Module
9

Non conventional Machining

Lesson
40
# Electron Beam and Laser Beam Machining

Instructional Objectives

    i.   Describe the basic mechanism of material removal in EBM & LBM
    ii.   Identify major components of EBM & LBM equipment
    iii.   State the working principle of EBM & LBM equipment
    iv.   Draw schematically the EBM & LBM equipment
    v.   Identify the process parameters of EBM & LBM
    vi.   Identify the machining characteristics of EBM & LBM
    vii.   List three applications of EBM & LBM
    viii.   List three limitations of EBM & LBM

1.   Introduction

Electron Beam Machining (EBM) and Laser Beam Machining (LBM) are thermal processes considering the mechanisms of material removal. However electrical energy is used to generate high-energy electrons in case of Electron Beam Machining (EBM) and high-energy coherent photons in case of Laser Beam Machining (LBM). **Thus these two processes are often classified as electro-optical-thermal processes.**

There are different jet or beam processes, namely Abrasive Jet, Water Jet etc. These two are mechanical jet processes. There are also thermal jet or beams. A few are oxyacetylene flame, welding arc, plasma flame etc. EBM as well as LBM are such thermal beam processes. Fig. 9.6.1 shows the variation in power density vs. the characteristic dimensions of different thermal beam processes. Characteristic length is the diameter over which the beam or flame is active. In case of oxyacetylene flame or welding arc, the characteristic length is in mm to tens of mm and the power density is typically low. Electron Beam may have a characteristic length of tens of microns to mm depending on degree of focusing of the beam. In case of defocused electron beam, power density would be as low as 1 Watt/mm^2. But in case of focused beam the same can be increased to tens of kW/mm^2. Similarly as can be seen in Fig. 9.6.1, laser beams can be focused over a spot size of 10 – 100 μm with a power density as high as 1 MW/mm^2. Electrical discharge typically provides even higher power density with smaller spot size.
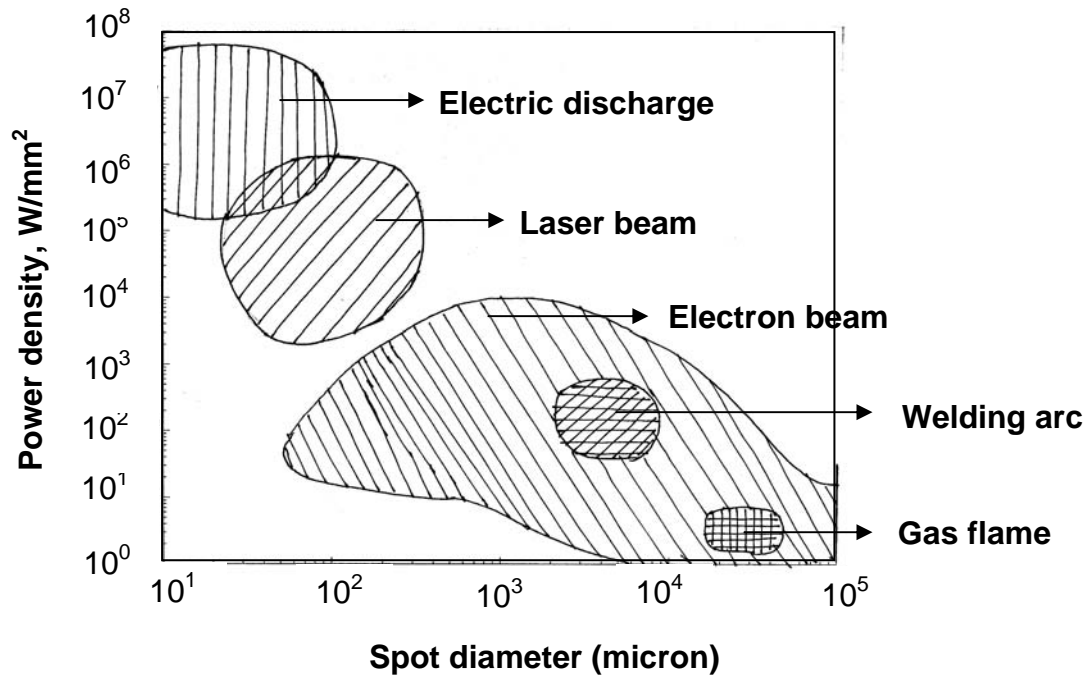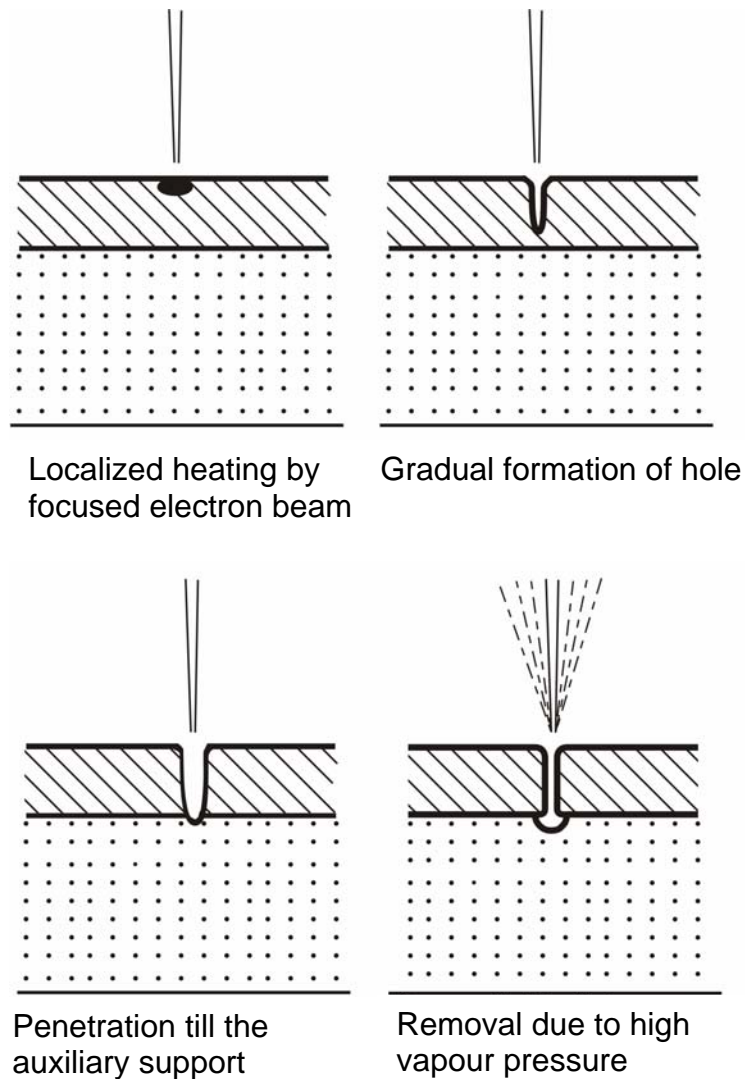
Fig. 9.6.1 *Variation in energy density with spot diameter of thermal beam processes*

EBM and LBM are typically used with higher power density to machine materials. The mechanism of material removal is primarily by melting and rapid vaporisation due to intense heating by the electrons and laser beam respectively.

## 2.   Electron Beam Machining – Process

Electron beam is generated in an electron beam gun. The construction and working principle of the electron beam gun would be discussed in the next section. Electron beam gun provides high velocity electrons over a very small spot size. Electron Beam Machining is required to be carried out in vacuum. Otherwise the electrons would interact with the air molecules, thus they would loose their energy and cutting ability. Thus the workpiece to be machined is located under the electron beam and is kept under vacuum. The high-energy focused electron beam is made to impinge on the workpiece with a spot size of 10 – 100 μm. The kinetic energy of the high velocity electrons is converted to heat energy as the electrons strike the work material. Due to high power density instant melting and vaporisation starts and "melt – vaporisation" front gradually progresses, as shown in Fig. 9.6.2. Finally the molten material, if any at the top of the front, is expelled from the cutting zone by the high vapour pressure at the lower part. Unlike in Electron Beam Welding, the gun in EBM is used in pulsed mode. Holes can be drilled in thin sheets using a single pulse. For thicker plates, multiple pulses would be required. Electron beam can also be manoeuvred using the electromagnetic deflection coils for drilling holes of any shape.

Localized heating by focused electron beam

Gradual formation of hole

Penetration till the auxiliary support

Removal due to high vapour pressure

`*Fig. 9.6.2*   *Mechanism of Material Removal in Electron Beam Machining*

3.   Electron Beam Machining – Equipment

Fig. 9.6.3 shows the schematic representation of an electron beam gun, which is the heart of any electron beam machining facility. The basic functions of any electron beam gun are to generate free electrons at the cathode, accelerate them to a sufficiently high velocity and to focus them over a small spot size. Further, the beam needs to be manoeuvred if required by the gun.
The cathode as can be seen in Fig. 9.6.3 is generally made of tungsten or tantalum. Such cathode filaments are heated, often inductively, to a temperature of around 2500^0C. Such heating leads to thermo-ionic emission of electrons, which is further enhanced by maintaining very low vacuum within the chamber of the electron beam gun. Moreover, this cathode cartridge is highly negatively biased so that the thermo-ionic electrons are strongly repelled away form the cathode. This cathode is often in the form of a cartridge so that it can be changed very quickly to reduce down time in case of failure.
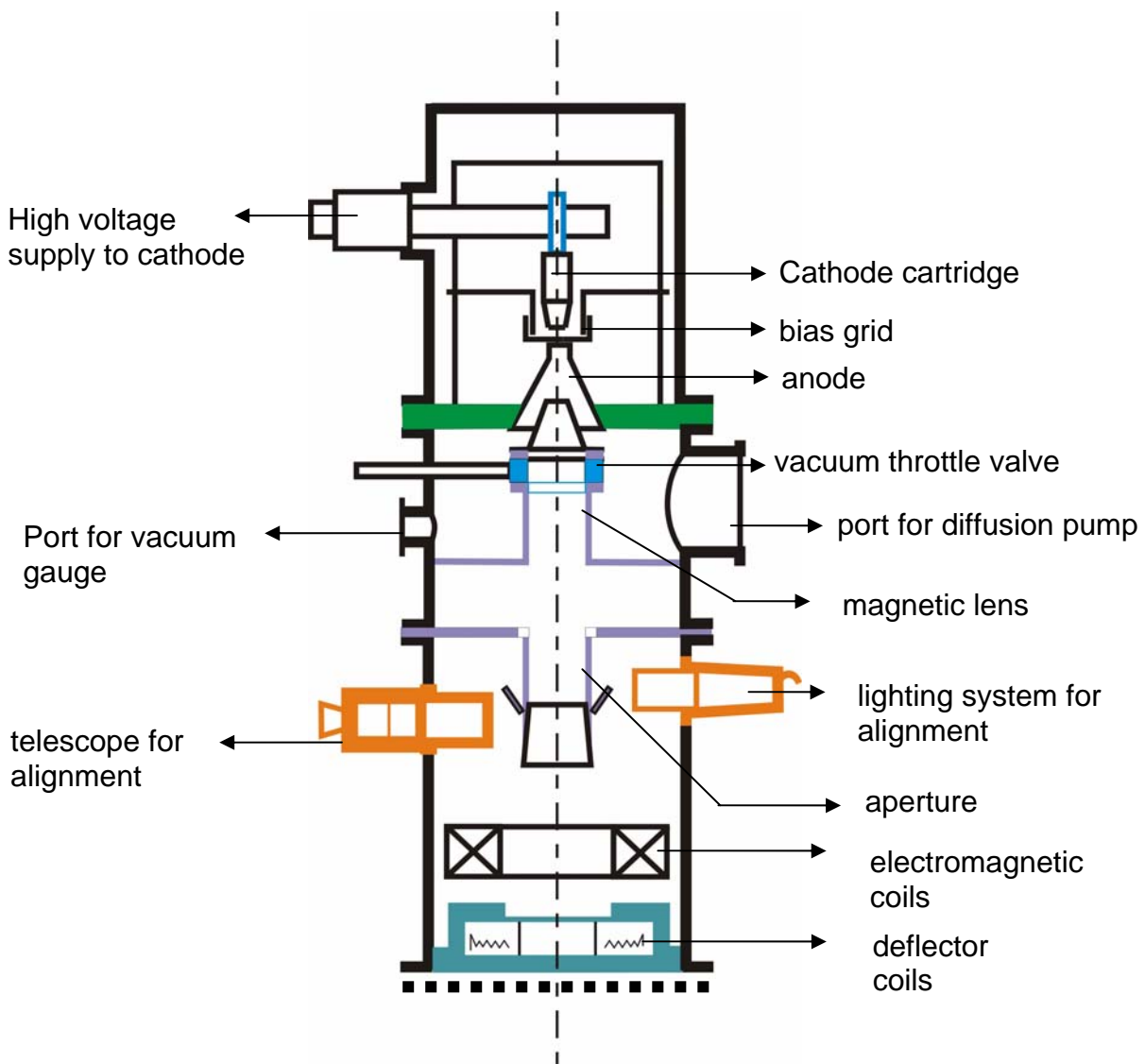
Fig. 9.6.3   *Electron Beam Gun*

Just after the cathode, there is an annular bias grid. A high negative bias is applied to this grid so that the electrons generated by this cathode do not diverge and approach the next element, the annular anode, in the form of a beam. The annular anode now attracts the electron beam and gradually gets accelerated. As they leave the anode section, the electrons may achieve a velocity as high as half the velocity of light.

The nature of biasing just after the cathode controls the flow of electrons and the biased grid is used as a switch to operate the electron beam gun in pulsed mode.

After the anode, the electron beam passes through a series of magnetic lenses and apertures. The magnetic lenses shape the beam and try to reduce the divergence. Apertures on the other hand allow only the convergent electrons to pass and capture the divergent low energy electrons from the fringes. This way, the aperture and the magnetic lenses improve the quality of the electron beam.

Then the electron beam passes through the final section of the electromagnetic lens and deflection coil. The electromagnetic lens focuses the

electron beam to a desired spot. The deflection coil can manoeuvre the electron beam, though by small amount, to improve shape of the machined holes.

Generally in between the electron beam gun and the workpiece, which is also under vacuum, there would be a series of slotted rotating discs. Such discs allow the electron beam to pass and machine materials but helpfully prevent metal fumes and vapour generated during machining to reach the gun. Thus it is essential to synchronize the motion of the rotating disc and pulsing of the electron beam gun.

Electron beam guns are also provided with illumination facility and a telescope for alignment of the beam with the workpiece.

Workpiece is mounted on a CNC table so that holes of any shape can be machined using the CNC control and beam deflection in-built in the gun.

One of the major requirements of EBM operation of electron beam gun is maintenance of desired vacuum. Level of vacuum within the gun is in the order of 10^{-4} to 10^{-6} Torr. *{1 Torr = 1mm of Hg}* Maintenance of suitable vacuum is essential so that electrons do not loose their energy and a significant life of the cathode cartridge is obtained. Such vacuum is achieved and maintained using a combination of rotary pump and diffusion pump. Diffusion pump, as shown in Fig. 9.6.4 is attached to the diffusion pump port of the electron beam gun (vide Fig. 9.6.3).

Diffusion pump is essentially an oil heater. As the oil is heated the oil vapour rushes upward where gradually converging structure as shown in Fig. 9.6.4 is present. The nozzles change the direction of motion of the oil vapour and the oil vapour starts moving downward at a high velocity as jet. Such high velocity jets of oil vapour entrain any air molecules present within the gun. This oil is evacuated by a rotary pump via the backing line. The oil vapour condenses due to presence of cooling water jacket around the diffusion pump.
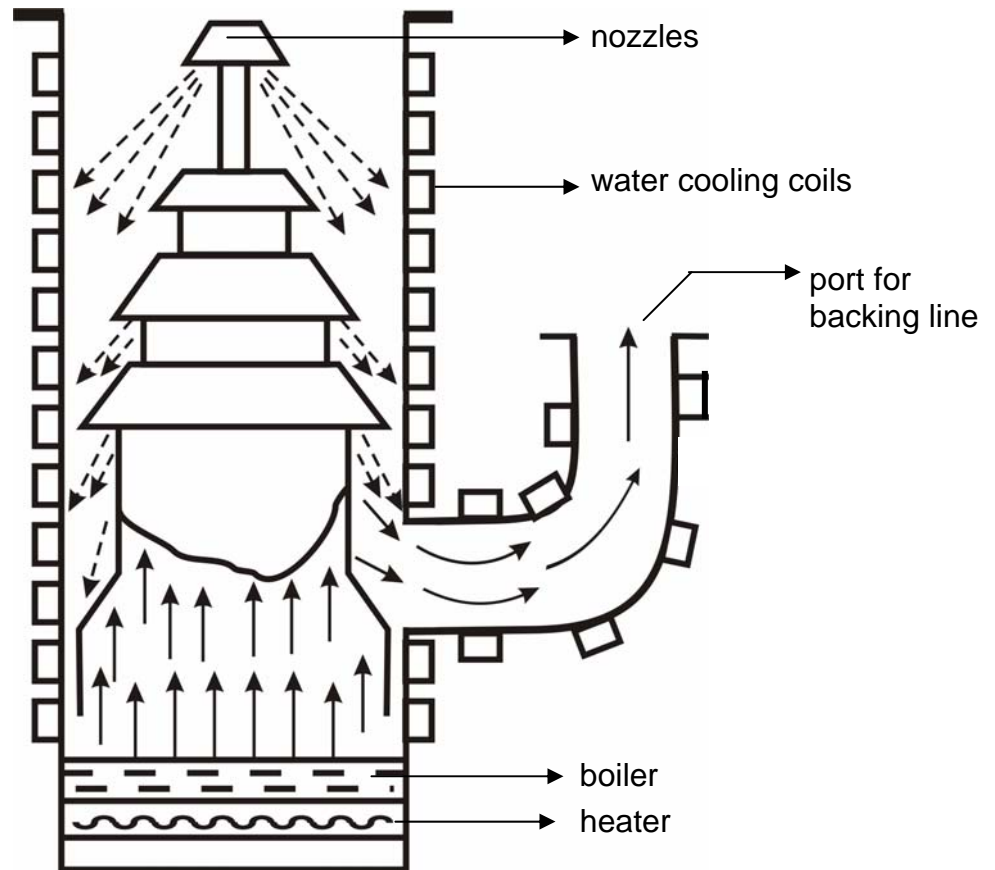
Fig. 9.6.4   *Working of a Diffusion Pump*

4.   Electron Beam Process – Parameters

The process parameters, which directly affect the machining characteristics in Electron Beam Machining, are:

- The accelerating voltage
- The beam current
- Pulse duration
- Energy per pulse
- Power per pulse
- Lens current
- Spot size
- Power density

As has already been mentioned in EBM the gun is operated in pulse mode. This is achieved by appropriately biasing the biased grid located just after the cathode. Switching pulses are given to the bias grid so as to achieve pulse duration of as low as 50 μs to as long as 15 ms.

Beam current is directly related to the number of electrons emitted by the cathode or available in the beam. Beam current once again can be as low as 200 μamp to 1 amp.

Increasing the beam current directly increases the energy per pulse. Similarly increase in pulse duration also enhances energy per pulse. High-energy pulses (in excess of 100 J/pulse) can machine larger holes on thicker plates.

The energy density and power density is governed by energy per pulse duration and spot size. Spot size, on the other hand is controlled by the degree of focusing achieved by the electromagnetic lenses. A higher energy density, i.e., for a lower spot size, the material removal would be faster though the size of the hole would be smaller.

The plane of focusing would be on the surface of the workpiece or just below the surface of the workpiece. This controls the kerf shape or the shape of the hole as schematically shown in Fig. 9.6.5.

resolidified layer
at entry

Auxiliary support
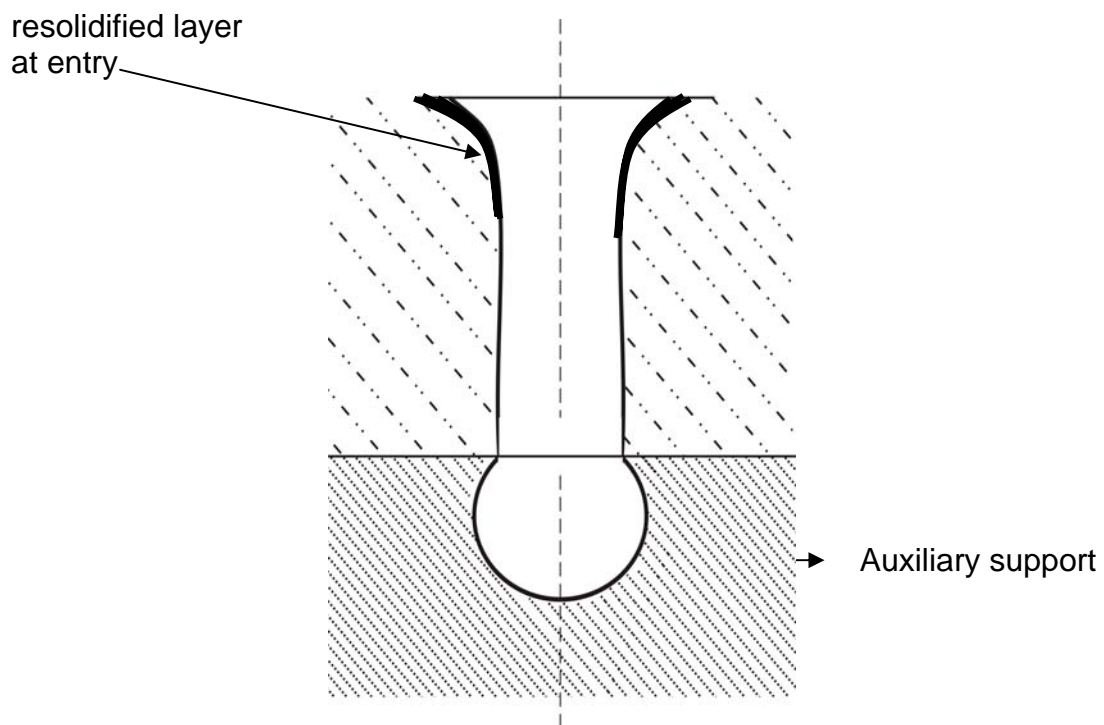
Fig. 9.6.5   *Typical kerf shape of electron beam drilled hole*

As has been indicated earlier, the final deflection coil can manoeuvre the electron beam providing holes of non-circular cross-section as required.

5.   Electron Beam Process Capability

EBM can provide holes of diameter in the range of 100 μm to 2 mm with a depth upto 15 mm, i.e., with a l/d ratio of around 10. Fig. 9.6.5 schematically represents a typical hole drilled by electron beam. The hole can be tapered along the depth or barrel shaped. By focusing the beam below the surface a reverse taper can also be obtained. Typically as shown in Fig. 9.6.5, there would be an edge rounding at the entry point along with presence of recast layer. Generally burr formation does not occur in EBM.

A wide range of materials such as steel, stainless steel, Ti and Ni super-alloys, aluminium as well as plastics, ceramics, leathers can be machined successfully using electron beam. As the mechanism of material removal is thermal in nature as for example in electro-discharge machining, there would be thermal damages associated with EBM. However, the heat-affected zone is rather narrow due to shorter pulse duration in EBM. Typically the heat-affected zone is around 20 to 30 μm.

Some of the materials like Al and Ti alloys are more readily machined compared to steel. Number of holes drilled per second depends on the hole diameter, power density and depth of the hole as well as material type as mentioned earlier. Fig. 9.6.6 depicts the variation in drilling speed against volume of material removed for steel and Aluminium alloy.

EBM does not apply any cutting force on the workpieces. Thus very simple work holding is required. This enables machining of fragile and brittle materials by EBM. Holes can also be drilled at a very shallow angle of as less as 20 to 30^0.
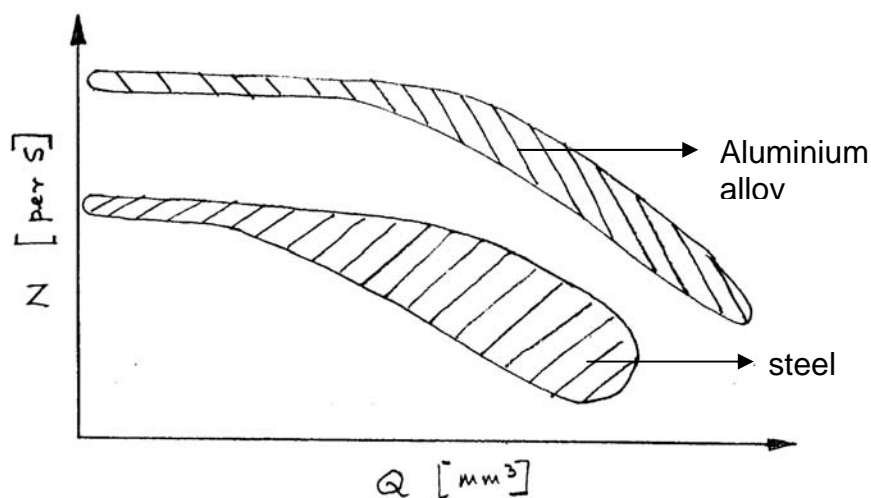

Fig. 9.6.6   Variation in drilling speed with volume of material removal for steels and aluminium

6.   Electron Beam Machining – Advantages and Limitations

EBM provides very high drilling rates when small holes with large aspect ratio are to be drilled. Moreover it can machine almost any material irrespective of their mechanical properties. As it applies no mechanical cutting force, work holding and fixturing cost is very less. Further for the same reason fragile and brittle materials can also be processed. The heat affected zone in EBM is rather less due to shorter pulses. EBM can provide holes of any shape by combining beam deflection using electromagnetic coils and the CNC table with high accuracy.

However, EBM has its own share of limitations. The primary limitations are the high capital cost of the equipment and necessary regular maintenance applicable for any equipment using vacuum system. Moreover in EBM there is significant amount of non-productive pump down period for attaining desired vacuum. However this can be reduced to some extent using vacuum load locks. Though heat affected zone is rather less in EBM but recast layer formation cannot be avoided.

7. Laser Beam Machining – Introduction

Laser Beam Machining or more broadly laser material processing deals with machining and material processing like heat treatment, alloying, cladding, sheet metal bending etc. Such processing is carried out utilizing the energy of coherent photons or laser beam, which is mostly converted into thermal energy upon interaction with most of the materials. Nowadays, laser is also finding application in regenerative machining or rapid prototyping as in processes like stereo-lithography, selective laser sintering etc.

Laser stands for light amplification by stimulated emission of radiation. The underline working principle of laser was first put forward by Albert Einstein in 1917 though the first industrial laser for experimentation was developed around 1960s.

Laser beam can very easily be focused using optical lenses as their wavelength ranges from half micron to around 70 microns. Focussed laser beam as indicated earlier can have power density in excess of 1 MW/mm^2. As laser interacts with the material, the energy of the photon is absorbed by the work material leading to rapid substantial rise in local temperature. This in turn results in melting and vaporisation of the work material and finally material removal.

8. Laser Beam Machining – the lasing process

Lasing process describes the basic operation of laser, i.e. generation of coherent (both temporal and spatial) beam of light by "light amplification" using "stimulated emission".

In the model of atom, negatively charged electrons rotate around the positively charged nucleus in some specified orbital paths. The geometry and radii of such orbital paths depend on a variety of parameters like number of electrons, presence of neighbouring atoms and their electron structure, presence of electromagnetic field etc. Each of the orbital electrons is associated with unique energy levels. At absolute zero temperature an atom is considered to be at ground level, when all the electrons occupy their respective lowest potential energy. The electrons at ground state can be excited to higher state of energy by absorbing energy form external sources like increase in electronic vibration at elevated temperature, through chemical reaction as well as via absorbing energy of the photon. Fig. 9.6.7 depicts

schematically the absorption of a photon by an electron. The electron moves from a lower energy level to a higher energy level.

On reaching the higher energy level, the electron reaches an unstable energy band. And it comes back to its ground state within a very small time by releasing a photon. This is called spontaneous emission. Schematically the same is shown in Fig. 9.6.7 and Fig. 9.6.8. The spontaneously emitted photon would have the same frequency as that of the "exciting" photon.

Sometimes such change of energy state puts the electrons in a meta-stable energy band. Instead of coming back to its ground state immediately (within tens of ns) it stays at the elevated energy state for micro to milliseconds. In a material, if more number of electrons can be somehow pumped to the higher meta-stable energy state as compared to number of atoms at ground state, then it is called "population inversion". Such electrons,
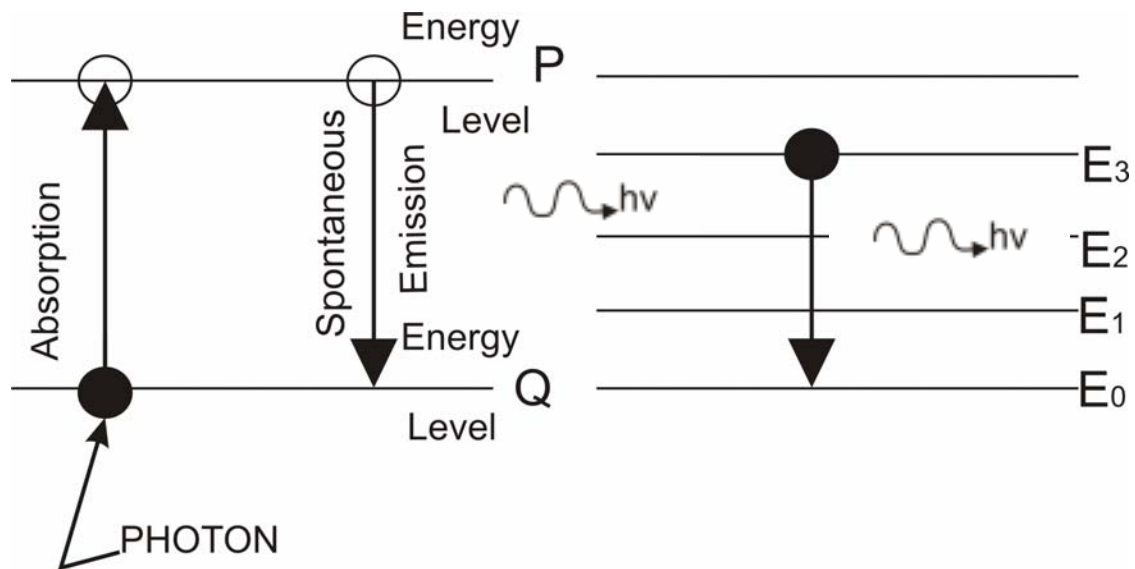
**Fig. 9.6.7**   *Energy bands in materials*
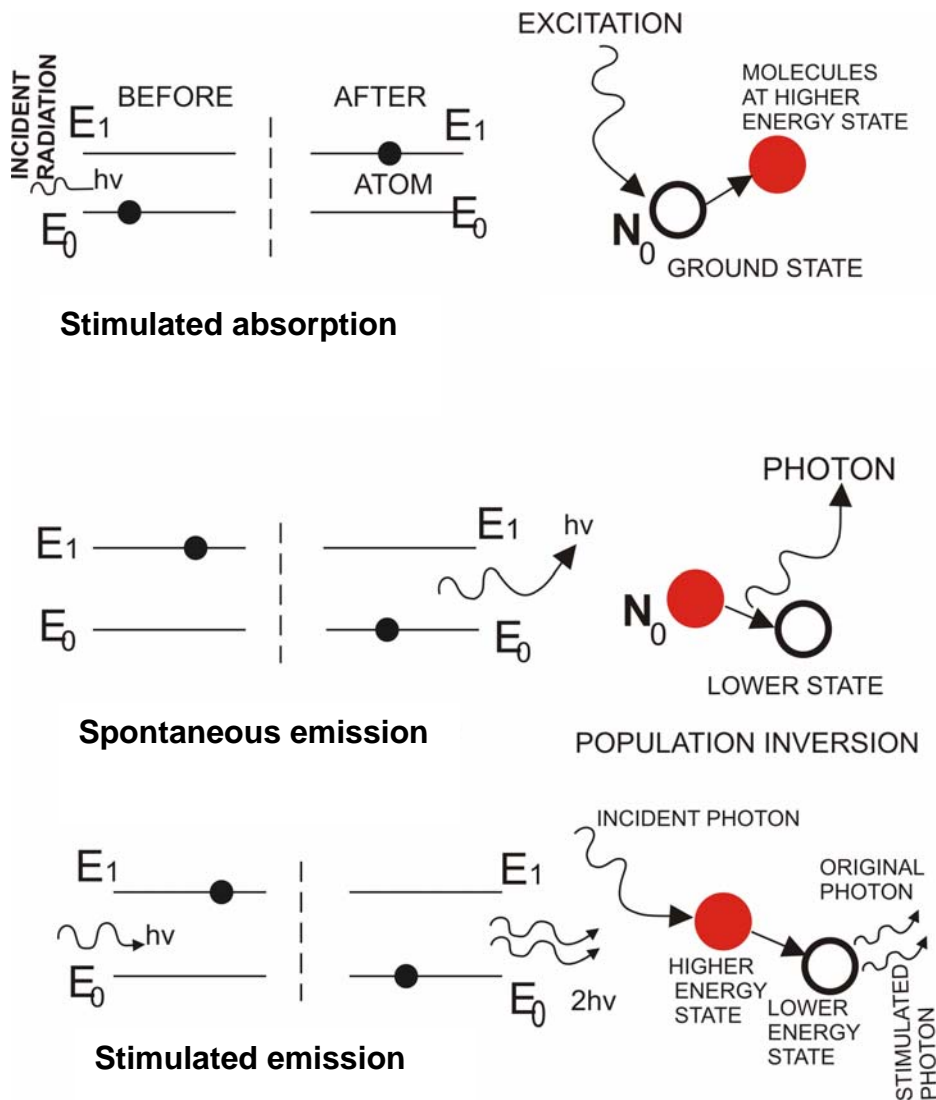
Fig. 9.6.8 *Spontaneous and stimulated emissions*

at higher energy meta-stable state, can return to the ground state in the form of an avalanche provided stimulated by a photon of suitable frequency or energy. This is called stimulated emission. Fig. 9.6.8 shows one such higher state electron in meta-stable orbit. If it is stimulated by a photon of suitable energy then the electron will come down to the lower energy state and in turn one original photon, another emitted photon by stimulation having some temporal and spatial phase would be available. In this way coherent laser beam can be produced.

Fig. 9.6.9 schematically shows working of a laser. There is a gas in a cylindrical glass vessel. This gas is called the lasing medium. One end of the glass is blocked with a 100% reflective mirror and the other end is having a partially reflective mirror. Population inversion can be carried out by exciting the gas atoms or molecules by pumping it with flash lamps. Then stimulated emission would initiate lasing action. Stimulated emission of photons could be in all directions. Most of the stimulated photons, not along the longitudinal direction would be lost and generate waste heat. The photons in the

longitudinal direction would form coherent, highly directional, intense laser beam.
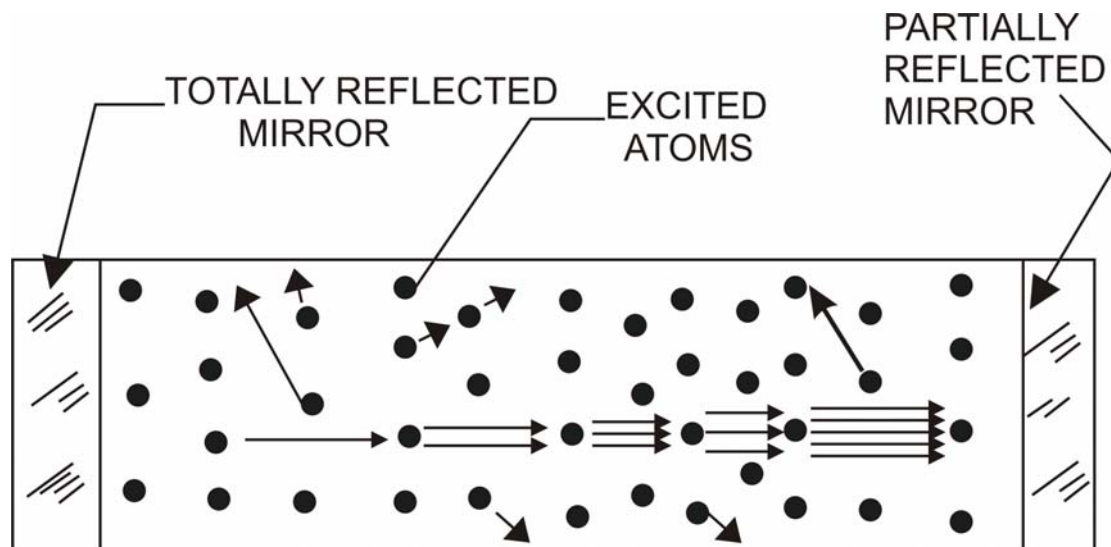
Fig. 9.6.9   *Lasing action*

9.   Lasing Medium

Many materials can be used as the heart of the laser. Depending on the lasing medium lasers are classified as solid state and gas laser. Solid-state lasers are commonly of the following type

- Ruby which is a chromium – alumina alloy having a wavelength of 0.7 μm
- Nd-glass lasers having a wavelength of 1.64 μm
- Nd-YAG laser having a wavelength of 1.06 μm

These solid-state lasers are generally used in material processing.

The generally used gas lasers are
- Helium – Neon
- Argon
- CO_2 etc.

Lasers can be operated in continuous mode or pulsed mode. Typically CO_2 gas laser is operated in continuous mode and Nd – YAG laser is operated in pulsed mode.

10.   Laser Construction

Fig. 9.6.10 shows a typical Nd-YAG laser. Nd-YAG laser is pumped using flash tube. Flash tubes can be helical, as shown in Fig. 9.6.10, or they can be flat. Typically the lasing material is at the focal plane of the flash tube. Though helical flash tubes provide better pumping, they are difficult to maintain.
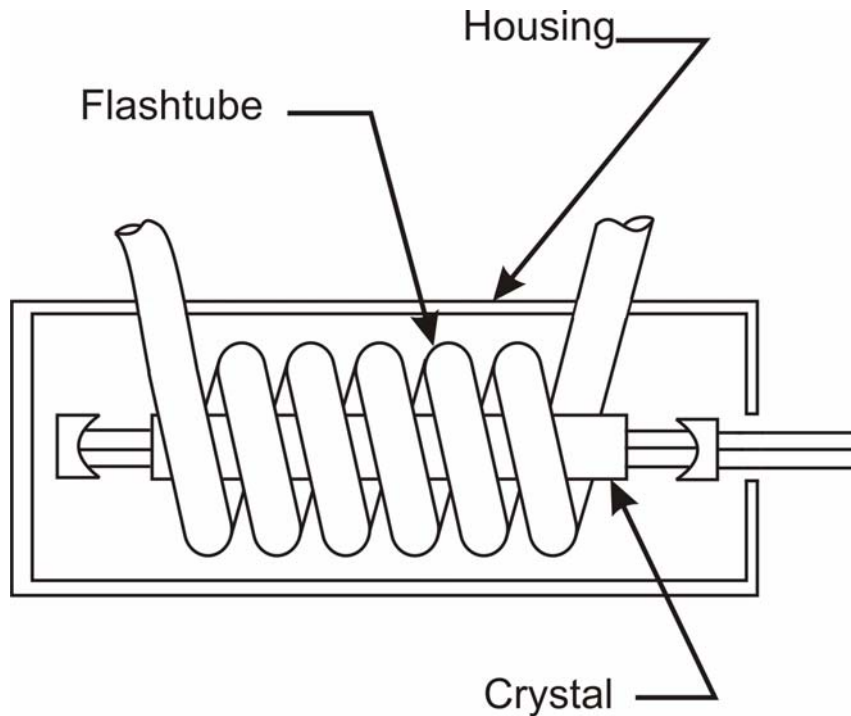
Fig. 9.6.10   Solid-state laser with its optical pumping unit

Fig. 9.6.11 shows the electrical circuit for operation of a solid-state laser. The flash tube is operated in pulsed mode by charging and discharging of the capacitor. Thus the pulse on time is decided by the resistance on the flash tube side and pulse off time is decided by the charging resistance. There is also a high voltage switching supply for initiation of pulses.
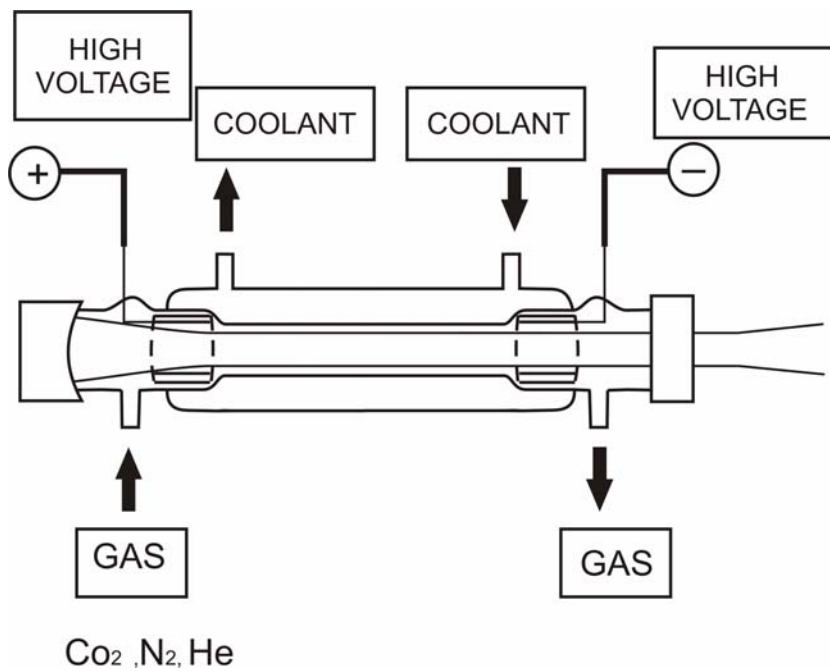
Fig. 9.6.12 shows a CO_2 laser. Gas lasers can be axial flow, as shown in Fig. 9.6.12, transverse flow and folded axial flow as shown in Fig. 9.6.13. The power of a CO_2 laser is typically around 100 Watt per metre of tube length. Thus to make a high power laser, a rather long tube is required which is quite inconvenient. For optimal use of floor space, high-powered CO_2 lasers are made of folded design.

In a CO_2 laser, a mixture of CO_2, N_2 and He continuously circulate through the gas tube. Such continuous recirculation of gas is done to minimize

25 KV

Switching electrode

Flash tubes

Capacitor

5 KV

Ruby rod
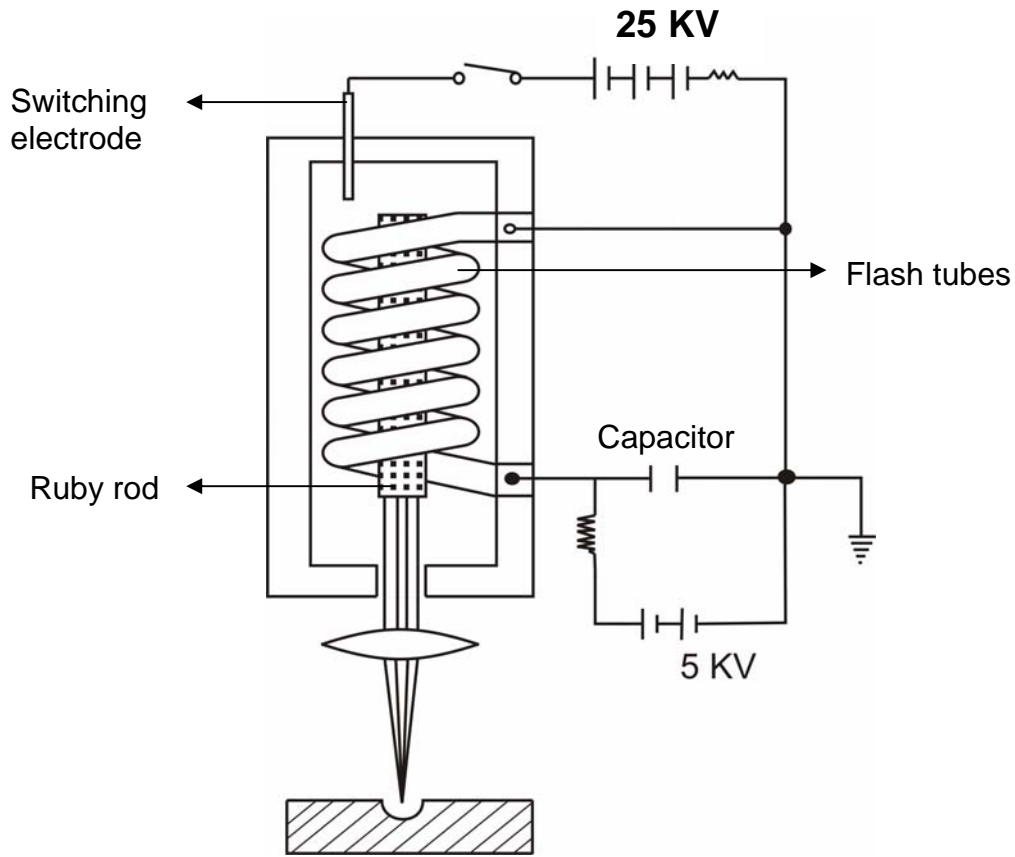
Fig. 9.6.11 *Working of a solid-state laser*

HIGH VOLTAGE

COOLANT

COOLANT

HIGH VOLTAGE

+

−

GAS

GAS

Co_2 ,N_2, He

Fig. 9.6.12 *Construction of a CO_2 laser*

consumption of gases. CO_2 acts as the main lasing medium whereas Nitrogen helps in sustaining the gas plasma. Helium on the other hand helps in cooling the gases.

As shown in Fig. 9.6.12 high voltage is applied at the two ends leading to discharge and formation of gas plasma. Energy of this discharge leads to population inversion and lasing action. At the two ends of the laser we have one 100% reflector and one partial reflector. The 100% reflector redirects the photons inside the gas tube and partial reflector allows a part of the laser beam to be issued so that the same can be used for material processing. Typically the laser tube is cooled externally as well.

As had been indicated earlier CO_2 lasers are folded to achieve high power. Fig. 9.6.13 shows a similar folded axial flow laser. In folded laser there would be a few 100% reflective turning mirrors for manoeuvring the laser beam from gas supply as well as high voltage supply as shown in Fig. 9.6.13.
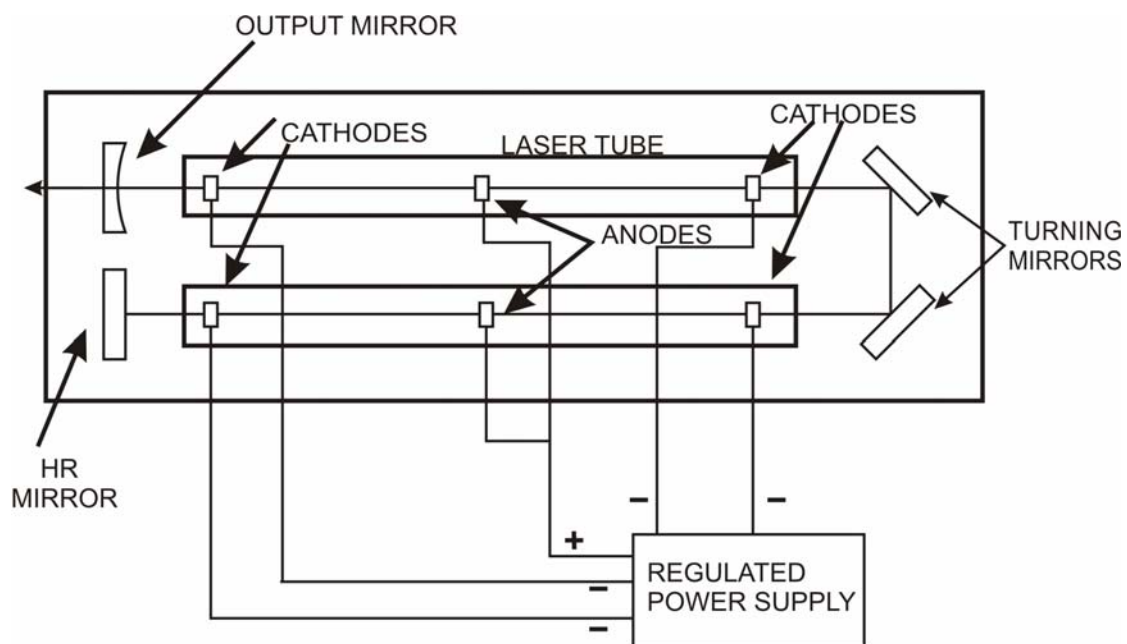
Fig. 9.6.13 *Construction of folded gas laser*

Table 9.6.1 shows the capability and characteristics of common lasers.

Table 9.6.1   Process characteristics of different lasers

Application	Type of laser
Large holes upto 1.5 mm dia.	Ruby, Nd-glass, Nd-YAG
Large holes (trepanned)	Nd-YAG, CO_2
Small holes > 0.25 mm dia.	Ruby, Nd-glass, Nd-YAG
Drilling (punching or percussion)	Nd-YAG, Ruby
Thick cutting	CO_2 with gas assist
Thin slitting of metals	Nd-YAG
Thin slitting of plastics	CO_2
Plastics	CO_2
Metals	Nd-YAG, ruby, Nd-glass
Organics, Non-metal	Pulsed CO_2
Ceramics	Pulsed CO_2, Nd-YAG

Lasing materials	Ruby	Nd-YAG	Nd-glass	CO_2
Type	Solid state	Solid state	Solid state	Gas
Composition	0.03 – 0.7% Nd in Al_3O_2	1% Nd doped Yttrium – Aluminium-Garnet	2-6% Nd in glass	CO_2+He+N_2 (3:8:4)
Wavelength (radiation)	0.69 μm	1.064 μm	1.064 μm	10.6 μm
Efficiency	1% max.	2%	2%	10-15%
Beam mode	Pulsed or CW	Pulsed or CW	Pulsed	Pulsed or CW
Spot size	0.015 mm	0.015 mm	0.025 mm	0.075 mm
Pulse repetition rate (normal operation).	1-10 pps	1-300 pps or CW	1-3 pps	CW
Beam output	10-100 W	10-1000 W	10 – 100 W	0.1 – 10 kW
Peak power	200 kW	400 kW	200 kW	100 kW

11.   Laser Beam Machining – Application

Laser can be used in wide range of manufacturing applications

- Material removal – drilling, cutting and tre-panning
- Welding
- Cladding
- Alloying

Drilling micro-sized holes using laser in difficult – to – machine materials is the most dominant application in industry. In laser drilling the laser beam is focused over the desired spot size. For thin sheets pulse laser can be used. For thicker ones continuous laser may be used.

12.   Laser Beam Machining – Advantages

- In laser machining there is no physical tool. Thus no machining force or wear of the tool takes place.
- Large aspect ratio in laser drilling can be achieved along with acceptable accuracy or dimension, form or location
- Micro-holes can be drilled in difficult – to – machine materials
- Though laser processing is a thermal processing but heat affected zone specially in pulse laser processing is not very significant due to shorter pulse duration.

13.   Laser Beam Machining – Limitations

- High initial capital cost
- High maintenance cost
- Not very efficient process
- Presence of Heat Affected Zone – specially in gas assist CO_2 laser cutting
- Thermal process – not suitable for heat sensitive materials like aluminium glass fibre laminate as shown in Fig.9.6.14
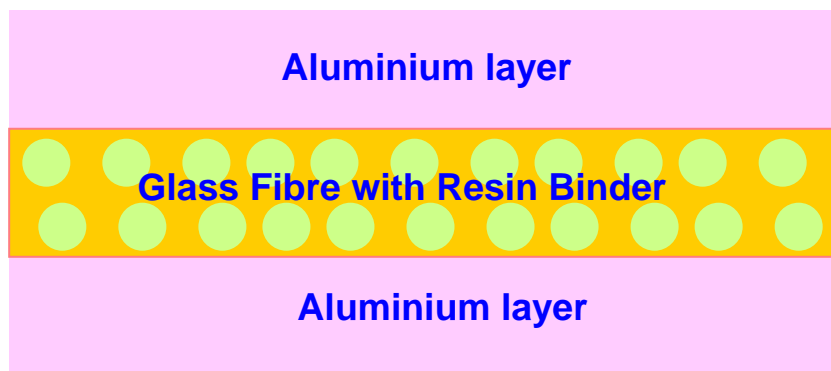
Fig. 9.6.14 Aluminium Glass Fibre Laminate – heat sensitive glass fibre layer due to presence of resin as binder

Quiz Questions

1. Mechanism of material removal in Electron Beam Machining is due to

   a) Mechanical erosion due to impact of high of energy electrons
   b) Chemical etching by the high energy electron
   c) Sputtering due to high energy electrons
   d) Melting and vaporisation due to thermal effect of impingement of high energy electron

   Answer – (d)

2. Mechanism of material removal in Laser Beam Machining is due to

   a) Mechanical erosion due to impact of high of energy photons
   b) Electro-chemical etching
   c) Melting and vaporisation due to thermal effect of impingement of high energy laser beam
   d) Fatigue failure

   Answer – (c)

3. Generally Electron Beam Gun is operated at

   a) Atmospheric pressure
   b) At 1.2 bar pressure above atmosphere
   c) At 10 – 100 mTorr pressure
   d) At 0.01 – 0.001 mTorr pressure

   Answer – (d)

4. Laser Beam is produced due to

   a) Spontaneous emission
   b) Stimulated emission followed by spontaneous emission
   c) Spontaneous emission followed by Spontaneous absorption
   d) Spontaneous absorption leading to "population inversion" and followed by stimulated emission

   Answer – (d)