and, while the laser is pumped, the electron population inversion of the laser medium is built-up to a population resulting in a gain which greatly exceeds the laser threshold value. When the shutter is opened, the intracavity optical intensity increases very rapidly because of the high gain of the laser medium. The rapid increase in intensity quickly depopulates the upper laser level and, at some point, the gain is driven below the threshold value terminating the laser pulse. The resulting output pulse is usually very short, ranging from 1 to 1000 ns depending on the laser gain and cavity length. The pulse repetition rate is usually in the range of 1 Hz to 50,000 Hz.

Certain lasers, such as the copper vapor laser and excimer laser, are inherently pulsed and produce pulse widths in the range of 10 to 100 ns. The inherent pulsed nature of these lasers greatly simplifies their design compared to Q-switched lasers.

Modelocking is a technique in which an intracavity shutter is operated at the cavity round-trip frequency for laser radiation. This phase-locks the longitudinal modes, and the pulse width of the laser is then the Fourier transform of the longitudinal mode spectrum's bandwidth. For a broad bandwidth laser, such as titanium sapphire, the pulse widths are as short as 5 fs with a pulse repetition rate in the megahertz range.

The pulse width and pulse repetition rate, along with other characteristics, such as laser wavelength and workpiece material characteristics, significantly influence the type of material interaction that occurs.

Laser Beam Manipulation

The output beam from most lasers is a collimated beam of several millimeter diameter, usually in the range of 2 mm to 20 mm for a machining laser. The intensity of the collimated beam is usually too low for most applications. The intensity at the workpiece is increased by focusing or imaging the beam with a lens or mirror. Although it is possible to machine small features directly with the laser beam, in many cases and especially for larger features, it is necessary to manipulate the laser beam or the workpiece or both. Beam manipulation techniques include focusing, imaging, and scanning. The beam is scanned by a variety of means including mirrors (galvo or piezo-driven), moving refractive optics (lenses and prisms), acousto-optic modulators, articulated mirror beam delivery systems, and fiber beam delivery. Practical examples of beam manipulation can be found in Refs. 2, 3.

Focusing. The diameter w of a focused laser beam was given in Eq. (3). The equation assumes that the lens is aberration-free, that the lens is in the near field of the beam, and that the f-number of the lens is much less then the inverse of the divergence ($1/\theta$). The general equation for the diameter of a beam at the focus of a lens (13) is given in Eq. (9) where the beam diameter at the lens is w_L:

$$w = (\lambda/\pi)\{\theta^2 + (w_{\mathrm{L}}/f)^2 - (2\lambda/f)[(\pi w\theta)^2 - 1]^{1/2}\}^{-1/2} \qquad (9)$$

When the lens is in the near field of the beam, this equation simplifies to Eq. (10):

$$w = f\theta[1 + (f\theta/w_{\mathrm{L}})^2]^{1/2} \qquad (10)$$

When the f-number is much less than $1/\theta$, then Eq. (10) reduces to Eq. (3), and the focused beam is located at a distance f from the lens.

Finally when the lens is placed in the far field of the beam, then Eq. (9) reduces to Eq. (11):

$$w = (\lambda/\pi)[(w_{\mathrm{L}}/f) - \theta]^{1/2} \qquad (11)$$

Assuming that the lens f-number is small compared to $1/\theta$, then Eq. (11) simplifies to Eq. (12).

$$w = \lambda f/\pi w_{\mathrm{L}} \qquad (12)$$

Lens Aberration. Equations (9)–(12) assume an aberration-free lens. If there is significant aberration, it is not usually possible to calculate the spot size exactly without using a ray-tracing software program. The common aberrations include spherical, astigmatism, coma, field curvature, distortion, and chromatic and are discussed in detail in Ref. 14e.

Spherical aberration is caused by rays distant from the optical axis focused at a different distance from the lens than those closer to the axis. For a positive lens, the distant rays are focused closer, and, for a negative lens, the distant rays are focused further. Combining a positive lens made from a low refractive index glass and a negative lens made from a high index glass produces a combination in which the spherical aberration cancels but the focusing power does not.

Astigmatism occurs when a lens effectively has two different focal lengths leading to a cylindrical component to the spherical lens. It is caused by a nonspherical curvature of the lens or because the lens is nonorthogonal to the optical axis.

Coma results from different parts of a spherical lens surface exhibiting different degrees of magnification. This causes an off-axis imaged point to appear as a flare rather than a point.

Field curvature is the tendency of optical systems to form an image on a curved surface rather than a flat plane. The field curvature varies with the square of the field angle or square of the image height. It is reduced by reducing the field angle. It is corrected to some extent by combining positive and negative lenses.

Distortion occurs when a point in the object plane is focused to a point in the image plane but not to the correct axial position. Distortion usually increases with image height. It does not reduce the resolution of the optical system but does distort the shape of the image.

Chromatic aberration results from the wavelength dependence of the focal length. This is only significant for a laser with broadband wavelength output.

Optimum Focal Position. When optimizing the focusing of a laser beam, the first task is to choose the appropriate lens for the desired machined feature. In addition to this, it is necessary to choose or experimentally determine the optimum position of the focus relative to the surface of the workpiece. This position depends very much on what type of laser is being used, the workpiece material, and the desired effect. When the laser beam is focused on the surface of the workpiece, then the minimum surface spot size is achieved. At focus, the beam is collimated, that is, it is neither diverging or converging, as shown in Fig. 4. It can be seen from Fig. 4 that if the beam is not focused on the surface then as it enters the material it is diverging or converging. This affects the machining as the beam propagates further into the material. Except for very thin workpieces (typically less than 0.2 mm thick), then the workpiece is thicker than the distance over which the focused beam is approximately collimated (depth of focus). Therefore the user must consider the effect that the out-of focus beam has on the workpiece. For example, if the focus is placed at the surface to drill a hole, then, as the beam propagates into the workpiece (as material is removed by the laser beam), the laser beam expands. This initially causes the diameter of the hole below the surface to increase. However, for a typical Gaussian profiled beam, a point is reached at which the intensity of the beam near its outer diameter is reduced to a value below the machining threshold (see Fig. 3). At this stage the diameter of the hole starts to reduce. This continues until the hole breaks through the lower surface or machining ceases. In some cases, the user finds that it is possible to drill a parallel-sided hole whose depth is much greater than the depth of focus of the beam. The reasons for this behavior are complex, but it is most likely to occur by guiding the beam through the material by reflection and scatter from the hole wall or by balancing the beam expansion and machining threshold. Experimental evidence suggests that both mechanisms occur and can be used to advantage. For example, take a laser beam focused on the surface of a material where the laser is removing material in an ablative mode. If the laser power is high enough, it is possible to drill a hole whose diameter increases into the material, creating a hole with a negative taper (15). Now if the laser power is reduced a little, then it is possible to balance the beam expansion with the lower intensity and losses to produce a parallel-sided hole.

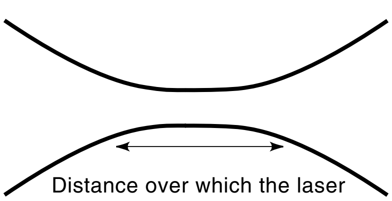

Figure 4. Propagation of a laser beam through focus. The distance over which the laser beam is nominally collimated is defined as the distance by which the diameter has increased by a factor $\sqrt{2}$. This distance is known as the confocal parameter.

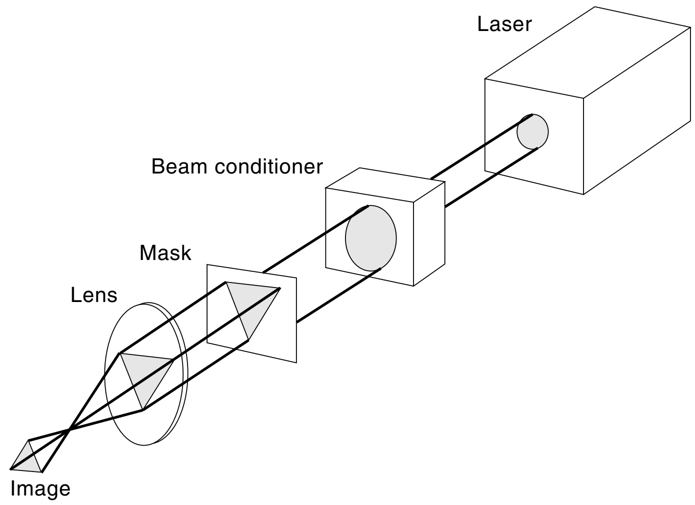

Figure 5. Typical optical configuration for a laser mask imaging system. Note that the image is inverted.

Mask Imaging. Mask imaging is a technique whereby a laser beam illuminates a mask and an image of the mask is projected onto the workpiece. A typical mask imaging configuration is shown in Fig. 5. Through appropriate optical design, magnified or demagnified images are created. In most cases the image is demagnified. One advantage that mask imaging has over conventional focusing of beams is that the user easily chooses and adapts the shape of the beam to the workpiece. With conventional focusing, the beam at the workpiece is the Fourier transform of the beam at the lens, and therefore it is typically circular with a Gaussian profile. Although this is suitable for many applications, mask imaging opens a wider range of possibilities to the user. To get the best results and maximum benefit from mask imaging, however, the material must be removed only where the workpiece is exposed, that is, it must be a "cold" process in which material is removed through vaporization, ablation, or chemical means. If there is a large degree of melting the edges of the interaction zone blur. Thus the laser beam must be strongly absorbed by the workpiece and in most cases this requires a UV laser source.

The most common type of UV machining laser is the excimer. These lasers use a rare gas-halide mixture as the gain medium. The usual gas mixes are XeCl, KrF, and ArF, which generate 308, 248, and 193 nm wavelengths, respectively. These short UV wavelengths are strongly absorbed by most materials including plastics, polymers, ceramics, diamond, and metals. In many materials the photon energy (inversely proportional to the laser wavelength) is high enough to break the atomic and molecular bonds of the workpiece material. Therefore the material is removed by photochemical dissociation. If the energy density greatly exceeds the machining threshold, then the excess energy introduces thermal input to the workpiece which leads to a loss in image definition.

To achieve a uniformly machined depth, the mask must be uniformly illuminated. Most laser beams are not uniformly intense across their beam area. For example, many have a Gaussian intensity beam profile. Even lasers with a nominally uniform beam profile, such as the excimer, are not uniform enough. Therefore optical beam homogenizers are employed. In addition the laser beam area may need to be compressed or expanded to use the mask efficienctly. In Fig. 5, these units are represented by the beam conditioner module. The beam then illuminates the mask, an inverted triangle in this case. The mask is usually formed in a metal sheet or by etching/depositing a metal film on a silica substrate. The lens is placed some distance after the mask. This distance is called the "object distance" represented by the symbol s in Eq. (13). The distance from the lens to the image is the "image distance," s'' in Eq. 13, and f is the focal length of the lens.

$$1/f = 1/s + 1/s'' \tag{13}$$

The ratio of the image size h'' to the object size h, called the magnification, is given by Eq. (14):

$$m = h''/h = s''/s \tag{14}$$

Typical values for m range from 0.05 to 1. The lens focal length is usually in the range 0.05 m to 0.2 m and so object distances are usually of the order 1 m. Because magnification values are often much less than unity, the mask is made without resorting to high precision micromachining techniques. Chemical etching and standard laser cutting techniques are often used to fabricate the mask.

The depth of focus of a lens is the distance over which the image is acceptably sharp and within certain dimensional tolerances. These criteria are set by the user and depend very much on the application. Depth of focus increases with increasing f-number, where the f-number is the effective focal length divided by the system clear aperature. In many cases the depth of focus is just a few tens of microns or less and therefore mask imaging techniques are best suited to surface structuring or cutting/drilling very thin layers.

Mask imaging techniques, when applicable, simplify the processing procedure and increase production rates. For example, if the workpiece requires reproducing a certain etched shape over the surface, this is achieved by using a mask with this shape repeated in it. The number of features that are etched simultaneously is limited by the laser pulse energy and the energy density required for machining. A simple CNC program is then used to repeat this pattern over a larger area. If a direct-writing technique is used, then the CNC programming required to etch the feature and repeat it is more complex, although the optical set-up is more straightforward.

When the laser wavelength is UV, then strong absorption means that the depth of absorption is shallow, typically in the range of 0.1 μm to 1 μm. Then it is possible to control the depth of the etch by using a fixed energy density and counting the number of laser pulses. In addition this technique is used to create 3-D structures in materials by overlapping images or changing the image as the depth of etch increases. Take, for example, a simple slit mask. If the workpiece is moved across the image plane, then, by programming the number of pulses per CNC position and the overlap of the image of the workpiece, the width of the etch as a function of depth is varied. An example is shown in Fig. 6. With some imaginative use of the mask and programming, complex shapes are generated. Some practical examples of mask imaging as applied to the marking of products can be found in Ref. 3.

Diffractive Optics for Beam Shaping. Diffractive optics are a new class of optics that replace conventional optics or produce effects not readily achievable with conventional optics (16). The structure and propagation of a laser beam is determined by the spatial distribution of its amplitude, phase, and polarization. Diffractive optics modify the spatial amplitude and phase of a beam to effect some change. The modification to the amplitude and phase is produced by etching the surface of an optic with micron resolution. The beam shape after the beam has propagated a great distance is called the "far-field" beam profile or beam shape. This condition is also achieved at the focus of a lens. Diffractive optics usually produce far-field beam shapes. Because the beam shape in the far field is the Fourier transform of the near field, then, for a desired far-field pattern, computational techniques are used to calculate the near-field pattern. Then an optic is manufactured which

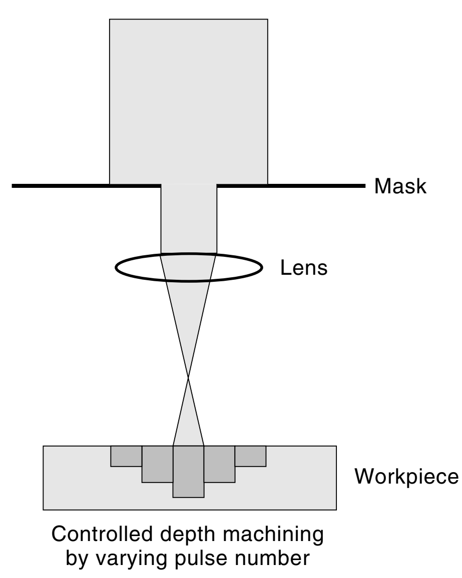

Figure 6. An example of 3-D machining by a mask imaging technique with step indexing of the workplace.

produces the required near-field pattern. In addition to custom optics, a wide range of standard diffractive optics are available. These include transformation from Gaussian to top-hat (super-Gaussian) and vice versa, transformation from Gaussian to an annulus or line or cross or square or arrays of dots. The efficiency of these devices is usually >70% and is as high as 95%. This is much higher than is often achieved with a mask, and so diffractive optics are being adopted in certain applications.

Adaptive Optics. Adaptive optics are optics, usually mirrors, that are deformed to modify the wave front (spatial phase distribution) of the beam. The mirror is usually deformed to a prescribed curvature with an array of piezo-actuators attached to the back face of the mirror. The advantages of this technique over diffractive optics are that the phase and hence far field of the beam is controlled from a PC in real time. Also the efficiency of the mirror should be >99%. The disadvantage is that the technique cannot modify the amplitude of the wave front, and this limits the range of shapes and their definition. A description of an adaptive optic mirror can be found in Ref. 16a.

Beam Scanning. The inertia of the workpiece and CNC tables limit the accelerations and velocities possible, especially for small movements. Optical deflection and scanning techniques achieve very high accelerations and velocities and are widely used in laser beam machining applications. The three techniques used conventionally are galvanometer-driven mirrors (galvo-mirrors), piezo-driven mirrors, and acousto-optic deflection.

Galvo-mirrors are standard optical equipment widely used in industrial applications of lasers. The optical configuration usually includes two independent galvo-mirrors, one to scan the beam in the X direction and the other in the Y direction. The beam is then focused onto the workpiece with a flat field lens which maintains the focus over a scanned area up to 300×300 mm for laser machining applications, although the highest precision is achieved only over smaller areas. The most common use is in laser marking systems in which the galvo-mirrors scan the beam over an area of material to etch text or graphics (3). Typically such a system writes at 300 dpi over an area of a few cm^2 in a few seconds. Very high accelerations and velocities (2 ms^{-1}) are achieved while maintaining positional accuracy to within 5 μm. The step response time for a step change of a few degrees (equivalent to a few mm movement on the workpiece) is approximately 5 ms. This should be compared to a response time of 50 ms to 150 ms for a typical linear translational stage. The controls and programming of the galvo-mirror drivers are integrated with the host controller of the production machine. Galvo-mirrors are also used in drilling, cutting, welding, and soldering applications.

After deflection by the mirror, the beam passes through the focusing lens. The angular deflection imparted to the beam becomes a positional change or displacement at the focus of the beam. The displacement is approximately equal to the product of the angular change and the focal length of the lens. This holds exactly when the angle is small and the beam

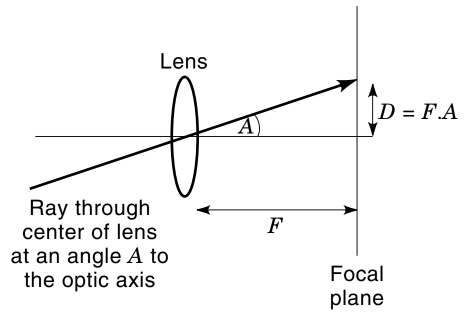

Figure 7. Rays passing through the center of a lens are not refracted.

passes through the center of the lens (Fig. 7) because elementary optics says that a ray traveling through the center of a lens is not refracted.

Piezo-Driven Mirrors. The principle of operation is similar to that of the galvo-mirror system, that is, the beam is deflected by a mirror and then focused by a lens. For the piezo-driven mirror, two piezo-actuators tilt the mirror in the X and Y directions, so that only a single mirror is required. The acceleration and velocities are similar to that of the galvo-mirror systems. However, the range of deflection is smaller but more precise. Therefore these systems are sometimes preferred for micromachining applications (16b).

Acousto-Optic Deflection. Acousto-optic deflectors operate by producing a dynamic acoustic standing wave in an optically transmissive crystal via the piezo-electric effect (16c). The compression/decompression of the crystal generates a standing wave that produces a periodic variation in optical density which behaves as a diffraction grating. By varying the drive amplitude and frequency, the dynamic diffraction grating deflects the laser beam. Again this angular deflection is converted to a displacement at the focus of the lens. This is an attractive solution because there are no moving parts and the response is very fast. The disadvantages are the lower efficiency (typically 80%) compared to a mirror (>99% efficiency) and the restricted range of deflections achieved at certain wavelengths where the choice of appropriate crystals is limited.

Beam Splitting. Beam splitting is used in laser beam machining to increase process speeds or spread the heat input into a component over a larger area. It is accomplished spatially or by amplitude. Spatial splitting is the simplest and is illustrated in Fig. 8(a). A mirror is inserted into the side of a beam and that part of the original beam is split off. The fraction split off is determined by the area of mirror presented to the beam relative to the original beam area. The disadvantages of this technique are that it is difficult to set the power in each beamlet exactly, the space occupied by the optics becomes large if more than a two-way split is required, and the change in dimensions of the beam changes the size and shape of the focused beam.

Amplitude splitting of the beam is achieved with partially reflecting mirrors [Fig. 8(b)] or diffractive optics [Fig. 8(c)]. Although the concept of the partially reflecting mirror is simple, in practice it is difficult to attain the exact reflectivity

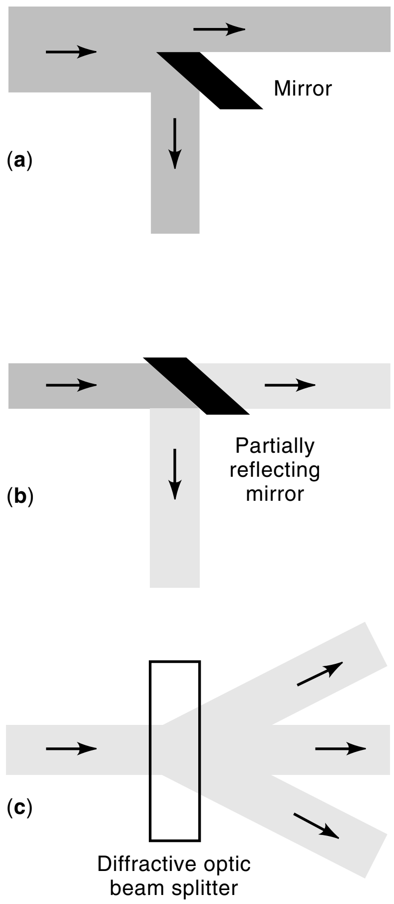

Figure 8. (a) A mirror is partially inserted into the beam to split off a fraction of it. (b) Amplitude splitting using a partially reflecting mirror. (c) Schematic of a diffractive optic producing three beamlets.

required, especially when a larger number of beamlets is needed. For example, a four-way split requires three mirrors with reflectivities of 25, 33, and 50%, respectively. In addition it is difficult to fabricate a compact system.

Diffractive beam splitting uses a custom-made optic which has a diffraction grating type pattern etched onto it. The pattern is optimized to create a finite number of orders (beamlets) with equal power in each order. The emerging beamlets are identical in size to the incoming beam and have an angular separation determined by the wavelength of the beam and the diffractive optic. The angular differences between the beamlets are converted to displacements in the focal plane of the focusing lens thereby creating a number of focused beams of equal intensity on a fixed pitch. The advantages of the diffractive optic are that it is extremely robust and simple to use. The disadvantages are the low efficiency (50% to 90%) and the high cost for custom designs.

APPLICATIONS OF LASER BEAM MACHINING

Surface Micromachining

Surface micromachining is the etching, texturing, or milling of a surface with micron-scale resolution. Applications of these techniques are used in a wide range of industries. For example, etching creates channels and reservoirs for fluids. Such features are used to aid lubricant delivery to specific components inside combustion engines. Another application is in the medical industry where microchannels and reservoirs are used in drug delivery systems (12). Similarly, excimer lasers are used to pattern and etch polyimides for use in desktop inkjet printers (11). Nd : YAG lasers (7) and copper vapor lasers are used to manufacture photovoltaic panels by scribing the large substrates into smaller panels. Isolation and connections between different layers are achieved through selective laser scribing steps.

Lasers alter the topography of a surface removing material by ablation or reshaping it via melting. Surface texturing alters the appearance of a component (for cosmetic reasons) or modifies its characteristics. Texturing increases surface area for catalytic or voltaic reasons and modifies the flow of a fluid over the surface (as is done conventionally on a macroscopic scale on golf balls).

Milling is an extension of the etching/scribing process whereby the small focal laser spot is scanned over the surface of a material to remove "bulk" material on a micron scale. This creates complex 3-D structures and could be used to take existing planar microelectronic fabrication technologies into a new dimension. Another use of laser milling is to replace a number of primary steps in the laser LIGA process by a single laser operation. LIGA is a German acronym for Lithographie Galvanoforming Abforming which translates as photoablation, metal deposition, and molding (12). An excimer laser ablates a master mold form in a polymer. This has a thin conductive coating applied using vapor deposition. Then electroforming makes a metal (nickel cobalt) mold which replicates the part in PMMA or polystyrene. Using a copper vapor laser or Nd : YAG laser and a milling technique, the master form is created directly in a metal substrate by laser ablation.

Photolithography. Photolithography is used to fabricate integrated circuits on silicon. One of the drivers of this technology is the market demand for dynamic RAM (DRAM). Each year the manufacturers increase the memory capabilities of these chips by etching smaller and smaller features onto the wafer (9,10). In the photolithographic process, a light source illuminates a mask which is imaged onto a photoresist for subsequent chemical etching. The feature size produced is primarily governed by the lithographic resolution although a great deal of technology is also involved in optimizing the rest of the process such as the chemical etch. The lithographic resolution is proportional to the exposing wavelength and the numerical aperture of the projection lens. Consequently the illumination sources have changed from mercury g-line lamps (436 nm) to the i-line (365 nm) to deep UV sources (248 nm excimer laser) and even to X-ray sources. Although the X-ray source has significant advantages in terms of resolution by virtue of its wavelength, the excimer laser has a number of practical advantages for production use. The 250 nm features needed for 64 Mbit DRAM fabrication is resolved using i-line lithography but 248 nm excimer lasers are required for the 250 nm resolution for the 256 Mbit generation. The design of the projection lens is so critical that although chromatic aberrations could be compensated, to do so would be at the expense of some other parameter. Therefore the illuminating source must have a narrow bandwidth. In the case of the excimer laser this is possible but involves the use of additional intracavity components and is at the expense of output power. However, modern excimer lasers produce adequate power for this application, and this is anticipated to be a major application for these lasers.

Microhole Drilling

The requirement for microhole drilling is increasing in many industrial sectors (5,6,8,11,15). For example, in the electronics interconnect industry, the sizes of via holes in printed circuit boards are limiting the packing density of components on the boards and are currently the factor limiting miniaturization. Although high speed twist drills drill holes down to 100 μm, the cost of the drills is high, their lifetime is short, and the reliability in the process is poor. International legislation is forcing automotive manufacturers to produce cleaner burning engines. Lower emissions are achieved when the fuel is injected at higher pressure and this in turn demands smaller injection orifices. The orifice sizes ($<$140 μm) are now going beyond the limit of conventional drilling techniques (mechanical twist drill and wire electric discharge machining). Laser drilled holes are increasingly used in the aerospace industry as cooling holes in turbine blades, vanes, and combustion chamber liners. Designers are examining the use of small holes over the aerofoil to improve the laminar flow and hence improve the lift efficiency. The size (typically $<$100 μm diameter) and number require high speed precision drilling for which the laser is the best solution.

Laser drilling involves the removal of material by vaporization or melt expulsion. The simplest mechanism to model is vaporization. When the laser beam strikes the surface of the workpiece a fraction of the incident power is absorbed. This heats the workpiece and if the laser beam intensity is high enough, typically greater than 10^5 Wcm^{-2}, vaporization occurs. Initially the workpiece surface reaches the vaporization temperature; if the laser continues to deliver more energy to the surface then the excess energy overcomes the latent heat of vaporization and material is removed as a vapor. The maximum depth that can be vaporized $d_{\max}$ using this model is expressed in Eq. (15).

$$d_{\max} = [(1-R)E/A\rho][c_p(T_v - T_0) + L_v + L_f] \qquad (15)$$

Equation (15) is a heat balance equation where R is the reflectivity of the workpiece surface, E is the laser pulse energy, A is the area of the laser beam on the workpiece, ρ is the density, c_p is the specific heat, T_v is the boiling temperature, T_0 is the ambient temperature, L_v is the latent heat of vaporization per unit mass, and L_f is the latent heat of fusion per unit mass. Applying the above equation to nickel and using a 10J pulse from an Nd:YAG laser (wavelength of 1064 nm) focused to a spot of 10^{-3}cm^2, then the maximum hole depth is 1.4 mm. This value is in broad agreement with that observed experimentally.

There are three basic laser drilling techniques; single-shot drilling, percussion drilling, and trepanning. As implied, single-shot drilling uses a single laser pulse to pierce the material and form the hole. Typically a Nd:YAG laser is used with a pulse energy of a few joules and a pulse width in the 0.1 ms to 5 ms range. The hole size is largely determined by the laser beam diameter when it hits the surface. The hole quality is quite poor but is adequate for some applications. The advantage is that the drilling rate is high and is often performed "on-the-fly" because only a single pulse is used. Percussion drilling is similar except that several pulses are used. One or more may be required to pierce the material, and then an additional pulse is fired to remove debris from the hole and give it its final shape. The hole quality is better than with single-pulse drilling but the drilling rate is lower. The best hole quality is usually achieved by a trepanning technique in which the laser beam is used to cut out the hole. The laser beam is focused to a spot size much smaller than the hole diameter required and then the beam is moved relative to the workpiece to form the hole. Generally a large number of laser pulses is used. The hole quality and precision are greatly enhanced because of the large number of pulses used (a lower pulse energy is used and a smaller amount of material is removed per pulse). In addition the size and shape of the hole are now controlled by the relative movement of the beam and workpiece and this is effected more easily and precisely than manipulating the beam focal spot size. The copper vapor laser is ideal for precise drilling of microholes because of its deal laser parameters for this application (high beam quality, high peak power, high average power, low pulse energy, high pulse repetition rate, short pulse length, and visible wavelength).

Micro Soldering

Higher integration density of electronic circuits demands improved mounting technology. Because of the reduced contact area of surface-mount packages, sophisticated soldering systems are required to ensure product quality and yield. Standard reflow soldering techniques thermally damage sensitive devices and mechanical tension occurs in the solder joints. These problems are avoided with a laser because the amount of energy delivered is precisely controlled and accurately directed, so that the heat input to the component is minimized. The laser also offers the possibility of controlling the heat flow to each individual solder joint (17). Using a fiber optic beam delivery or scanning galvo-mirror system, the Nd:YAG laser is well suited to this task and similar tasks such as microspot welding.

Laser soldering occurs when the laser energy absorbed by the solder surface melts the surface, and the melt front propagates inwards until the energy of the pulse is dissipated in the melt process. The melt process then stops and a resolidification from moves back towards the surface. For simplicity this model ignores energy which is dissipated into the components to be soldered. Assuming that the laser pulse has a square temporal profile of length t_0, so that the incident power is either P_0 or zero, then the temperature T of the materials at a depth z and time t is given by Eqs. (16,17), where ierfc is the integral of the complimentary error function.

$$T(z,t) = (1-R)\{[2P_0\sqrt{(\kappa t)}]/K\}\mathrm{ierfc}(z/(2\sqrt{(\kappa t)}) \qquad \text{for } t \le t_0 \qquad (16)$$

$$\begin{aligned} T(z,t) = &(1-R)[[2P_0\sqrt{\kappa}]/K]\{\sqrt{t}\,.\mathrm{ierfc}[z/(2\sqrt{(\kappa t)}]\} \\ &- \sqrt{(t-t_0)}.\mathrm{ierfc}\{z/[2\sqrt{\kappa(t-t_0)}]\}\} \qquad \text{for } t > t_0 \end{aligned} \qquad (17)$$

The energy required to melt an area of material A to depth d is given by Eq. (18).

$$E = [c_p(T_f - T_0) + L_f]\rho\pi A^2 d/[4(1-R)] \qquad (18)$$

Further information on thermal modeling of these processes can be found in texts such as Refs. 17a and 17b.

Welding

As with laser soldering, welding benefits from the laser's ability to precisely heat a certain area or volume of material. Lasers are used extensively for welding in the automotive industry because of their flexibility, precision and cost effectiveness (18). Laser welding is used in one of two ways, either conduction welding or keyhole welding. In conduction welding, the laser beam melts the surface of the metal to a depth determined by the heat input and conduction properties of the metal. This technique is limited to shallow welds because of the limited conduction depth. Keyhole welding is used for deep, high penetration welds. The impinging laser energy is concentrated by focusing the beam, and this heats the metal above its boiling point, forming a hole in the metal. The vaporized cavity is full of ionized metallic gas (plasma), trapping some 95% of the laser power in a cylindrical volume called a keyhole. Heat is transferred from the keyhole region outward rather than from the surface down, forming a molten region around the vapor. As the laser beam moves relative to the workpiece, the molten metals fills in behind the hole and solidifies, forming the weld. The process happens very rapidly so that welding speeds of several meters per minute are obtainable with minimal heating, a small heat affected zone, minimal thermal distortion, and limited residual stress. The keyhole enables high aspect ratio welds. In addition keyholing induces a stirring motion within the weld puddle. This allows gases to escape and provides low-porosity welds. The intense heat also lowers the impurity content and provides very rapid cooling rates, so that the resultant weld nugget has average tensile strengths equivalent to or greater than the parent material. Detailed discussions of the theory and practice of laser welding can be found in Refs. 2, 3, and 18a.

The ability of high power CO_2 lasers (1 to 20 kW) and high power Nd : YAG lasers (1 kW to 5 kW) to produce high integrity, deep welds at high speeds has enabled their uptake by automotive industry, replacing electron beam welding, which must operate in a vacuum and is sensitive to magnetic fields. Laser welders are used extensively in welding transmission gear assemblies, body panels, and other automotive components. They are used in the electronics industry to seal hermetic packages, spot-weld TV guns, and other structural components. An example of laser welding on a household item is the spot welds on the Gillette Sensor razor which attach the flexible blade to its support.

Cutting

Laser cutting is the largest application for industrial lasers accounting for about 40% of the industrial laser market. High speed cutting is usually performed by high-power CO_2 or Nd : YAG lasers. The copper vapor laser is emerging as the leading candidate for precision cutting in micromachining applications on metals, ceramics, and diamond.

High-speed laser cutting (using either CO_2 or Nd : YAG lasers) is similar to laser welding except that a high-pressure (2 bar to 20 bar) assist gas removes the melted material, thereby forming a cut (2,19). The gas is delivered coaxially to the laser beam and removes the melt material by virtue of the gas pressure, blowing the material out of the bottom of the cut, or a

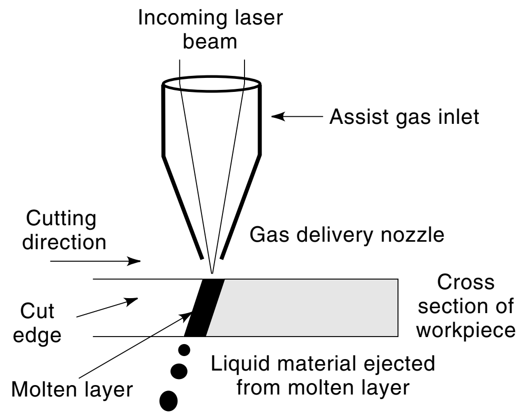

Figure 9. Illustration of the coaxial-assist gas nozzle and laser-melt cutting process.

reactive gas, such as oxygen, is used which chemically reacts with the melt to aid decomposition. Figure 9 shows the gas nozzle for coaxial delivery of the gas and illustrates the cutting mechanism.

Gas-assisted laser cutting uses a lens to focus the laser beam on the surface of a workpiece. The assist gas, introduced coaxially with the focused laser beam, blows the heated material away. When the cutting head or workpiece is moved, a kerf or cut is formed. This type of cutting is most often applied to metals and cuts thicknesses from 0.1 mm to 20 mm. With high-power lasers, cutting speeds of several meters per minute are achieved in moderate thicknesses (0.5 mm to 2 mm). However, this process does not lend itself to high precision cutting which is best accomplished by ablative material removal. Laser ablation usually refers to the direct removal of material through vaporization or the removal of molten material via an explosive ejection of the molten zone. The explosive ejection results from a very rapid rise in the temperature of the zone during irradiation and the consequent rapid rise in pressure which ejects the melt. This ablative process therefore requires a short laser pulse and high pulse repetition frequency produced by the copper vapor laser and some Nd : YAG lasers.

PROCESS MONITORING

Process monitoring keeps track of key parameters or influences in a machining operation to maintain the reproducibility of the production process. Although modern lasers are very reliable and their performance is reproducible, laser machining is complex and the results are subject to many influences including the laser, the environment, the workpiece material, the workpiece handling (CNC), and the skill of the operator. The process monitor is used to warn the operator of a problem or is part of a feedback system to actively control the process. One of the key laser parameters to control is the focus position of the laser beam relative to the workpiece surface. Nonuniformities in the flatness of the workpiece, CNC errors, or complex workpiece shapes all lead to focus errors. This in turn changes the laser spot size on the workpiece resulting in either too large a spot which does not have the required intensity for the process and is too large or too small a spot whose higher intensity damages the component or produces too small a feature. The position of the workpiece relative to the focus is determined by various metrological means (height monitors) or by observing the effect that the focused intensity has on the laser-induced plasma or the acoustic noise generated. Some other examples of process monitoring and control can be found in Ref. 2.

Height Monitors

Many different height monitors have been developed and often it is necessary to tailor the device to the application. For example, in machining flat metal sheets, a capacitative monitor is used. The capacitance between a probe (which is attached to the assist gas nozzle) and the workpiece is measured. A calibration of the capacitance relative to the focus position is determined and used to monitor the process. This technique is simple and benefits from being noncontact. Commercial devices are readily available. Simple mechanical probes are also used but are not appropriate for thin, flexible, or soft materials. A range of optical techniques have also been developed. The most common uses a low-power pointing laser, such as a helium neon laser or semiconductor laser. This is directed at an angle onto the workpiece at or near the point to be machined by the main laser. The pointing beam is reflected off the surface of the workpiece onto a linear array detector. As the height of the workpiece changes, the position of the beam on the linear array changes. This technique is used on materials that are nonconductive and therefore cannot use the capacitative technique. However, a direct line of sight is required for the pointing laser and linear array onto the workpiece, and changes in the slope of the workpiece surface produce erroneous measurements.

Laser-Induced Plasma Characteristics

When a focused laser beam impinges on a workpiece, the high beam intensity and subsequent high temperatures induced in the workpiece produce an ion plasma above the workpiece surface. These ions emit electromagnetic radiation, usually in the UV, visible, and IR parts of the spectrum. Greater intensities generate higher plasma temperatures and therefore the plasma becomes more highly ionized or excited. This is observed as an increase in intensity of the shorter wavelengths emitted and an additional contribution of spectral lines from more highly ionized species. For example, at a given (moderate) intensity, blackbody radiation occurs and superimposed upon that are spectral lines of the neutral and singly ionized species of the workpiece. At higher intensities, additional lines from doubly ionized species are expected. For a fixed laser power, then, the intensity is a measure of the beam diameter and hence focal position.

Acoustic Monitoring

The acoustic noise generated by laser machining is also related to laser intensity at the workpiece. A low-intensity beam does not strongly interact with the material except to warm it. As the intensity increases and material is removed, then the acoustic noise increases. To the experienced operator, the sound of the machining is a useful diagnostic. However, a simple microphone and spectrum analyzer characterizes the acoustic emission as a function of laser intensity (focal position) and can be developed into a useful diagnostic.

Beam Profile Control

The laser beam profile (spatial intensity distribution) is also an important parameter especially in micromachining applications where the beam shape is important in defining the machined feature. Laser beam profiles are readily measured by amplitude sampling the beam on-line via the leakage through a mirror or by the reflection off an appropriately coated optic. The sampled beam is focused or imaged onto a CCD which is coupled to a PC with image analysis software. This displays the beam profile in section, as an intensity map or isometric 3-D plot. Comparison of the beam profile against a standard is used to indicate alignment errors in the laser or beam delivery system. Alternatively the data could be fed to an adaptive optic to correct the laser beam profile in real time.

BIBLIOGRAPHY

1. T. H. Maiman, Stimulated optical radiation in ruby. *Nature,* **187**: 493–494, 1960.
2. W. M. Steen, *Laser Material Processing,* London: Springer-Verlag, 1991.
3. S. S. Charscham, *Guide to Laser Materials Processing,* Orlando: Laser Institute of America, 1993.
4. G. Chryssolouris, *Laser Machining, Theory, and Practice,* New York: Springer-Verlag, 1991.
5. S. A. Weiss, Think small: lasers complete in micromachining, *Photonics Spectra,* **29** (10): 108–114, 1995.
6. J. A. Morrison, Lasers and the fabrication of PWB vias, *Industrial Laser Rev.,* **10** (11): 9–14, 1995.
7. J. Golden, Green lasers score good marks in semiconductor material processing. *Laser Focus World,* **28** (6): 75–88, 1992.
8. M. R. H. Knowles et al., Visualization of small hole drilling using a copper laser, *Proc. ICALEO'94,* Orlando, October 17–24, **79**: 352–361, 1994.
9. H. Ito, Deep-UV resists: evolution and status, *Solid State Technol.,* **39** (7): 164–173, 1996.
10. S. Wittekoeket al., New developments in wafer stepper technology for submicron devices, *Proc. Optical Microlithography Metrology Microcircuit Fabrication,* **1138**: 2–13, 1989.
11. C. Rowan, Excimer lasers drill precise holes with higher yields, *Laser Focus World,* **31** (8): 81–83, 1995.
12. T. Lizotte, T. O'Keeffe, and J. Bruere, Micromachining with excimer lasers, *Industrial Laser Rev.,* **12** (5): 11–14, 1997.
13. D. R. Hall and P. E. Jackson (eds.), *The physics and technology of laser resonators,* Bristol: Adam Hilger, 1989.
14. W. Koechner, *Solid State Laser Engineering,* Berlin: Springer-Verlag, 1988.

14a. A. E. Siegman, *Lasers,* University Science, Mill Valley, California, 1986.

14b. W. P. Latham and A. Kar, Laser optical quality, *Proc. ICALEO 97,* San Diego, Nov. 17–20, **82**: A197–A206, 1997.

14c. A. Kar, J. E. Scott, and W. P. Latham, Effects of mode structure on three-dimensional laser heating due to single or multiple rectangular laser beams, *J. Appl. Phys.,* **80**: 667–674, 1996.

14d. J. Xie et al., Temperature dependent absorptivity and cutting capability of CO_2, Nd : YAG and chemical oxygen-iodine lasers, *J. Laser Applications,* **9**: 77–85, 1997.

14e. E. Hecht, *Optics,* Addison-Wesley, Reading, MA, 1987.

15. M. R. H. Knowles et al., Drilling of shallow angled holes in aerospace alloys using a copper laser, *Proc. ICALEO'95,* San Diego, November 13–16, **80**: 321–330, 1995.

16. M. R. Feldman and A. E. Erlich, Diffractive optics improve product design, *Photonics Spectra,* **29** (9): 115–120, 1995.

16a. R. Q. Fugate, The use of copper vapor lasers in guide-star applications, *Proc. of the NATO Advanced Workshop on Pulsed Metal Vapour Lasers,* St. Andrews August 6–10 1995, Kluwer Academic, Boston, MA, 1996.

16b. R. E. Warner et al., Industrial applications of high power copper vapour lasers, *Proc. of the NATO Advanced Workshop on Pulsed Metal Vapour Lasers,* St. Andrews, August 6–10 1995, Kluwer Academic, Boston, MA, 1996.

16c. M. Gottlieb, C. L. M. Ireland, and J. M. Ley, *Electro-optic and acousto-optic scanning and deflection,* Marcel Dekker, New York, 1983.

17. M. Hartmann, H. W. Bergmann, and R. Kupfer, Experimental investigations in laser microsoldering, *Proc. Lasers Microelectronic Manufacturing,* SPIE, **1598**: 175–185, 1991.

17a. M. Bass (ed.), *Laser Materials Processing,* North Holland, Amsterdam, 1983.

17b. A. M. Prokhorov et al., *Laser heating of metals,* Adam Hilger, IOP Publishing, New York, 1990.

18. D. Havrilla and T. Webber, Laser welding takes the lead, *Lasers Optronics,* **10** (3): 30–40, 1991.

18a. N. Rykalin, A. Uglov, and A. Kokora, *Laser machining and welding* (English edition), MIR Publishers, Moscow, 1978.

19. J. Powell, *CO_2 Laser Cutting,* London: Springer-Verlag, 1993.

MARTYN R. H. KNOWLES
GIDEON FOSTER–TURNER
KEITH ERREY
ANDREW J. KEARSLEY
Oxford Lasers Ltd.

LASER CAVITY RESONATORS. See LASER BEAM MACHINING.