CHAPTER

6

Laser Beam Machining

ABSTRACT

Laser beam machining (LBM) is another thermal-based nontraditional machining process. Similar to the electrical discharge machining (EDM) process, LBM also relies on the incident heat flux of a laser beam, which results in the melting and evaporation of the materials. This chapter focuses on the basics of laser beam generation, different types of lasers-based on the lasing material and laser-material interaction and associated physical transformation during the process. Applications of the LBM process to various fields have been highlighted in the chapter. The chapter also consists of focusing on the laser beam and material removal rate evaluation in the LBM process, along with the advantages and disadvantages of the LBM process.

6.1 INTRODUCTION

LBM is one of the most frequently used thermal-based nontraditional machining processes. Similar to the EDM process, LBM also relies on the incident heat flux of a laser beam, which results in the melting and evaporation of the materials. Laser-material interaction is the primary phenomenon in the LBM process, which decides the extent of melting/evaporation and material removal. LASER is an abbreviation for *Light Amplification by the Stimulation Emission of Radiation*. The incident light beam (photons) is focussed on the workpiece to attain high energy density for melting and evaporation of the workpiece material. The light emitted by the laser is coherent, monochromatic and collimated such that high power density is possible to obtain. Since laser utilizes optical energy, besides thermophysical properties, the material's optical properties, namely absorptivity, reflectivity, etc. also influence the performance of the process.

6.1.1 Properties of Laser Beam

The laser beam is electromagnetic radiation with wavelength ranging from infrared to ultraviolet region (Dahotre and Harimkar 2008). The laser beam has certain unique properties like it is coherent, i.e. it travels in phases. It is monochromatic, as it is composed of a single wavelength, contrary to an ordinary light beam which consists of more than one wavelength. The laser beam is collimated in nature because of its directional nature (Jain VK 2007; Sun and Brandt 2013). Due to this property, laser beams are easily focussed to a small spot without any significant loss of beam intensity by divergence. The degree of collimation is estimated in terms of divergence. In addition, laser light has high energy density and brightness, and it can be focussed to an infinitesimally small spot (Jain VK, 2007). These distinctions of the laser beam from other electromagnetic radiations make the laser a unique tool for varieties of engineering applications.

The power density and laser-material interaction time are the critical parameters that determine the capabilities of a laser beam. A defocused beam with a lower power density can be used for surface heating without any phase change. However, a highly focussed beam of power density ranging from 1.5×10^4 to 1.5×10^5 W/cm^2 is utilized for surface melting, namely, welding or cladding operations. For cutting or hole drilling operations, it is desired to position the workpiece surface at the focus point of the beam to obtain a high laser power density of 10^6–10^8 W/cm^2. Power density greater than 10^8 W/cm^2 is possible to obtain with the appropriate focusing of the laser beam to sublimate the workpiece without transforming it into the molten phase (Benedict, 1987).

6.2 PRINCIPLE OF LBM

Production of the laser beam and its transmission to the desired spot is the foremost steps in any laser material processing technique. LBM system essentially consists of a medium (lasing materials), which serves as a source of molecules or atoms. This lasing material can be in solid, liquid or gas form depending upon the machining requirements, power and nature of the cut. According to the hypothesis proposed by Einstein, if a light beam of certain characteristics (frequency/wavelength) is incident on an atom, it stimulates the electrons in that atom from a lower energy level to a higher energy level, and this event is termed *absorption* (Benedict, 1987; Jain, 2007). The atom does not remain at a higher energy level forever and returns to its original state, emitting light during the event termed *emission*. The emission of a photon can be spontaneous or stimulated depending upon the nature of emitted light. In spontaneous emission, the emitted light characteristics are independent of the incident light beam, whereas, in stimulated emission, it is highly influenced by the incident light beam (Paul *et al*. 2013). Therefore, stimulated emission is desirable in the LBM process.

Consider an atom at lower energy level E_0, as shown in Fig. 6.1. The horizontal lines in the figure represent different levels of energy owned by the atom. When this atom is exited through some external energy source (heat, light, chemical or electrical), it goes to a higher energy level (say E_4). At this particular energy level, the atom remains for a while and descends back to its ground/initial energy level, simultaneously releasing a photon. This photon interacts with other atoms (s) existing at the higher energy level, and additional photons are released. This process continues, and shortly the number of atoms at higher energy levels become greater than that at the ground energy level, and this phenomenon is called population inversion (Dahotre and Harimkar, 2008; Jain, 2007). Population inversion necessitates powerful external energy sources. The emission of twin photons from the excited atoms is termed as stimulated emission, as the emitted photons have a similar wavelength, phase, direction and energy to that of the incident photon. A certain fraction of released photons are directed and exit as a light beam (laser beam) for performing the various operation, whereas a small fraction of photons is sent back to the lasing system to continue the emission process. To achieve these functions, partial and fully reflective mirrors are used as a feedback mechanism in the laser beam generation setup. The schematic illustration of a typical LBM system is shown in Fig. 6.1. The laser beam is manipulated (focussed) to the desired spot through a series of lenses installed in the setup. Different machining operations require varying energy densities; therefore, the laser beam spot or beam diameter at the focal point becomes an important factor in determining the laser energy density. Assist inert gases are also supplied to the machining zone to enhance the machining performance, as these gases prevent the divergence of the laser beam and loss of power due to interaction with the surrounding medium.

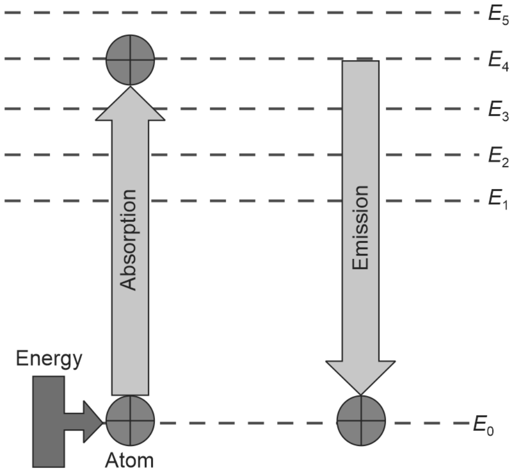


Fig. 6.1: Schematic illustration of laser beam generation. Redrawn from Ref. Jain VK 2007

6.2.1 Population Inversion

Population inversion refers to the state wherein the number of atoms at higher energy levels is substantially higher than those at lower energy conditions. For stimulation emission, population inversion is inevitable; otherwise, there would be no emission from the system due to absorption of the emitted photons. The number density of atoms at various energy levels is determined by Boltzmann's distribution law, given as follows (Dahotre and Harimkar, 2008):

$$n_2 = n_1 e^{-\left(\frac{E_2 - E_1}{KT}\right)} \tag{6.1}$$

where, n_2 and n_1 are number of atoms at energy levels E_2 and E_1, such that $E_2 > E_1$. K and T are the Boltzmann's constant and temperature, respectively. According to Boltzmann's law, there is an exponential decrease in the number of atoms at the higher energy level, as it is the least populated state. Population inversion is a nonequilibrium phenomenon wherein the atoms exited to a higher energy level (say E_4) decays to a lower energy level, say E_3 (metastable state), without producing any emission. The net emission occurs during the atom's transition from metastable (say E_3) to the original energy level (E_0), as shown in Fig. 6.1 (Dahotre and Harimkar, 2008).

6.3 COMPONENTS OF THE LBM SYSTEM

A typical LBM system comprises a lasing material/medium (solid, gas, semiconductor or dye), external energy source, reflective mirrors, focusing lenses, active gas, etc. Figure 6.2 shows a laser beam system schematically, with a feedback mechanism and output laser beam. The flash tube serves the purpose of supplying energy for lasing action to initiate. The external energy supplied for this purpose can vary depending upon the nature of lasing material, power requirement, etc. Solid state lasers use flash lamp/tube as the source of excitation energy, however, lasing medium in gas lasers may be excited using electric field. Flash tube which surrounds the solid lasing material produces light, which is used to excite the atom of the solid medium.

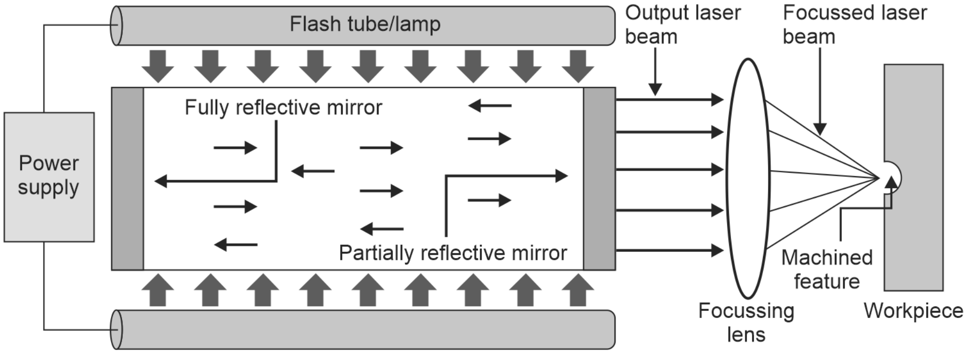


Fig. 6.2: Illustration of a laser beam machining system

6.4 TYPES OF LASERS

Industrial lasers are broadly classified in the four major domains based on the physical state of the lasing medium, i.e. solid-state laser, gas laser, semiconductor laser, and liquid dye laser. Under each category of laser, there is a variation of laser beam wavelength, mode of operation (continuous wave or pulsed) and specific applications.

6.4.1 Solid-state Laser

The solid-state laser consists of lasing material in solid form with a certain percentage of doping materials. These lasers are usually operated under low frequency (1–2 Hz) and light cut. Under this category, there are a number of lasers, namely, Nd: YAG, Nd: glass, Ti: Sapphire, etc. Nd: YAG is the most frequently used laser in the solid-state laser category (Jain VK 2007).

6.4.2 Gas Laser

As the name depicts, the active medium is a volume of gas instead of a solid material. Gas laser offers some advantages over solid-state lasers due to its homogenous nature. It is easy to transport, and gases are less expensive than solid materials. However, due to lower density, gas lasers necessitate a higher volume of gas for lasing process, thus occupying a larger space than a solid-state laser. Depending upon the energy transitions between different energy levels, the gas laser can be atomic, ionic or molecular. CO_2, N_2, He and excimer lasers are the prominent gas lasers extensively being used in industries (Jain VK 2007).

6.4.3 Semiconductor Laser

This laser utilizes a semiconductor material as an active medium. These lasers are not solid-state lasers, as they produce laser beam due to the recombination of charge carriers. The electrons and holes in the semiconductor materials (GaAs or AlGaAs) under the action of external power source injected to the p-type and n-type as a charge carrier. These charge carriers experience recombination during this process and result in the spontaneous emission of photons (Dahotre and Harimkar 2008). The semiconductor lasers have a relatively higher beam divergence angle (around 40°) (Ready 1997).

6.4.4 Liquid Dye Lasers

These liquid-state lasers consist of organic dyes dissolved in a solvent. Due to the inherent nature of dye material, a wide range of wavelengths can be obtained with these lasers. Moreover, they offer advantages such as easy to fabricate, easy to transport, low density, and homogenous nature (Dahotre and Harimkar 2008).

Table 6.1 shows different types of lasers with their operating wavelength and mode of operation.

Table 6.1: Different types of lasers, their wavelength, power and mode of operation (Borisov *et al* 1998; Dahotre and Harimkar, 2008; El-Hofy, 2005; Raju and Varadarajan, 1995)

Type of laser	Name of laser	Wavelength	Power and mode of operation
Solid	Ruby	694 nm	5W, P
	Nd: Yag	1064 nm	800 W, P and CW
	Nd: Glass	1064 nm	2 mW, P and CW
Semiconductor	GaAs	800–900 nm	2–10 mW, P and CW
Gas (molecular, ionic and neutral)	CO_2	10.6 µm	15 kW, P and CW
	Ar	330–530 nm	1 W–5 kW, P and CW
	Excimer	200–500 nm	600 W, P
	He-Ne	633 nm	20 mW, CW
Liquid dye lasers	Rhodamine	570–640 nm	900 W, CW
	Coumarin	460–515 nm	400 kW, P

P: refers to pulsed mode, CW: refers to continuous wave mode.

6.5 LASER-MATERIAL INTERACTION

Upon the incidence of the laser beam on the substrate (workpiece), a number of phenomena occur. These include reflection, scattering and absorption of the laser beam. The workpiece's molecules receive the energy of the absorbed beam and undergo physical transformations. Figure 5.3 depicts the distribution of laser beam energy.

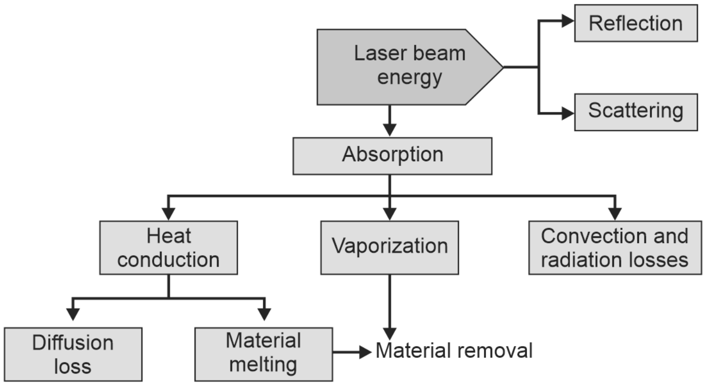


Fig. 6.3: Distribution of laser beam energy. Redrawn from Ref. Jain VK 2007

The laser-material interaction results in the following possible phenomena:

1. A fraction of the laser beam is reflected, absorbed and transmitted through the workpiece. Reflection and absorption of the beam are determined by the reflectivity and absorption coefficient of the material. Moreover, the higher the thermal conductivity of the workpiece material, the greater it diffuses the input heat rapidly, thus lowering the energy efficiency of the process. Due to these reasons, aluminium, copper, silver, and gold are not efficiently machined through the LBM, as they have high reflectivity and thermal conductivity (Jain VK 2007; Liang and Shih 2016). Moreover, oxidation of the aluminium surface forms a higher melting point layer of alumina (Tunna *et al* 2005).
2. Depending upon the energy density of the incident laser beam and absorption capacity of the workpiece material, heat conduction, material melting, evaporation or ablation takes place, as depicted in Figs 6.4(a) to (e). During the pulse-on period of the beam, vapours escape the workpiece surface. The vapours over the melt pool get ionized as it interacts with the irradiated laser beam, resulting in plasma formation Fig. 6.4(d)]. Plasma is the ionized state of a fluid consisting of ions and electrons at elevated temperatures.

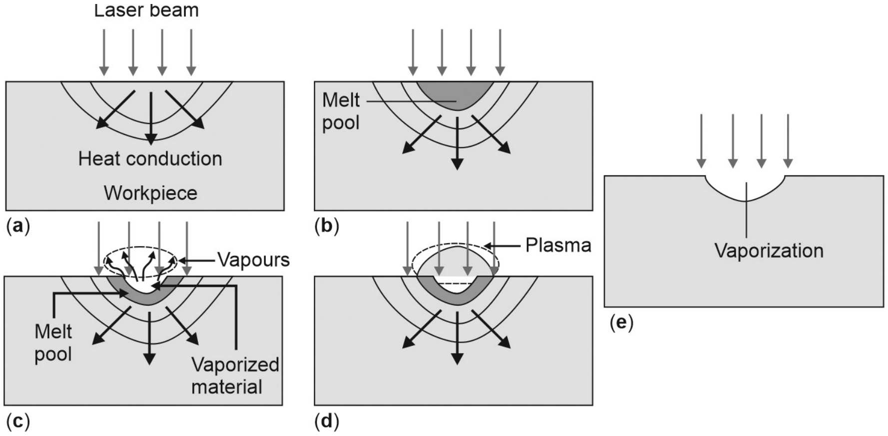


Fig. 6.4: Physical transformation occurring in the workpiece during various stages of laser-material interaction (a) heating (b) melting (c) vaporization (d) plasma formation (e) ablation. Redrawn from Ref. Dahotre and Harimkar 2008

The physical transformation occurring during the laser–material interaction is explained in the following sub-sections:

6.5.1 Heat Conduction

As the surface of the workpiece is irradiated with the laser beam, workpiece heating occurs due to the conduction of absorbed energy in the materials. This results in the temperature rise of the workpiece, which is maximum at the end of pulse-on time. Subsequently, temperature decreases during the pulse-off period. The attainment of maximum temperature at increasing depth from the surface (below the surface) is delayed, and it is always higher than the time required to reach the maximum surface temperature.

The intensity (energy density) of a typical laser beam varies along with the depth of the workpiece, as shown in Fig. 6.5. The intensity of the incident beam is maximum at the surface of the workpiece and decreases exponentially as the depth of the workpiece increases, as per Lambert's law (Ghosh and Mallik 2010):

$$I = I_0 e^{-\mu z} \tag{6.2}$$

where, I_0 is the peak intensity at the workpiece surface, μ is the absorption coefficient, and z is the coordinate in the direction of workpiece depth. It has been observed that a significant fraction of energy is absorbed by a thin layer at the workpiece surface. The depth up to which the intensity of the beam reduces to $1/e$ of the peak intensity is referred to as optical penetration depth (Mishra and Yadava 2015).

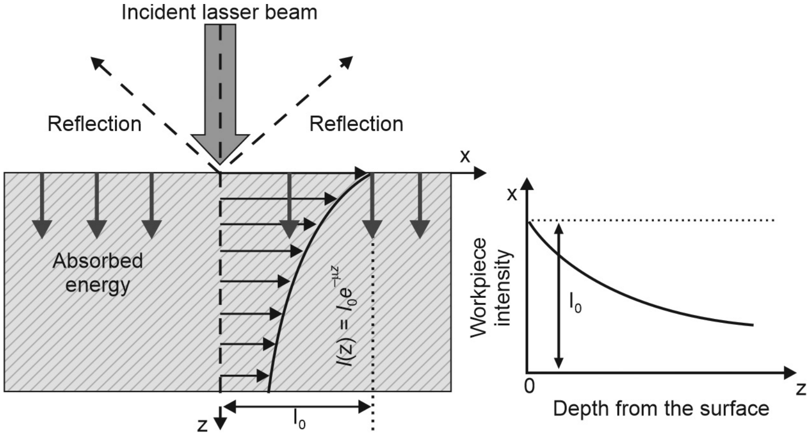


Fig. 6.5: Variation in laser beam power intensity along with the depth of workpiece. Redrawn from Ref. Ghosh and Mallik 2010

6.5.2 Melting

Figure 6.6 shows the variation of workpiece surface temperature with time, i.e. during heating, up to the melting and subsequent cooling/solidification. At time t_1, the surface temperature is $T_1 < T_m$, where T_m represents the melting temperature. With the progression of pulse duration, the workpiece temperature increases, and it reaches the melting temperature (T_m) of the workpiece at a time t_m. If the pulse duration of the laser beam is higher than t_m, the surface temperature exceeds T_m and may reach its peak/maximum temperature indicated by T_{max} at time t_p. After that, the cooling phase begins, which is indicated by a decline in surface temperature. At time t_s, the surface begins to solidify and cool further, as depicted by the cooling phase in Fig. 6.6.

6.5.3 Vaporization

There is a maximum depth of melting corresponding to the evaporation temperature of the material. Once the surface temperature of the workpiece exceeds the boiling point temperature, the melting depth is maximum at this moment, and the material starts vaporizing for any further increase in the energy density. Figure 6.7 represents the variation in depth of melting with time, the melting depth ceases as soon as the surface temperature exceeds the boiling point of the workpiece.

6.5.4 Laser Ablation

Thermal ablation by the incident laser beam refers to the phenomenon wherein material removal from the target material occurs due to thermal stresses and subsequent rapid vaporization. When a substantially high energy beam irradiated on the metal surface having inhomogeneities such as coated material or composites, thermal stresses ablate the thin layer through thermal stresses, and as soon as the temperature rises to the evaporation temperature rapid evaporation occurs. As per the blow-off model, to achieve thermal ablation, the laser beam energy must exceed the threshold energy (Dahotre and Harimkar 2008).

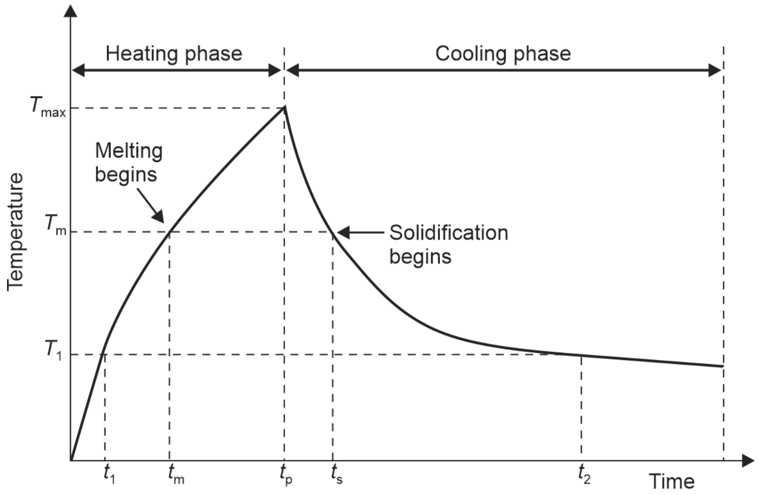


Fig. 6.6: Variation of the surface temperature of the workpiece ($z=0$) with time. Redrawn from Ref. Dahotre and Harimkar 2008

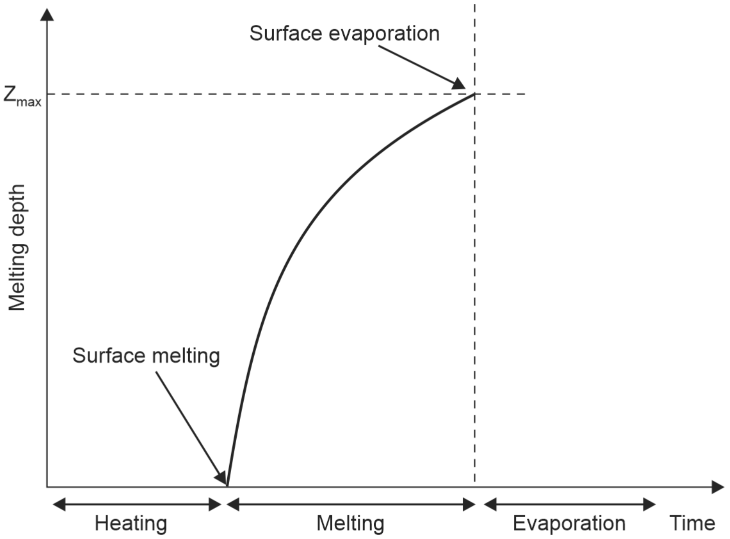
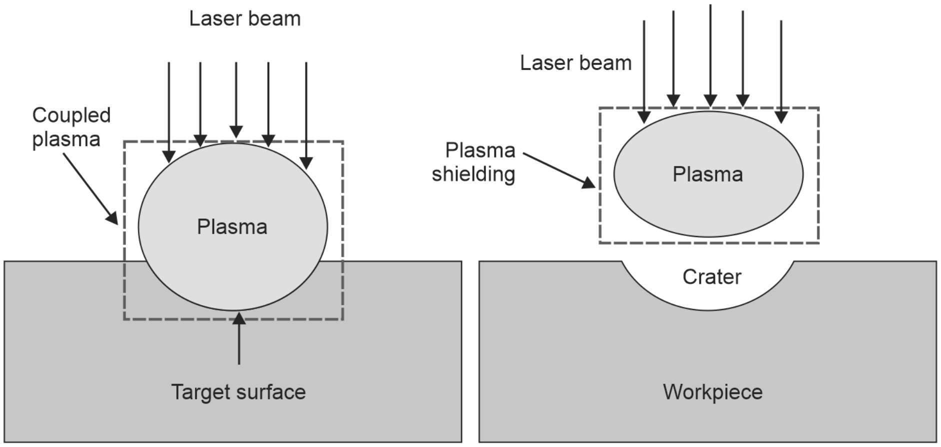


Fig. 6.7: Variation of melting depth with time. Redrawn from Ref. Dahotre and Harimkar 2008

6.5.5 Plasma Formation

With the onset of laser pulse interaction with the surface, material evaporation begins if the power density is sufficiently high. The escaping vapours interact with the incident laser beam, thus causing ionization of the vapours. This ionization results in the formation of a plasma surrounding the melt pool/target surface. The phenomenon of plasma formation occurs due to avalanche breakdown mechanism and multiphoton absorption. In the former case, the free electron in the vapour phase interacts with the incident laser beam, and if the energy acquired by the free electron exceeds the ionization potential of the molecule, it ionizes the molecules of the vapours. The ionization results in the creation of ions and electrons. This electron absorbs the energy of the photon and causes further ionization, and finally, the vapours convert in the plasma phase due to avalanche breakdown. In the multiphoton absorption process, each electron receives the incident beam's energy, i.e. photons and causes ionization. In this case, there is no seed electron and no particle-particle interaction (Dahotre and Harimkar 2008).

The formation of plasma occurs above a threshold power density of the laser beam to cause ionization of the vapours. The plasma is usually confined to the region near the target surface or near the liquid-vapour interface, and therefore it is termed *plasma coupling* [Fig. 6.8(a)]. Plasma coupling assists in the absorption of the laser beam to the target surface, especially when the surface is highly reflective. It also transfers energy to the dense phase. The plasma expands rapidly beyond a threshold laser power density and spreads slightly away from the target surface or near the laser beam [Fig. 6.8(b)]. In this event, the plasma absorbs the laser beam and prevents its absorption to the target surface, and this process is known as plasma shielding (Dahotre and Harimkar 2008).



(**a**) (**b**)

Fig. 6.8: (a) Plasma coupling (b) plasma shielding.
Redrawn from Ref. Dahotre and Harimkar 2008

6.5.6 Chemical-based LBM

In the preceding sections, the laser-material interaction results in the melting or evaporation of the base material; thus, material removal occurs due to thermal-based LBM. However, LBM also removes material due to the dissociation and breaking of the chemical bonds between the molecules of the workpiece material, provided the energy of the laser beam, i.e. photon energy, is sufficiently high to exceed the bond energy. The energy of a photon is inversely proportional to its wavelength. Therefore, smaller wavelength photons are recommended for obtaining higher energy from the laser pulse. Ultrashort pulse lasers having smaller wavelengths are preferred for this particular material removal process. In chemical-based material removal from the laser, first, the energy of a photon is absorbed by the material, followed by the dissociation of chemical bonds between the molecules and eventually, the removed material escapes the workpiece surface in the form of gases or ashes. Materials, namely, Teflon or plastics have bond energy ranging from 1.8 to 7 eV are machined photochemically through an excimer laser (wavelength ~157 nm) with a photon energy of around 7.5 eV. However, CO_2 lasers have significantly lower photon energy of 0.1 eV, thus cannot machine plastics chemically though they can be machined thermally (Liang and Shih 2016).

6.6 THE MATERIAL REMOVAL RATE IN LBM

The material removal due to LBM initiates if the power density of the incident beam is significantly higher than the combined energy losses due to heat conduction in the workpiece, convective and radiative losses. Moreover, a certain fraction of beam energy is lost in the reflection. Therefore, to estimate the material removal rate in the LBM machining, an idea of the power density of the beam is essential.

The laser spot diameter (d) from Fig. 6.9 is given as follows (Dahotre and Harimkar 2008; Liang and Shih 2016):

$$d = F\alpha \tag{6.3}$$

where, F is the focal length of the beam, α is the beam divergence angle in radians.

The power density (W/mm^2) of the incident laser beam is expressed as follows:

$$P = \frac{L}{A} \tag{6.4}$$

where, L is the laser power, A is the laser spot area = $\frac{\pi(F\alpha)^2}{4}$. Putting A in Eq. (6.4), we have following expression for power density:

$$P = \frac{4L}{\pi F^2\alpha^2} \tag{6.5}$$

Linear material removal rate (mm/min) is determined by the following expression:

$$MRR_l = \frac{CL}{EA} \tag{6.6}$$

where, C is the energy conversion efficiency, which depends on workpiece material, E is the energy of vaporization of the workpiece (J/mm^3).

$$MRR_l = \frac{4CL}{\pi E(F\alpha)^2} \tag{6.7}$$

The MRR_l depicts the feed rate during the laser drilling operation. Volumetric material removal rate (MRR_v) can be evaluated by multiplying the MRR_l with the laser spot area (A).

$$MRR_v = \frac{CL}{E} \tag{6.8}$$

The energy conversion efficiency (C) highly influences the material removal rate (MRR) (linear and volumetric) in the LBM. The incident beam energy is reflected from the surface. Some of the energy is conducted through the workpiece, whereas the remaining energy is capitalized for workpiece melting/evaporation. Therefore, the surface finish of the workpiece material, its properties, oxidation and temperature and wavelength of the beam determine the reflection behaviour of the beam. Most of the metals have high reflectivity compared to nonmetals, due to which they reflect a substantial part of the incident laser beam. Due to the higher reflectivity of the metal, the maximum cutting speed is limited to 150 mm^2/s at low power densities, whereas it can be as high as 1000 mm^2/s for nonmetallic materials (El-Hofy 2005). Therefore, higher power lasers are recommended for machining metals to obtain cutting speeds comparable to nonmetallic materials. Surface modification can improve the reflective properties of workpiece materials.

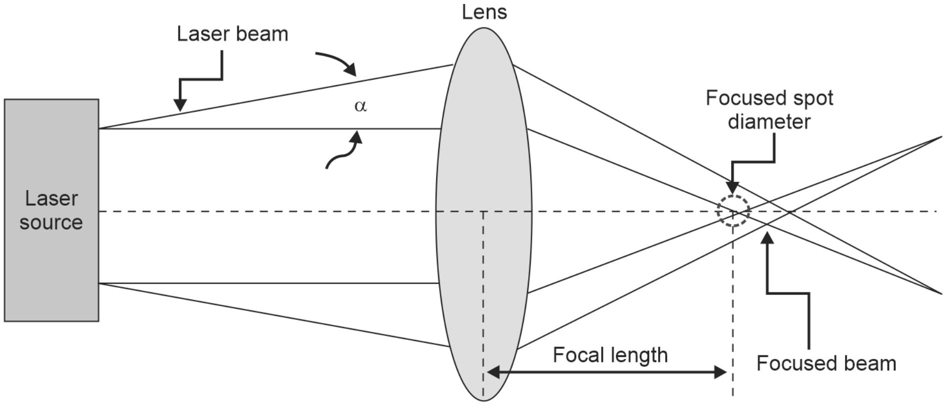


Fig. 6.9: Beam divergence and focusing of the laser beam

6.7 LASER MACHINING TECHNIQUES

To achieve laser micromachining, the following two techniques are predominantly adopted:

6.7.1 Direct Writing Method

In the direct writing technique of laser machining, either the laser beam or the workpiece stage moves such that the desired pattern is machined on the workpiece surface. This is the simplest laser machining technique, as it does not necessitate any extra elements; it can produce high resolution and require a low power laser. However, the machining rate is relatively low (Liang and Shih, 2016). The critical parameters associated with the direct writing method include focus size, workpiece distance from the lens, and length of focus (Dahotre and Harimkar, 2008).

6.7.2 Mask Projection Method

In this technique, the desired pattern is machined by projecting the laser beam through a mask having the desired pattern. The laser beam illuminates the openings in the mask, which is further lowered in size through a lens, and finally, a miniature pattern of the mask is machined on the workpiece. Another version of the mask projection method consists of a mask directly placed over the workpiece. Therefore, the profile machined on the mask is copied on the workpiece through laser illumination. A very high resolution is possible to attain with this method. However, the mask can sometimes damage the workpiece (Dahotre and Harimkar 2008; Liang and Shih 2016).

6.8 BEAM INTENSITY DISTRIBUTION

In a most simplistic model, it is assumed that the laser is irradiated on a small spot of the workpiece, which is approximated as a point. Therefore, the point heat distribution obtains a substantially high energy density, as energy is applied over a point. However, in actual machining conditions, there is a finite radius over which the beam is irradiated. Further, the energy of the laser beam is assumed to be uniformly distributed over an infinitesimal area (laser top-hat beam), thus allowing constant energy at every point within the laser-material interaction. Both these distributions of the laser beam are simplistic and do not comply with the actual energy distribution in the LBM. The most realistic energy distribution of the laser beam follows the Gaussian distribution function. According to which the energy of the beam at a certain radius from the centre of the beam is defined as follows (Dahotre and Harimkar 2008):

$$C = I_0 \exp\left[-2\left(\frac{r}{w}\right)^2\right] \tag{6.9}$$

where, r is the beam radius, I_0 is the peak intensity of the laser beam at the centre of the beam, i.e. at $r=0$, and w is the instantaneous radius of the beam. When w approaches to the radius of the beam, i.e. $w=r$, the beam intensity becomes $I=I_0e^{-2}$.

Besides the point, disc and Gaussian distribution of the beam's energy, other beam shapes, namely uniform heat flux on a large area, circular and rectangular, are employed in the LBM through-beam shape method (Dahotre and Harimkar 2008).

6.9 FOCUSING OF THE LASER BEAM

Figure 6.10 represents the focusing of a laser beam through a focusing lens, depth of focus, the diameter of the focus spot and beam divergence (McNally *et al* 2004). The focus spot diameter (d) of the beam is calculated as given below (Dahotre and Harimkar 2008):

$$d = F\alpha \tag{6.10}$$

Depth of focus is determined as follows:

$$\Delta f = \frac{2dF}{D} = \frac{2\alpha F^2}{D} \tag{6.11}$$

where, D is the beam diameter, F is the focal length, α is the beam divergence angle. Equations (6.10) and (6.11) revel that lower spot diameter is possible to attain with a smaller focal length of the beam, which increases the power density of the laser beam. However, a smaller focal length also reduces the depth of focus of the beam. Thus limiting the placing of the workpiece and the depth of the drilled holes (Dahotre and Harimkar 2008). For better quality hole drilling, it is always recommended to position the workpiece such that the focal point of the beam should be below the workpiece surface. As shown in Fig. 6.10, the depth of focus is the length over which the beam diameter remains invariably constant (Jain VK 2007).

6.10 GAS-ASSISTED LASER MACHINING

Almost all machining operations through lasers are assisted by a gas-jet (usually inert), either coaxial to the laser beam or supplied at an inclination angle to the laser-jet. Gases, namely oxygen, nitrogen, compressed air, helium, etc. are commonly used in the LBM. The assist gases serve the following major purposes in the LBM (Dahotre and Harimkar 2008).

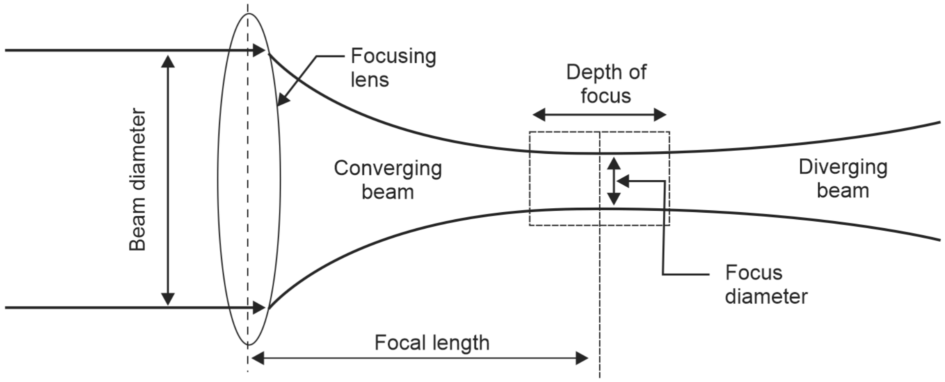


Fig. 6.10: Focussing of a laser beam, focal length and depth of focus. Redrawn from Ref. McNally *et al* 2004

1. It prevents the energy loss of the laser beam due to its interaction with the molecules of the surrounding medium. It ensures a higher energy density beam without any appreciable beam divergence.
2. The assist gas provides an inert environment in the vicinity of the machining zone, thus allowing the contamination-free machining. It also reduces the defects in the machined components originating due to the entrapment of air or other contaminants.
3. A certain portion of molten metal is evacuated due to shear stress induced in the molten metal, especially for low power laser beams wherein melting predominates.
4. At a higher power laser beam, assist gases removes the vapours or debris particles, which otherwise obstruct the incident laser beam and reduce its energy.

Oxygen as an assist gas enhances the material removal rate due to the exothermic reaction of the oxide layer formed over the machined spot. Therefore, it contributes additional energy for machining operation (Dahotre and Harimkar 2008; Jain VK 2007).

6.11 LBM: MODE OF OPERATION

Initially, the lasers were operated in continuous wave (CW) mode in which the energy of the laser beam is supplied unceasingly; therefore, the energy density remains invariably constant with time. CW lasers are commonly employed for operations, namely welding, joining, or surface hardening (Liang and Shih, 2016). With CW laser operations though the energy is available continuously, there are many defects in the machined materials. These include large heat-affected zone (HAZ), thermal residual stresses, higher kerf width, etc. Pulsed lasers are invented to mitigate these thermal defects in the workpiece, which operate in the intermittent mode, i.e. the laser power is withdrawn after a pulse of a certain duration (pulse-width). Therefore, there is a pulse-off period in which there is no power available for machining in the pulsed mode lasers. Owing to the pulsating nature of the supplied energy, the thermal defects are significantly reduced to produce a surface with superior properties. Moreover, using low wavelength pulsed lasers, material removal occurs predominantly due to vaporization, thus recast layer formation, burrs, etc. are lowered. Based on the pulse-width (pulse-on time) of a single pulse, the lasers are categorized as micro, nano, pico, femto, atto, etc. lasers. Pulsed mode lasers are preferred for operations like cutting, precise hole drilling or marking (Liang and Shih 2016).

6.12 LBM: APPLICATIONS

Laser finds extensive applications in different areas of engineering. The applications of the lasers range from joining, material deposition, subtraction, etc. However, the present chapter only concentrates on machining applications of the laser beam. Following are some of the major applications of the LBM process.

6.12.1 Laser Drilling

Drilling of high-density miniature holes in difficult to machine materials is one of the major applications of the LBM. An array of micro-holes in turbine blades for cooling operations, holes for inkjet printers and diesel engine fuel injector nozzle are some noticeable applications of the laser drilling operation (Beck 2011). Figure 6.11 shows physical phenomena during a typical laser drilling operation. Laser drilling operation can be accomplished through different modes, i.e. using a single pulse, trepanning mode and percussion drilling, which are briefly explained as follows (Dahotre and Harimkar 2008):

Drilling of a hole with a diameter around 1 mm in a 1 mm thin sheet is achieved by irradiating the workpiece surface with a high energy density beam. The entire material can vaporize in a single pulse. However, when drilling larger diameter through holes (3-4 mm diameter) in a relatively thicker workpiece (up to 10 mm), drilling the hole by removing the whole material is an uneconomical process. To overcome this problem, the trepanning approach of hole drilling is adopted. Trepanning hole drilling operation is similar to the blanking operation, wherein the circumference of a circular hole or periphery of a noncircular feature is machined by controlling the trajectory of the laser beam around the feature. In this way, a blank is produced, and a through-hole is machined. When it comes to machining holes in a thick material (up to 25 mm), a single pulse drilling is inadequate. A series of laser pulses are applied one after another to accomplish a hole drilling process, i.e. percussion drilling. There is a pulse-off period between two successive pulses.

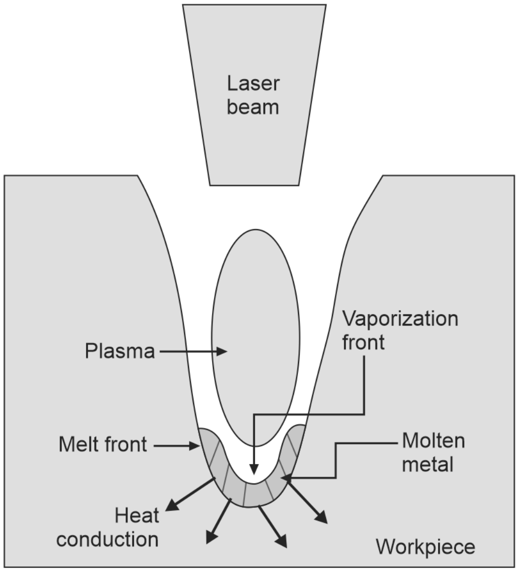


Fig. 6.11: Schematic illustration of a typical laser drilling operation and associated physical phenomena. Redrawn from Ref. Dahotre and Harimkar 2008

6.12.2 Laser Cutting

Unlike laser drilling operation, wherein only unidirectional control of laser beam, the laser cutting involves the movement of laser cutting front. This can be possible to achieve either the movement of the laser beam or workpiece. Laser cutting is accomplished by the evaporative as well as fusion mode of operations. A high-density laser beam vaporizes the material from the workpiece up to the full depth; expulsion of molten material is assisted by the assist gas used in operation. Subsequently, the melt front progresses in the cutting direction to accomplish the required cutting operation. Figure 6.12 represents the laser cutting operation. Laser cutting is usually considered a fast process. Cutting speed as high as 3 m/min has been reported for slicing 4 mm thick steel sheets using a CO_2 laser of 1200 W power. Laser cutting can be accomplished through direct evaporation, melting, reactive fusion and controlled fracture (mechanical stresses caused by laser beam) depending upon the energy density of the laser beam and workpiece material (Dahotre and Harimkar 2008).

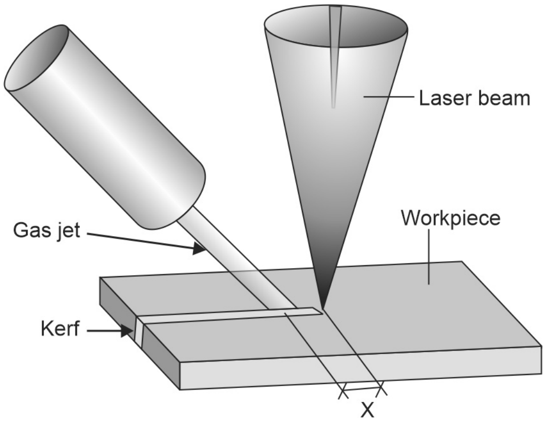


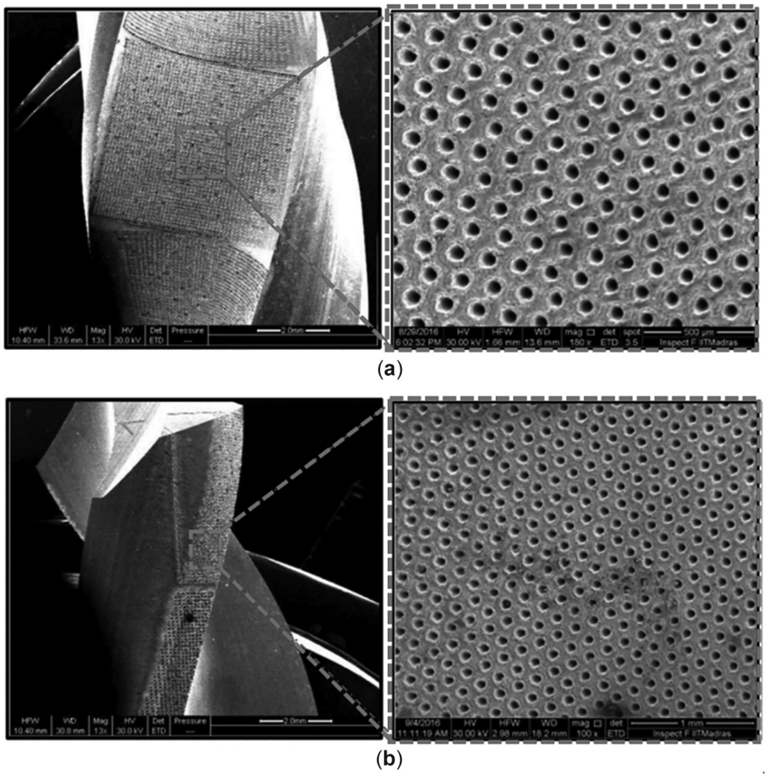
Fig. 6.12: Schematic of laser-cutting operation (Quintero *et al* 2006)

6.12.3 Laser Texturing

An array of micro-patterns, namely micro-dimples, micro-channels or micro-pillars, are machined over a relatively large surface area for various applications. The micro-textures fabrication through LBM has shown its capabilities in the plethora of engineering applications such as drag reduction, friction reduction between cylinder liner and piston in internal combustion engines, painless drug delivery and ultrasonic monitoring of hypodermic needles, etc. (Etsion 2005; Yin, *et al* 2012). An array of micro-dimples is machined on the rake face of a turning tool or the flute and margin of a twist drill, as shown in Fig. 6.13. These micro-textures essentially reduces the coefficient of friction and cutting forces during machining and improve the machinability of hard materials, namely titanium alloys (Kümmel, *et al* 2015; Niketh and Samuel 2017).

6.12.4 Laser-assisted Conventional Machining

A laser beam can be utilized to heat the workpiece materials ahead of the cutting tool in the conventional machining operations, namely turning using a single point tool or milling and grinding using a multipoint tool electrode. Figure 6.14 represents a schematic illustration of a laser-assisted turning operation. Laser-assisted machining is



(**a**)

(**b**)

Fig. 6.13: An array of micro-dimples machined on (a) flute (b) margin side of a twist drill (Niketh and Samuel 2017)

particularly useful for machining hard and difficult-to-cut materials, namely titanium alloys, ceramics, etc. The primary aim of heating the workpiece is to convert the cutting mechanism from brittle to ductile due to the thermal softening of the material. It also lowers the shear yield stress or other mechanical properties of the material. (Chryssolouris, *et al* 1997) Therefore, it assists in reducing the cutting forces, improving the tool life and surface finish, and finally, enhancing the productivity (Wei, *et al* 2017). It is important to mention here that the laser beam does not melt/evaporate the workpiece; instead, it raises the workpiece's temperature without any phase changes. Moreover, the distance between the spot of laser heating and the tooltip must be optimized to account for the relative motion of the tool (Chryssolouris, *et al* 1997). Lasers have also been integrated with other conventional or advanced machining processes (electrochemical machining, electrical discharge machining) to augment the machining efficiency of the process (Gupta, *et al* 2016).

6.12.5 Miscellaneous Applications

Besides the applications mentioned above, LBM can be appropriately applied for grooving, milling, turning or threading operations using multiple laser beams. Marking of numbers, letters on various materials can also be performed using LBM (Jain VK 2007). Micro-holes for wire drawing dies and sharp-edge knife fabrication for surgical operation are also performed through LBM (Meijer 2002).

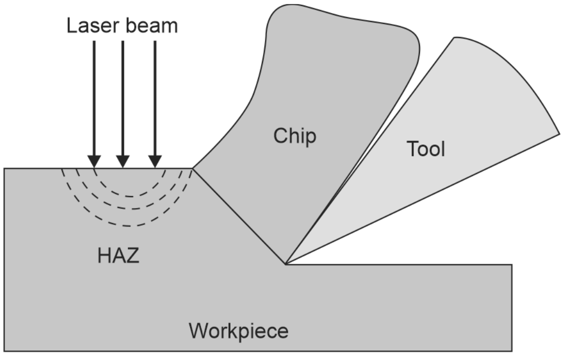


Fig. 6.14: Schematic of laser-assisted turning operation

6.13 LBM: ADVANTAGES

LBM offers the following advantages for the machining of almost any materials (Jain VK 2007; Liang and Shih 2016; Adamas MC *et al* 1965):

1. The machinability of the LBM process is independent of the mechanical properties of the workpiece materials. However, it depends on the thermophysical and optical properties of the work material.
2. Due to the noncontact working mechanism of the LBM, mechanical forces are absent in the process. Therefore, delicate parts or thin sheets are possible to machine through this process.
3. Both electrically conductive and electrically nonconductive materials are machined through the LBM process, unlike the EDM and electrochemical mechining (ECM) processes, wherein only electrically conductive materials are processed.
4. Through appropriate focusing of the laser beam and accurate positioning of the workpiece surface with respect to the focus point of the beam, a substantially small beam/spot diameter can be obtained.
5. It is possible to drill holes at different entrance angles (10–15°) from the surface through LBM.

6.14 LBM: LIMITATIONS

Despite a number of advantages of the LBM process, there are some limitations of the LBM process, listed as follows (Jain VK 2007; Liang and Shih 2016):

1. LBM equipment cost is very high.
2. LBM requires significantly high-power consumption for machining. Moreover, the energy conversion efficiency of the LBM is relatively low (around 1%).
3. Materials with high reflectivity and thermal conductivity, namely aluminium, copper, gold and silver are difficult-to-machined through the LBM.
4. Thermal defects such as residual thermal stresses, micro-cracks, surface oxidation, etc. are prone to the LBM. However, with the advent of a pulsed laser with pulse-width in picoseconds to femtoseconds, the thermal defects are minimized to a larger extent.
5. The machining rate of the LBM is relatively low. Deep hole drilling necessitates an appropriate mechanism for the expulsion of molten material; otherwise, machining cannot proceed further.

SUMMARY

The LBM process is perhaps one of the most versatile machining processes in the nontraditional machining domain. Laser beam generation, laser-material interaction, and associated physical phenomena are the foremost steps in the overall working of the LBM. The advent of pulsed lasers with pulse width as low as in femtoseconds allows the minimization of thermal defects in the machined features compared to continuous-wave lasers. The laser beam can be operated in different modes depending on the specific requirements. LBM has been utilized in various applications, namely drilling, cutting, and texturing, besides assisting the cutting phenomenon of the conventional/ advanced machining processes. The energy efficiency of the LBM process is relatively low, which requires higher power, especially for machining high aspect ratio features.

Acronyms

CW	Continuous wave
ECM	Electrochemical machining
EDM	Electrical discharge machining
HAZ	Heat-affected zone
LBM	Laser beam machining
MRR	Material removal rate
MRR_l	Linear material removal rate
MRR_v	Volumetric material removal rate

Symbols

C	Energy conversion efficiency
D	Beam diameter
d	Laser spot diameter
E	Energy of vaporization
E_1, E_2	Energy levels
F	Focal length
I_0	Peak intensity
K	Boltzmann's constant
L	Laser power
n	Number of atoms
P	Power density
T	Temperature
w	Instantaneous radius of the beam
α	Beam divergence angle
μ	Absorption coefficient

PRACTICE QUESTIONS

1. **Explain the principle of laser beam generation briefly.**
2. **Briefly define the following terms related to laser generation: Population inversion, stimulated emission, coherence, monochromic, ablation.**
3. **Classify the lasers based on the state of lasing material and mode of operation.**
4. **With the help of a schematic diagram, briefly explain various features of a laser-drilled hole in a thick stainless-steel plate.**
5. **With the help of a figure, show the variation of temperature along with the depth of the workpiece with time. Also, represent how heat intensity varies with workpiece's depth.**
6. **How does plasma form in the laser beam machining, and what is the effect of plasma on the machining?**
7. **Why is laser heating employed in conventional turning or grinding operations?**
8. **Briefly discuss the role of gas assistance in laser beam machining.**
9. **Show three different modes of hole drilling through laser drilling operation. What is the limitation of hole drilling through trepanning mode?**
10. **What are the key limitations of laser beam machining?**
11. **Explain why LBM has low energy efficiency?**
12. **Compare LBM and EDM processes in terms of similarities and differences.**

REFERENCES

Beck T. Laser drilling in gas turbine blades: Shaping of holes in ceramic and metallic coatings. Macro materials processing 2011;8:40–3. https://doi.org/10.1002/latj.201190024

Benedict GF. *Nontraditional Manufacturing Processes*, 1987.

Borisov VM, *et al*. High average power excimer lasers. Proceedings of SPIE - *The International Society for Optical Engineering* 1998;3574:56–66. https://doi.org/10.1117/12.334492

Chryssolouris G, *et al*. *Laser assisted machining: An overview. Journal of Manufacturing Science and Engineering, Transactions of the ASME* 1997;119:766–9. https://doi.org/10.1115/1.2836822

Dahotre NB, *et al*. *Laser Fabrication and Machining of Materials*, Springer, 2008.

El-Hofy H. *Advanced Machining Processes: Nontraditional and Hybrid Machining Processes*, 2005. McGraw-Hill. https://doi.org/DOI: 10.1036/0071466940

Etsion I. State of the art in laser surface texturing. *Journal of Tribology* 2005;127:248–53. https://doi.org/10.1115/1.1828070

Ghosh A, *et al*. *Manufacturing Science*, 2nd edn. Affiliated East-West Press Private Limited, 2010.

Gupta K, *et al*. *Hybrid Machining Processes Perspectives on Machining and Finishing*, 2016.

Jain VK. *Advanced Machining Processes*, 2007. Allied Publishers Private Limited, New Delhi, India.

Kümmel J, *et al*. Study on micro texturing of uncoated cemented carbide cutting tools for wear improvement and built-up edge stabilization. *Journal of Materials Processing Technology* 2015;215:62–70. https://doi.org/10.1016/j.jmatprotec.2014.07.032

Liang SY, *et al*. *Analysis of Machining and Machine Tools*, 2016. Springer.

Adams MC, *et al*. *Fundamentals of Laser Beam Machining and Drilling*. IEEE Transactions on Industry and General Applications, 1965. https://doi.org/10.1109/tiga.1971.4181322

McNally CA, *et al*. Laser drilling of cooling holes in aeroengines: State of the art and future challenges. *Materials Science and Technology* 2004;20:805–13. https://doi org/10.1179/026708304225017391

Meijer J. Laser Micromachining, in: McGeough J (Ed), *Micromachining of Engineering Materials*. 2002;pp203–39.

Mishra S, *et al*. Laser Beam MicroMachining (LBMM)—A review. *Optics and Lasers in Engineering* 2015;73:89–122. https://doi.org/10.1016/j.optlaseng.2015.03.017

Niketh S, *et al*. Surface texturing for tribology enhancement and its application on drill tool for the sustainable machining of titanium alloy. *Journal of Cleaner Production* 2017; 67:253–70. https://doi.org/10.1016/j.jclepro.2017.08.178

Paul CP, *et al*. Laser-Assisted Manufacturing: Fundamentals, Current Scenario, and Future Applications. In: Davim JP (Ed.), *Nontraditional Machining Processes* 2013;pp.1–34.

Quintero F, *et al*. Optimization of an off-axis nozzle for assist gas injection in laser fusion cutting. *Optics and Lasers in Engineering* 2006:44:1158–71. https://doi.org/10.1016/j.optlaseng.2005.10.001

Raju BB, *et al*. Photophysical properties and energy transfer dye laser characteristics of 7-diethylamino-3-heteroaryl coumarin in solution. *Laser Chemistry* 1995;16:109–20. https://doi.org/10.1155/1995/51920

Ready JF. *Industrial Applications of Lasers*, 1997. Academic Press, San Diego.

Sun S, *et al*. Laser Beam Machining, In: Davim JP (Ed.), *Nontraditional Machining Processes*, 2013. Springer.

Tunna L, *et al*. Analysis of laser micro drilled holes through aluminium for micro-manufacturing applications. *Optics and Lasers in Engineering* 2005; 43:937–50. https://doi.org/10.1016/j.optlaseng.2004.11.001

Wei Y, *et al*. Experimental Evaluation of Direct Laser Assisted Turning through a Sapphire Tool. *Procedia Manufacturing* 2017;10:546–56. https://doi.org/10.1016/j.promfg.2017.07.044

Yin B, *et al*. Effect of laser textured dimples on the lubrication performance of cylinder liner in diesel engine Bifeng. *Lubrication Science* 2012;24:293–312. https://doi.org/10.1002/ls