Laser Drilling Technologies

During the early 1960s, the range of drilling applications for various lasers was very narrow such as perforation of baby bottle nipple and piercing diamonds. Today, lasers are used in the aerospace and automobile industries for production of large-volume holes for cooling and lubrication purposes in engine components. Laser hole drilling is also used to produce tiny orifices for nozzles, apertures for electron beam instruments, and pin-holes for optical work. Via hole formation for multi-layer electronics packaging processing is using the laser drilling technology to provide vertical paths for the packaging interconnection network. The high precision drilling of ink-jet printer heads is most recently introduced into commercialised production to enable very high volume manufacturing. One hundred or more nozzles can be drilled in parallel over a field of about 10 - 20 mm, with hole diameters between 20 to 100 μm, and tolerances in the sub-micron range. Laser drilling techniques are also widely used in medical applications, such as fabrication of bio-sensors. Clearly, drilling of various materials (e.g. metals, non-metals, plastic, and ceramics) has been an accepted production-line facility for many years.

1 Physics of Laser Drilling

1.1 Material Removal Mechanism

A variety of physical and chemical processes can take place during laser drilling such as heating, melting, vaporisation, and molten material expulsion. Two of these processes, vaporisation and molten material expulsion, result in removal of the sample material, i.e., drilling. The material removal mechanism and the removal rate depend on the laser wavelength, pulse duration, incident laser power level, thermal properties of the material, and whether or not an assistant gas jet is used.

A laser beam from a laser system radiates on the surface of a workpiece to be drilled. The workpiece absorbed partially the laser energy depending on the absorption coefficient for a given laser wavelength. The absorbed laser beam energy is conducted axially and radially into the surrounding colder material, and heats up the material via the heat-conductivity mechanism. If the absorption rate is high enough, the surface region of the workpiece will melt and perhaps begin to vaporise, causing rapid materials removal. The time for the material to reach its boiling temperature is determined by beam energy, wavelength, absorptivity and the surface conditions of the material. An entire vaporisation of the irradiated area is always desired for good hole quality. However, due to the reduced beam power density at the end of a laser pulse, a fraction of the liquid phase remains on the walls. The redistribution of the liquid phase prior to crystallisation, together with other laser parameters, controls the hole formation process and the hole quality.

For excimer laser drilling, the material removal mechanism is different from the thermal processes prevalent in CO_2 and YAG laser drilling, as shown in Figure 1. For excimer laser beams incident on organic compounds, it is generally accepted that the removal of materials, e.g. polyimide, is through ablation, where the absorbed UV photons directly break the chemical bonds. Hence, if sufficient photons are incident on a thin layer of material in a short time interval, an increase in pressure is generated due to the rapid formation of lower molecular weight components. The process is essentially photochemical in nature leading to small amount of thermal heating.

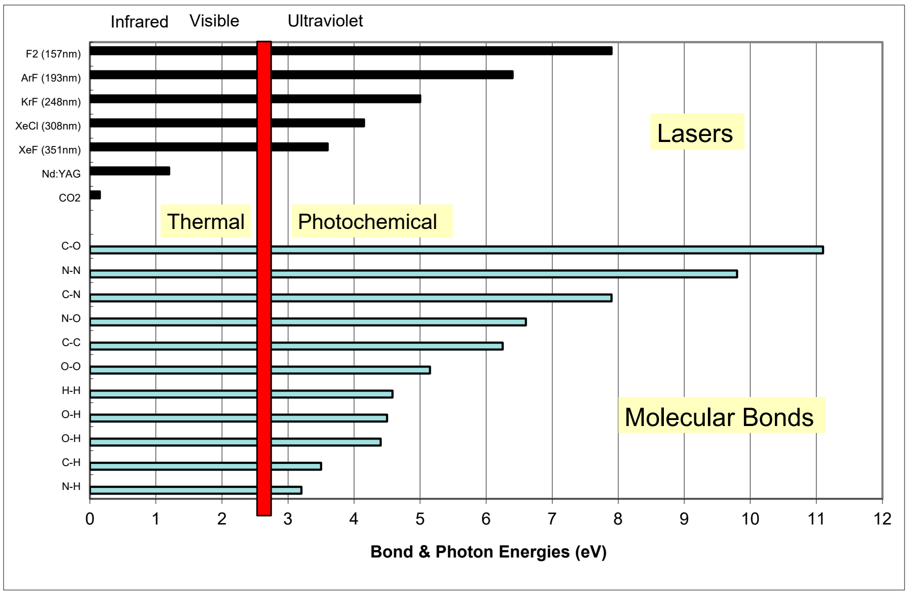

Figure 1 Strengths of some common molecular chemical bonds compared with laser photon energies

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When a laser pulse from an excimer laser impacts on a polymer surface (as shown in Figure 2), the penetration of the radiation through the solid follows a simple relation which is known as Beer's law

$$I_l = I_0 \bullet 10^{-\alpha_0 l} \tag{2.28}$$

where I_0 and I_l are the intensities of the beam before and after transmission through a slice of material of thickness l, and α_0, the absorption coefficient, is a characteristic property of the material. If the fluence F of the laser beam exceeds a certain threshold value, F_0, then a depth, l_f of the material is ablated by the pulse. The next pulse will go through virgin material underlying it, till the required depth of the hole is reached.

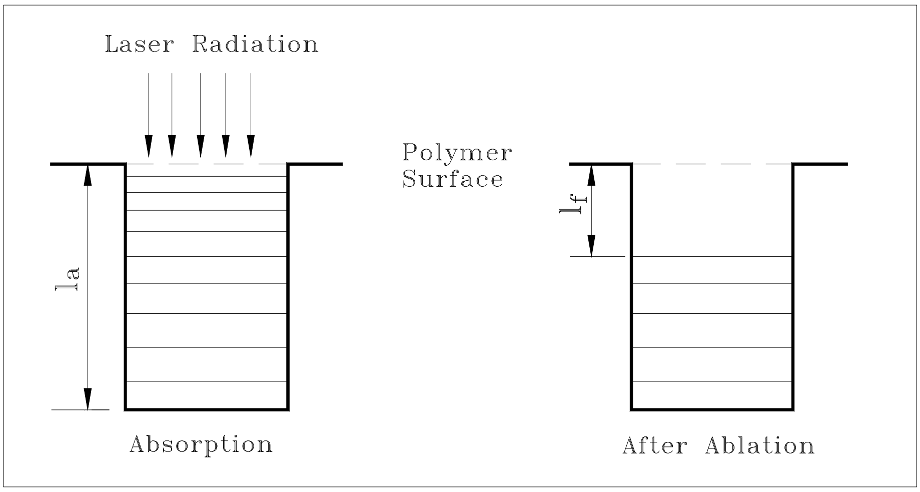


Figure 2 Schematic representation of impact of laser pulse on polymer surface

Experiments have shown that the threshold fluence for ablation typically lies in the range of a few tens to a few hundred mJ/cm^2, being dependent on the type of polymer involved and laser wavelength, and is only weakly influenced by the pulse duration. There is not a precise transition to the ablation regime. To some extent, the ablation threshold is dependent on how accurately the experimentalist is able to determine the loss of material. For example, the threshold values for polyimide and PETP are 36 and 25 mJ/cm^2, respectively at the wavelength of 248 nm, but 162 and 100 mJ/cm^2, respectively at the same wavelength.

Experiments have also shown that all absorbed energy appears as heat below the threshold fluence F_0. The absorbed energy density needed to produce ablation, expressed in the product of the threshold fluence F_0 and the (effective) UV absorption coefficient α, is approximately constant for a given polymer. Above the ablation threshold, the etch depth per pulse (or so-called etch rate), l_f, can be given by an equation of the form

$$l_f = \frac{1}{\alpha_p} \ln\left(\frac{\alpha_p F}{\alpha_0 F_0} - \frac{\alpha_p}{\alpha_0} + 1 \right) \tag{2.29}$$

where F is the applied fluence and α_p is the absorption coefficient of the ablation plume produced during the laser ablation process.

When $\alpha_p = \alpha_0$, Equation (2.29) reduces to

$$l_f = \frac{1}{\alpha_0} \ln\left(\frac{F}{F_0} \right) \tag{2.30}$$

It is found that the etch depth is independent of the surrounding gas in which the experiment is performed, and the etch depth is independent of the pulse duration over a practical etch depth range of 0.1 to 1 µm per pulse for XeCl laser ablation of polyimide. However, in general, the amount of material removed increases with increasing wavelength and fluence although the threshold fluence for the onset of etching decreased with decreasing wavelength.

1.2 Types of Laser Drilling

A hole has been defined as (a) an opening in or through anything, (b) a hollow place, (c) a cavity in a solid body or area, or (d) a three-dimensional discontinuity in the substance of a mass or body. A hole with a diameter less than 1 mm is called a micro-hole. Other holes are called small holes, large holes, and bores depending on their specific sizes. Generally, there are three approaches to laser drilling, these being direct drilling, drill and ream, and trepanning; two of these are shown in Figure 3. Direct drilling is also called percussion drilling, which is the oldest form of drilling. The process involves a stationary beam and one or more pulses to penetrate the thickness of the material. A variation of this is the "drill-on-the-fly" process in which the pulses are delivered while the workpiece moves relative to the beam; if more than one pulse is required, motion and laser pulsing are synchronised so that subsequent pulses are delivered at the same location. Drill and ream consists of directly drilling a pilot hole and then, changing the laser parameters, increasing the spot size to open out the hole to the desired diameter. Trepanning, on the other hand, involves producing a hole or feature by contour cutting the feature shape from the part. It is often used to produce shaped features or holes that are larger than those which can be produced by percussion drilling. Commercial high-speed trepanning heads are available. For micro-drilling, the approach most commonly used is percussion. However, excimer laser drilling often uses mask-imaging drilling method, which is different from the above-mentioned methods. Therefore, the micro-drilling techniques are investigated with both the Nd:YAG laser (fundamental, second, and fourth harmonic wavelengths) and the excimer laser for typical engineering materials in the subsequent sections of this thesis.

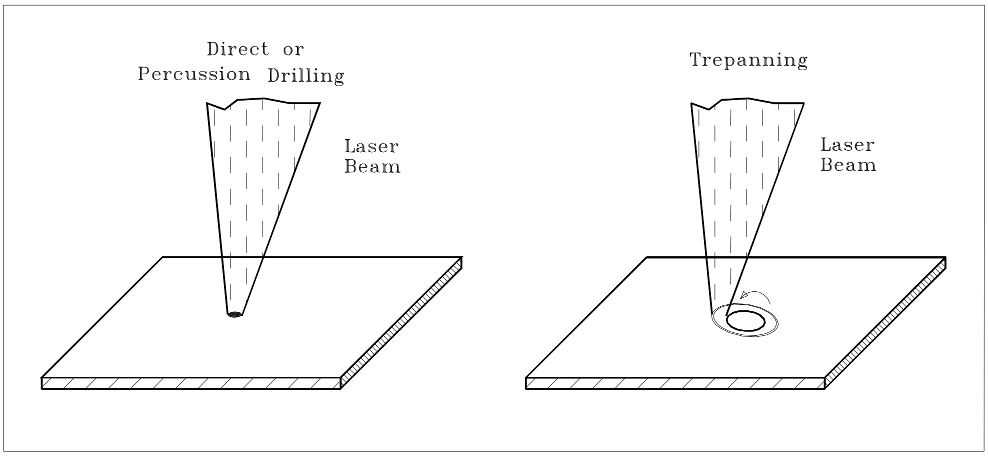


Figure 3 Illustration of the two primary laser drilling processes

1.3 Types of Lasers Used in Laser Drilling

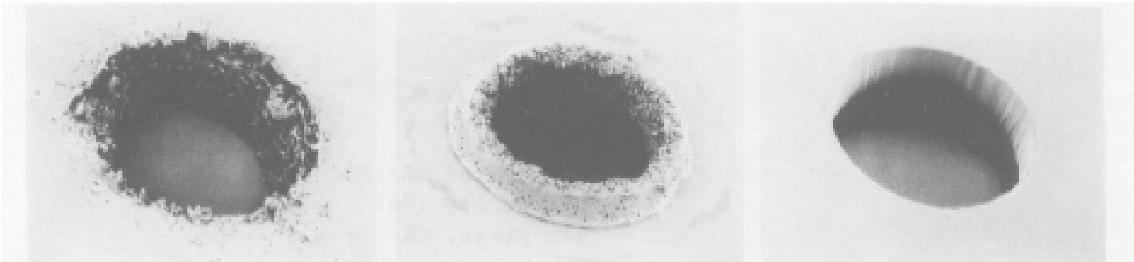
The most common types of lasers used for drilling applications are CO_2 lasers, Nd:YAG lasers and excimer lasers. CO_2 lasers operate in both continuous and pulsed modes at the infrared wavelength of 10.6 m. Their interaction mechanism with material is a thermal process, whereby the laser radiation heats the materials so as to cause melting and evaporation. When drilling polymers, unwanted flow of melted material can substantially degrade the edge quality or limit the minimum thickness that can be processed .

A Nd:YAG laser emits a typical wavelength of 1.06 m in the near infrared region. Its interaction mechanism with material is also a thermal process, which induces heat-affected-zone (HAZ). When coupled with a second harmonic generator, the Nd:YAG laser emits at the wavelength of 532 nm. This shorter wavelength is better absorbed by most materials. The wavelengths of the 3rd and 4th harmonic generators are in the UV light range (355 nm and 266 nm, respectively) and thus compete with excimer lasers due to the lower cost.

Excimer lasers are a group of gas lasers, which typically emit in the UV range (193 - 351 nm) depending on the gas medium. The pulse width varies between 10 - 20 ns. For KrF excimer laser, the wavelength is 248 nm. Its beam photon energy is about 5 eV, which exceeds the C-H bond energy of about 3.5 eV. A single photon from the KrF laser can therefore directly break the C-H bond without requiring multi-photons (or thermal) absorption. This bond-breaking process is a photo-chemical process without thermal effect. Drilling of polymers such as polyimide could thus be a non-thermal process leaving well defined hole edges.

Examples of polyimide drilling by the three types of lasers are shown in Figure 4. The left-hand photograph corresponds to a pulsed Q-switched Nd:YAG laser operating at 1.06 m, the middle photograph corresponds to a fast axial flow CO_2 laser operating at 10.6 m in a pulsed mode, and the right-hand photo corresponds to an excimer laser at 248 nm. Note the high degree of precision in the excimer case, and the absence of any damage to the surrounding materials.

In general, the reflectance of a metal drops as the wavelength decreases. For example, gold reflects about 99% of the energy at 1.06 μm, thereby absorbing only 1%. At 0.532 μm, the reflectance drops to about 60%, corresponding to an absorption of 40%. Figure 5 shows, for metals and semiconductors, the relationship between the absorption coefficient and the wavelength. Therefore, lasers should be properly selected for drilling different materials.



(a) Drilled by YAG laser (b) Drilled by CO_2 laser (c) Drilled by excimer laser

Figure 4 Holes of 300um diameter drilled in 75um thick polyimide sheet using the three common types of industrial lasers

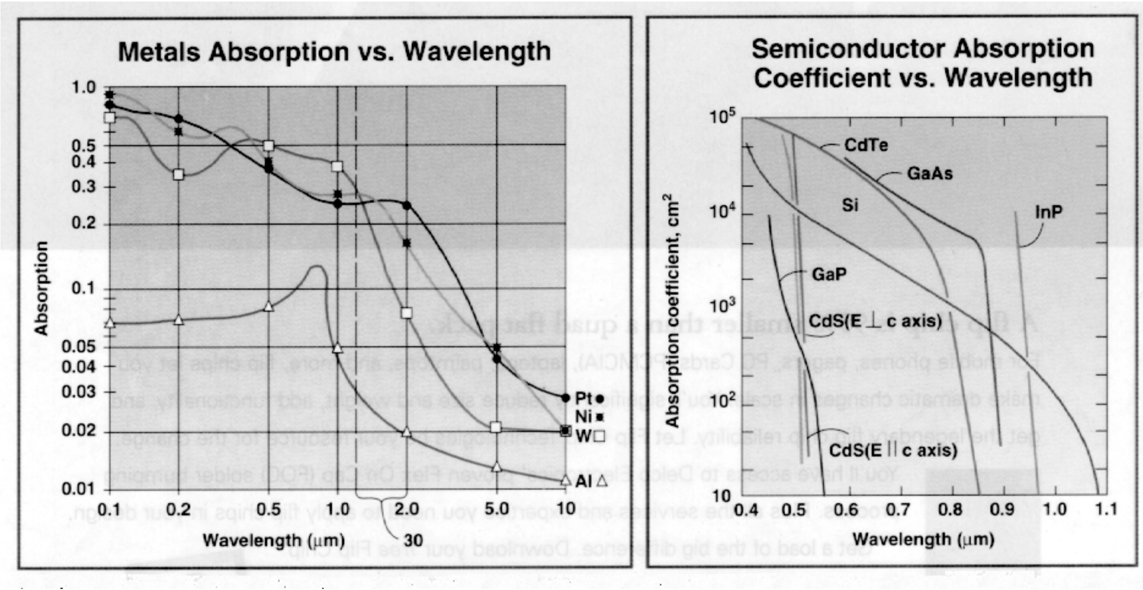


Figure 5 Metal absorption and semiconductor absorption coefficients vs. wavelength

For the CO_2 and Nd:YAG laser machining systems, one or more focusing lenses are used to focus the laser beam to a small spot size. For the excimer laser machining systems, a projection lens is often used to project an aperture to the workpiece surface. The difference in focusing for the laser systems depends on laser beam energy distributions and optical coherence.

2 Effects of Process Parameters on Laser Drilling

2.1 Effects of Pulse Shape and Pulse Repetition Rate

Pulse shape plays an important role in determining the power intensity and the times at which maximum intensity occurs. The laser power intensity is given by the following formula:

$$I = I_0\left(e^{-\beta t} - e^{-\gamma t}\right) \quad (2.31)$$

where I_0 is a constant describing the power intensity; β and γ are constants which determine the pulse shape. A typical laser pulse is shown in Figure 2.16. Here β and γ are 0.672×10^5 s^{-1} and 1.43×10^5 s^{-1}, respectively.

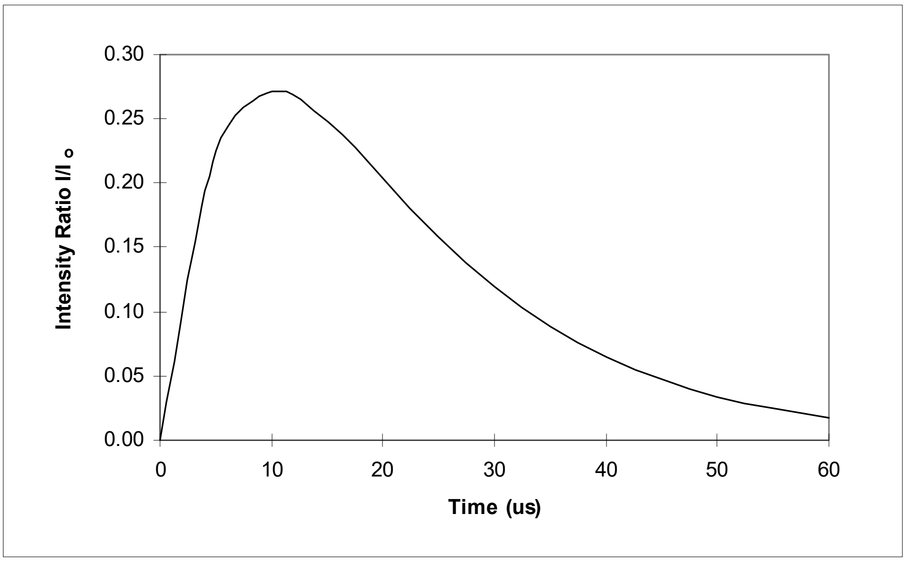


Figure 6 A typical laser pulse

The time, t_{max}, at which the maximum pulse intensity occurs can be obtained by differentiating the pulse with respect to t for the pulse:

$$t_{max} = \frac{ln\left(\frac{\gamma}{\beta}\right)}{\gamma - \beta} \tag{2.32}$$

The maximum temperature T_{max} at the surface is

$$T_{\max} = \frac{2I_0}{K\sqrt{\frac{\alpha}{\pi\beta}}} F\left(\sqrt{\beta t_m}\right)\left(1 - \frac{\beta}{\gamma}\right) \tag{2.33}$$

where α is the thermal diffusivity, K is the thermal conductivity, t_m is the time at which maximum value of surface temperature occurs, and $F(x)$ is Dawson's integral, i.e.:

$$F(x) = exp\left(-x^2\right)\int_0^x exp\left(t^2\right)dt \tag{2.34}$$

Plots showing the effects of β and γ on the times at which the maximum pulse intensity and maximum surface temperature occur are given in Figure 2.17 [2.159]. It is clearly seen that: (a) the time at which the maximum temperature occurs is a function of the pulse parameters; and (b) the position of maximum temperature and maximum pulse intensity never coincide and there is a time lag between the maximum surface temperature and the maximum pulse intensity. The time lag may increase or decrease depending on the pulse shape. A minimum time lag is desired to achieve a good hole quality particularly in the case of multiple-pulse drilling.

A study has shown that a lower slope for the leading edge of the pulse could lead to a larger HAZ and thus a larger hole-diameter. The effect of increasing the rise time of the pulse is also to increase the drilling depth (shown in Figure 2.18). It is suggested by Mr. Metev and Mr. Veiko [2.143] that the duration of the trailing edge should not exceed that of the leading edge.

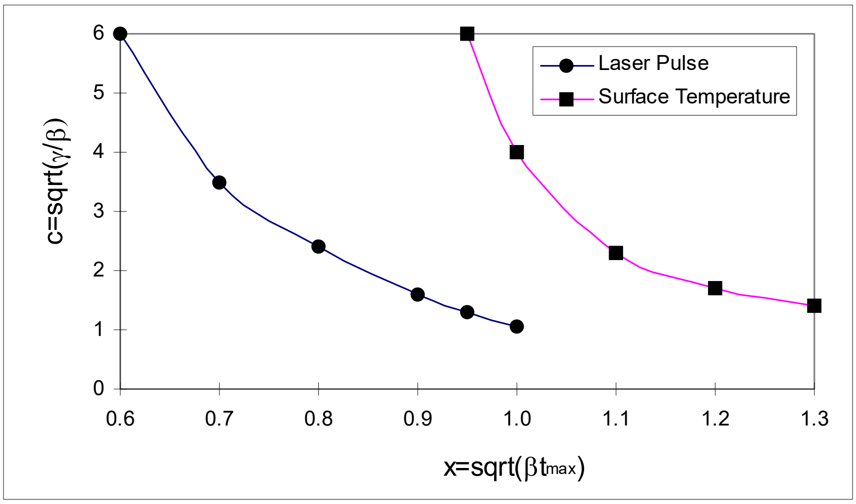


Figure 7 Effects of pulse parameters on times at which maxima occur

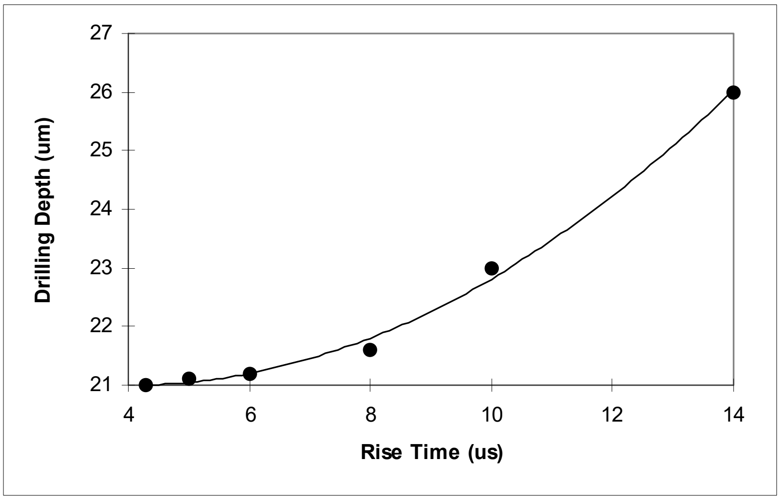


Figure 8 Effect of rise time on drilling depth

Pulse repetition rate is another factor of interest in laser drilling. If sufficient time is left prior to the arrival of next pulse, the material cools down to about ambient temperature. Applications of the subsequent pulses will produce very similar temperature profile in the material as the preceding pulses. In this multiple-pulse drilling process, the hole depth grows gradually owing to the layer-by-layer vaporisation by each pulse. The final-hole depth is determined by the total energy of the series of pulses. The hole diameter is controlled by the duration of the short pulses. A maximum depth with good precision can be achieved by this multiple-pulse drilling process.

2.2 Effects of Peak Power and Pulse Energy

The best drilling results are obtained only when there is a proper combination of pulse energy, pulse duration, and pulse repetition rate. From Equation (2.31), the overall energy (E_{ov}) can be calculated as:

$$\begin{aligned} E_{ov} &= I_0 \int_0^{\infty} \left[\exp(-\beta t) - \exp(-\gamma t)\right] dt \\ &= \frac{\gamma - \beta}{\beta\gamma} I_0 \end{aligned} \tag{2.35}$$

The pulse duration (μ) is defined as the subtraction of the times at which the laser power intensities are 50% of the maximum power intensity (i.e. full-width half-maximum or FWHM). The peak power is determined by the following equation:

$$P_p = \frac{E_{ov}}{\mu} \tag{2.36}$$

For lasers with high pulse repetition rate, the peak power is usually expressed in terms of average power:

$$P_p = \frac{P}{\mu \bullet PRR} \tag{2.37}$$

where P is the average power, and PRR is the pulse repetition rate.

A high peak power is often preferred in the drilling process for fast vaporisation. As described in Equation (2.36), the peak power is determined by the pulse energy and the pulse duration. Shorter pulse duration leads to a smaller HAZ, thus better hole quality. However, it should be noted that the pulse energy is usually high for high order beam modes, which produce large divergence angles. In the case of very fine drilling, this situation is undesirable except for mask projection drilling such as excimer laser drilling.

2.3 Effects of Beam Focus Position

A gaussian beam of finite diameter is focused by a lens onto a workpiece to obtain a beam of smaller diameter, as shown in Figure 9.

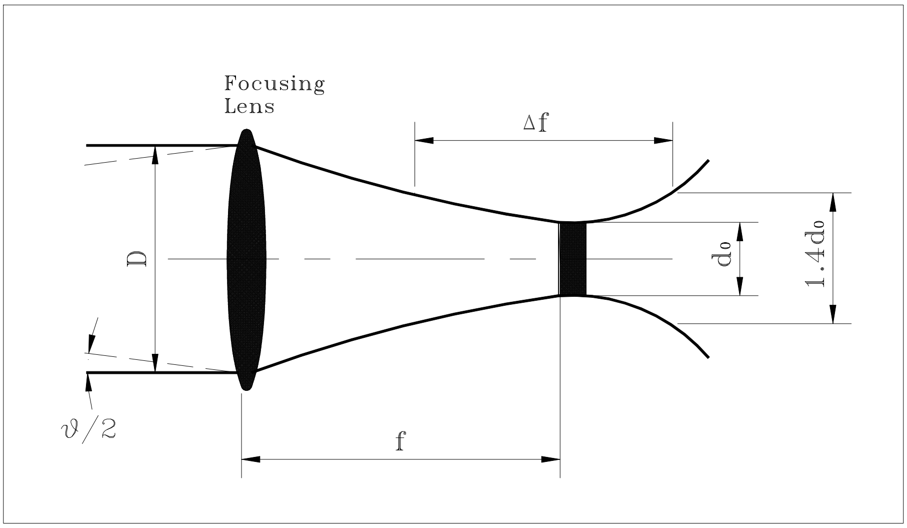


Figure 9 Focusing of a gaussian beam

If the diameter of focused spot d_0 is defined as a diameter which contains 86% ($=1- e^{-2}$) of the focused energy, and the beam diameter entering the lens is known, the focal spot size is given by

$$d_0 = \frac{2f\lambda}{D} \tag{2.38}$$

where f and D are the focal length of the focusing lens and the beam diameter entering the lens, respectively.

If the full beam divergence angle θ is known, the diameter of the focal spot size is given by

$$d_0 = f \bullet \theta \tag{2.39}$$

Because the gaussian beam is focused from a lens down to a waist and expands again, the full distance between the $\sqrt{2}\ d_0$ spot size points is defined as the depth of focus (or 2 times Rayleigh range Z_R). It can be written as

$$\Delta f = 2Z_R \approx 2\pi\lambda F'^2 \tag{2.40}$$

or

$$\Delta f = \frac{2f^2\theta}{D} \tag{2.41}$$

where F' is the f-number of a focusing lens, which is defined as

$$F' = \frac{f}{D} \tag{2.42}$$

It is concluded from Equations (2.38) to (2.42) that a lens with a longer focal length gives a larger depth of focus and a larger focal spot size than those produced by a lens with a shorter focal length. Thus the focal length of the lens should be selected properly according to the requirements of the hole.

Moreover, the position of the focal point of the beam with respect to the working surface has a critical effect on the shape, diameter and depth of holes. For good edge quality, the best focal position occurs when the focus of the beam lies just below the surface of the material.

2.4 Effects of Beam Mode and Spot Size

A gaussian beam structure is preferred for drilling uniform holes. However, in practice, the laser beam is always in a transient mode for a period of time after the laser beam is switched on. The transient mode is characterised by variations of the radiation parameters such as pulse energy and pulse duration. The range of the variations and the duration of the transient mode depend on the pump energy, repetition rate, thermophysical properties of the active medium, cooling rate, and the cavity design. At the end of the transient mode, the pulse energy can increase by a factor of 5 - 10 compared with the energy of the first pulse. Concurrently, the pulse duration can also increase by a factor of 5 - 10, and the divergence by a factor of 2 - 3. Obviously, identical holes could only be obtained after the transient period. The most important factor affecting the scatter of the hole-size is the instability of the laser-pulse parameters. For an industrial Nd:YAG laser, the energy instability is typically around ±5%.

Since the order of the mode has great effects on both the focused spot size and the depth of focus, which affect the laser power density, the beam structure becomes extremely important in laser materials processing. High-order-mode beams diverge more rapidly, focus to larger spot sizes and have shorter depth of focus than TEM_{00} gaussian beam. The spot size and the depth of focus for TEM_{pq} circular modes are:

$$d_{pq} = \frac{\lambda f (2p + q + 1)}{\pi D} \tag{2.43}$$

and

$$\Delta f = 2\pi \sqrt{\rho^2 - 1} \frac{d_{pq}^2}{(2p + q + 1)\lambda} \tag{2.44}$$

where ρ is a factor determined by the application. Essentially, ρ determines the amount by which the spot size can vary and still produce acceptable results. This is clearly different for different applications. Generally, more than a 10% variation in spot size will cause a substantial degradation of quality in cutting.

In drilling, it is generally desirable to achieve highest possible speed and therefore the highest possible power density. Thus the lowest order mode is desirable (TEM_{00} or gaussian mode for stable resonators). However, a low-order mode often means a lower conversion efficiency and lower output laser power. Therefore process optimisation is needed to obtain good hole quality, proper processing speed, and efficient use of the laser power.

2.5 Effects of Assistant Gas

In most drilling applications an assistant gas jet is used coaxially with the laser beam to protect optics and facilitate material removal. Research has shown that the oxide layer formed during the oxygen-assisted laser drilling process affects the drilling time in two ways. One effect is the changing of the surface absorptivity due to oxide formation, and the other is the change in the temperature required to expel the molten material because of the difference in the melting point of metal and oxide.

Compressed air and oxygen are the two most commonly used assistant gases in industry. Sometimes an inert gas such as argon or nitrogen gas is also used depending on the material, thickness, and laser power. The choice of an assistant gas during laser drilling of metals affects the drilling time. It was observed that as the assistant gas pressure increased the drilling time increased for Al6061 and Cu until a critical value of pressure was reached. Beyond this critical pressure, the drilling time remained constant for further increase in the pressure. However, no assistant gas is needed for excimer laser drilling for some non-metals since the removal of the material is through ablation.

3 Summary

The physical mechanisms and effects of process parameters on laser drilling are discussed. It is found that vaporisation and molten expulsion are the main processes of material removal for a thermal process. For drilling with short wavelengths, such as the use of excimer lasers, the process is photo-chemical in which chemical bonds are cleaved. Laser drilling process parameters - such as pulse shape, pulse repetition rate, peak power, pulse energy, beam mode, spot size, beam focus position, and assistant gas - have significant effects on hole quality. Therefore, laser drilling processes should be optimised for a given material and laser wavelength, usually adopting empirical methods such as curve fitting and design of experiment.

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