CHAPTER 1

INTRODUCTION

1.1 Laser Beam- An Introduction
Planck has given the concept of quanta or packets in 1900 and in 1920 it was well accepted that apart from wavelike characteristics of light it also shows particle nature while interacting with matters and energy transferred to each other in the form of photons [Chryssolouris (1991)]. In the present scenario, photons have replaced the electrons and it is a very important concept in modern science. In this context, lasers turn out to be the most useful source of photons for various industrial applications.

Lasers were discovered nearly sixty years ago. The fundamental concepts of lasers came into existence when Einstein proposed possibility of stimulated emission of photons apart from usual spontaneous emission [Majumdar et al. (2003)]. The first functional ruby laser was developed by Townes and Schawlow in 1957 [Chryssolouris (1991)]. Lasers are regarded as one of the most outstanding inventions of the present century. They are one of the most versatile forms of the energy ever known.

The light emitted by the lasers differs from all other natural and manmade light sources and is able to process almost all categories of materials due to its properties of monochromaticity, coherence, low diffraction (divergence) and high radiance [Jain (2005)]. High monochromaticity implies that the range of frequencies emitted by light source is small, i.e. its wavelength occupies a very narrow portion of spectrum. The net result is that a simple lens may be used to focus and concentrate the laser beam to much smaller diameter and hence much power density than other light. Coherence means that the laser light travels in the same phase with respect to time and space. There are two types of coherence: spatial and temporal. Spatial coherence refers to the correlation of phases at different points in space at single moment of time. Temporal coherence refers to the correlation of phases at a single point in space over the period of time [Benedict (1987)]. The bending phenomenon of light along a sharp edge corner is known as
diffraction. The laser produces a beam with very low diffraction, i.e. collimated beam. Therefore, a laser beam can be focused over a distance with a very low divergence of beam or loss in beam intensity. This property of light produces a directional energy source which can focus a large amount of energy over a very small area. The radiance of a light source is the amount of power emitted per unit area for a given solid angle of that light source. Laser lights have a very high power output per unit area, i.e. laser light source process extremely high radiance. The radiance of laser beams cannot be changed by the optical manipulation but it depends upon the design of laser cavity.

Laser light differs from ordinary light in the sense that it consists of photons of same frequency, wavelength and phase. Thus, unlike ordinary light, laser beams are highly directional, high power density and better focusing characteristics as shown in Figure 1.1 [Chryssoulouris (1991)]. The term LASER is as an acronym for ‘Light Amplification by Stimulated Emission of Radiation’. For laser beam generation, stimulated emission and population inversion are required. Emission is the process of the movement of atoms/molecules from higher energy to lower energy level by emitting photons while absorption is a process through which the atoms/molecules of lasing material move from lower energy level to higher energy level.

![Figure 1.1](image1.png)

**Figure 1.1:** Normal light Vs Laser light

The emission process may be classified into two categories: first, spontaneous emission and second, stimulated emission. Stimulated emission is the triggering of the photons having same characteristics such as wavelength, phase, direction and energy to the photon coming in contact with the atoms/molecules at higher energy states [Steen (1991)]. To produce a working laser, the pumping source should be so power full that most of the atoms of lasing medium are at higher energy level. This is known as population inversion. When a photon comes in contact with the atoms at higher energy state, this photon stimulates the atoms/molecules to emit a clone photon. This type of chain event produces
many photons having the same characteristics. These stimulated photons are directed and amplified in the lasing cavity with the help of optical resonators. Finally, the laser beam comes out to the partially reflective mirror which is focused at a particular spot with the help of beam delivery system.

There are different types of lasers available in the market such as Nd:YAG, Nd:Glass, Ruby, He – Ne (Helium - neon), CO₂, CO and excimer lasers. The lasers are classified based on the lasing medium such as solid, liquid and gas. All the types of lasers may be operated in both continuous and pulsed mode. In the continuous mode, the laser beam is emitted without any interruption while in pulsed mode, it is periodic. Based on the composition of lasing medium (neutral atoms, ions and molecules), the gas lasers are further divided into three subgroups. The He – Ne (Helium - neon) laser is based on neutral atoms lasing medium and is most popular visible light laser with the wavelength of 0.6328µm. The actual lasing occurs during an electron transition in the Ne atom, but the presence of He is essential since it is excited first by an electrical discharge, and then its energy is transferred to the Ne atoms. Ion gas lasers, the second type of gas lasers, use ionized gas such as argon (Ar), krypton (Kr), and xenon (Xe) as a lasing medium to produce the laser beam of wavelength ranging from 0.5 to 1.0 µm. In molecular lasers, the third type of gas lasers, the gas molecules are used as lasing medium where these molecules are excited by some external means and vibrational mode of molecules may be changed due to excitation which produces photons. Carbon dioxide (CO₂) lasers and carbon monoxide (CO) lasers are most common examples of these types of lasers which are commonly used for laser processing of materials [Steen (1991)].

In the CO₂ laser, the lasing medium is a combination of CO₂, nitrogen (N₂) and He gases. The actual pumping is achieved by an electrical discharge by which N₂ atoms get excited and absorb most of the energy. Most of the CO₂ molecules are excited by collision with N₂ molecule and only some CO₂ molecules are excited by direct electrical discharge. For CO₂ molecules, the rate of energy release through heat is much lower than energy release through light, so the energy efficiency for producing the laser beam is higher as compared to the other lasing materials [Steen (1991)]. The energy efficiency obtained for most of the industrial applications by CO₂ laser is about 10-15%. CO₂ lasers are widely used for the laser processing of materials such as machining, welding and surface treatments.
In the recent years, the applications of excimer lasers for the laser processing of materials have been increased. Majority of eximer lasers use an excited complex of a noble gas and halogen atom as the actual lasing medium. Typical excimer complexes are argon fluoride (ArF), krypton fluoride (KrF), xenon fluoride (XeF) and xenon chloride (XeCl). The output wavelength of excimer lasers vary from 0.193 to 0.351 µm in the ultraviolet to near ultraviolet spectra. Excimer lasers produce high powered, pulsed beam with average power 100W and pulse frequency of 1000 Hz. Excimer lasers are used to machine solid polymer, micromachining of ceramics and semiconductors, and mark thermally sensitive materials. The mechanism of material removal process differs from the CO₂ and Nd:YAG lasers. The excimer laser removes the material through ablation by breaking the chemical bonds of the material until it dissociates into its chemical components [Chryssoulouris (1991)].

Solid lasers use ions suspended in the crystalline matrix as lasing medium. The two main dopants used in the lasing medium are chromium ion (Cr³⁺) for Ruby laser and neodymium ion (Nd³⁺) for Nd:YAG & Nd:Glass lasers. There are limited applications of Ruby lasers because it gives low energy efficiency and low beam power. Among the solid state lasers, Nd:YAG laser is most commonly used for laser processing of materials in different industries. In this laser, excitation is achieved with a Xe or Kr lamp and the wavelength of the laser beam obtained is 1.06 µm in the infrared region of the spectrum. Nd:YAG lasers have low beam power but when operating in pulsed mode, high peak powers enable it to machine even thicker materials. Also, shorter pulse duration suits for machining of thinner materials. Due to shorter wavelength, Nd:YAG laser can be absorbed by highly reflective materials which are difficult to machine by CO₂ lasers. The Kr flash lamps are useful for the optical pumping of continuous mode operation due to its low operating current and high energy efficiency. The Xe flash lamps are used for pulsed mode operation due to better spectral coupling with the energy states of Nd ions. This provides higher current density as required for pulsed mode operation [Steen (1991)].

The Nd:YAG laser system produces a waste heat which is thirty times the laser output. This waste heat is removed by flowing de-ionized water within the elliptical cavity holding the YAG rod and flash lamp. Due to the use of Kr flash lamp, the operating efficiency is low about 2% because pumping is done with a broad band illumination of which only small proportions is absorbed by the Nd ions. This means that a considerable energy has to be pumped into the crystal rod giving a serious cooling problem. The
operating efficiency of YAG lasers may be increased about 8-10% by providing effective pumping system such as diode pumping. A further advantage of diode pumping is that the lifetime of the diodes which is about ten times longer than the lamps (1000 hours for lamps compared to 10,000 hours for the diode) [Chryssolouris (1991)]. The important characteristics of different lasers are shown in the Table 1.1 [Chryssolouris (1991), Mishra (2005)].

### 1.1.1 Mechanisms of Laser Beam Generation

There are three basic concepts of lasers: absorption, spontaneous, and stimulated emission. In absorption, the energy is absorbed by an atom; the electrons are excited into vacant energy shells. The atom decays from energy level 2 to energy level 1 through the emission of a photon with the energy $h\nu$. It is a completely random process in the spontaneous emission and atoms in an upper energy level can be triggered or stimulated in phase by an incoming photon of a specific energy. Lasers convert electrical energy into a high energy density of light through stimulation and amplification. Stimulation occurs when electrons in the lasing medium are excited by an external source such as an

<table>
<thead>
<tr>
<th>Operating Parameters</th>
<th>Ruby Laser</th>
<th>Nd:YAG Laser</th>
<th>Nd:Glass Laser</th>
<th>CO₂ Laser</th>
<th>Excimer Laser (KrF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength</td>
<td>0.69 µm</td>
<td>1.064 µm</td>
<td>1.064 µm</td>
<td>10.6 µm</td>
<td>0.248 µm</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>30 %</td>
<td>40 %</td>
<td>40 %</td>
<td>45 %</td>
<td>80 %</td>
</tr>
<tr>
<td>Operating Efficiency</td>
<td>1 %</td>
<td>4 %</td>
<td>2 %</td>
<td>12 %</td>
<td>0.5 – 2%</td>
</tr>
<tr>
<td>Composition ArF, XeF</td>
<td>0.03-0.07 %</td>
<td>1 %</td>
<td>2 – 6 Nd</td>
<td>CO₂+He+N₂</td>
<td>KrF</td>
</tr>
<tr>
<td>Beam Mode</td>
<td>Nd in Al₂O₃ Pulsed/CW</td>
<td>In YAG Pulsed/CW</td>
<td>In Glass Pulsed</td>
<td>(3:8:3) Pulsed/CW</td>
<td>Pulsed</td>
</tr>
<tr>
<td>Spot Size</td>
<td>0.015 mm</td>
<td>0.015 mm</td>
<td>0.025 mm</td>
<td>0.075 mm</td>
<td>0.020 mm</td>
</tr>
<tr>
<td>Pulse Frequency</td>
<td>1 – 10 Hz</td>
<td>1 – 300 Hz</td>
<td>1 – 3 Hz</td>
<td>1 – 500 Hz</td>
<td>1000–10000 Hz</td>
</tr>
<tr>
<td>Beam Output</td>
<td>10 - 100 W</td>
<td>10-1000 W</td>
<td>10–100 W</td>
<td>0.1–10 kW</td>
<td>10 – 100 W</td>
</tr>
<tr>
<td>Peak Power</td>
<td>200 kW</td>
<td>400 kW</td>
<td>200 kW</td>
<td>100 kW</td>
<td>30-50 MW</td>
</tr>
<tr>
<td>Beam Divergence</td>
<td>5-7 mRad</td>
<td>1-5 mRad</td>
<td>5-7 mRad</td>
<td>0.1-10 mRad</td>
<td>Not found</td>
</tr>
</tbody>
</table>
electrical arc or a flash lamp, resulting in the emission of photons see Figures 1.2 and 1.3. The energy required to raise an electron from one energy state to another is provided by an excitation process, or pumping. The lasing medium typically contains ions, atoms, or molecules whose electrons are conductive to changes in energy level.

The amplification of light in a laser is accomplished by an optical resonator, which is composed of a cavity with the lasing medium set between two high-precision, aligned mirrors [Chryssoulakis (1991)].

**Figure 1.2:** Basic concepts of lasers (a) Absorption (b) Spontaneous emission (c) Stimulated emission

**Figure 1.3:** Basic mechanisms in the lasing action
1.1.2 Laser Beam Generation Unit

There are some common components for all types of lasers like active medium, excitation mechanism, high reflectance mirror and partially transmissive mirror. The active medium may be solid crystals such as ruby or Nd:YAG, liquid dyes, gases like CO₂ or Helium/Neon, or semiconductors such as GaAs. Active mediums contain atoms whose electrons may be excited to a metastable energy level by an energy source. In the excitation mechanisms, the energy is pumped into the active medium by one or more of the three basic methods; optical, electrical or chemical. In the optical resonator one mirror is fully reflective (100%) and other is partially transmissive (95%) to allow for the beam output. Two parallel mirrors are placed around the gain medium. Light is reflected by the mirrors back into the medium and is amplified. The design and alignment of the mirrors with respect to the medium is crucial. Spinning mirrors, modulators, filters and absorbers may be added to produce a variety of effects on the laser output as shown in Figure 1.4.

![Diagram showing the components of a laser beam generation unit]

**Figure 1.4**: Different components of beam generation unit

1.1.3 Characteristics of Laser Beam

Laser beam has certain unique characteristics, namely monochromaticity, diffraction, coherence and radiation. High monochromaticity implies that the laser concentrates in a narrow range of wavelengths (around one specific colour). Most important applications of monochromaticity are interferometry, holography, velocimetry, isotope, separation, and communications in which the laser beam frequency content has great importance. In a coherent beam, all the emitted photons maintain a constant phase relationship with each other in both time and phase.
The diffraction phenomenon is described as the slight bending of light as it passes around the sharp edges of an object. Diffraction means that the beam is well collimated and travels over long distances with very little spread. The range of beam divergence ranges from 0.2 milliradians for He-Ne lasers to ten milliradians for Nd:YAG lasers. Due to this property, the laser light generates a beam direction energy source which may focus a large amount of lambent energy on a small area. The radiance is measured by the amount of power per unit area emitted by the light source for a given solid angle from a surface. Total emission or reflection is the radiance characteristic. The sources of laser lights have very high radiance.

For the laser beam machining, high monochromaticity, high coherence, or low diffraction are not desired individually. The combinations of these properties make the laser beam a powerful tool for machining.

1.1.4 Gas, Liquid and Solid Laser Types
According to the state of lasing medium, lasers may be divided into three basic categories: gas, liquid and solid lasers [Dubey and Yadava (2008a), Koechner (2002) and Meijer (2004)]. All the three types of laser can operate one or two modes: continuous wave (CW) and pulsed modes. In continuous mode, the laser beam is emitted without interruption from the surface, whereas, the laser beam is emitted periodically in pulsed mode.

**Gas Lasers**
On the basis of composition of the lasing medium it may be divided into three subcategories: neutral atom, ion or molecular [Koechner (2002)]. The helium-neon (He-Ne) laser is a typical neutral atom laser and it the most popular visible light laser. For example: Neutral atom, Molecular laser (CO₂, CO, HF) and Excimer (Kr-F, Ar-F, Xe-Cl).

**Liquid Lasers**
Liquid lasers are primarily dye lasers which use an organic dye as the lasing medium. It has much wider wavelength compared with gases and solid state lasing media. The wide bandwidth makes this liquid laser particularly suitable for the tunable lasers and pulsed lasers. Continuous operation is difficult to get because population inversion is difficult to maintain; therefore, a pulsed mode operation with an average power upto 10 mW is generally used, e.g. inorganic liquid lasers, organic liquid lasers.
Solid Lasers

Solid laser is a laser that uses a solid gain medium. In this laser ions suspended in a crystalline matrix are used to generate laser light as shown in Figure 1.5. The ions or dopants allow the electrons for excitation, while the crystalline matrix dissipates the energy between ions. The two main classes of dopants in the laser medium are chromium (Cr$^{3+}$) for ruby lasers and Neodymium (Nd$^{3+}$) for Nd:Y$_3$Al$_5$O$_{12}$ (neodymium-doped yttrium aluminium garnet) and Nd : glass lasers [Chryssoulouris (1991)].

![Solid laser medium](image)

**Figure 1.5:** Excitation process in a solid-state laser

1.1.5 Laser Applications in Various Fields

Laser has applications in various fields such as science, military, medical and industry for commercial use. Its scientific applications are spectroscopy, lunar laser ranging, photochemistry, laser cooling, nuclear fusion, etc. Its military applications are death ray, laser sight, illuminator, rangefinder, target designator, etc. In medical field, it has applications in eye surgery and cosmetic surgery. In industry it is used for cutting, welding, marking, CD player, DVD player, laser printers, laser pointers, photolithography and laser light display etc. In manufacturing industries, laser is used to measure the ball cylindricity in bearings by observing the dispersion of a laser beam when reflected on the ball. Yet another example is to measure the shadow of a steel band with the help of a laser light to find out the thickness of the band. In pulp industry, the concentration of dye is measured by observing how the laser beam refracts in it. Laser also works as a spirit level and can be used to indicate a flat surface by just sweeping the laser beam along the surface. This is used while making walls at building sites. In the mining industry, laser is used to point out the drilling direction. Laser technologies have also been used in environmental areas, e.g. the ability to determine from a distance the environmental toxins in a column of smoke. Another example is to predict and measure the existence of
photochemical smog and ozone, both at ground level where it is not required and in the upper layers of the atmosphere where it is needed. Laser is also used to supervise wastewater purification [Koechner (2002)].

1.2 Laser Beam Machining

Laser beam machining (LBM) is one of the most widely used thermal energy based, non-contact type, advanced machining process. Here the material is removed by a focused laser beam at a particular spot. Depending upon the prevailing conditions, the material is removed by different mechanisms such as vaporization, fusion, reactive fusion, ablation and controlled fracture. The molten material is removed with the help of high pressure coaxial assist gas jet. The effectiveness of this process depends on thermal and optical properties of the material to be machined rather than the mechanical properties [Steen (1991)]. Therefore, the materials which exhibit a high degree of brittleness, hardness and favorable thermal properties such as low thermal diffusivity and conductivity, are well suited for laser beam machining. LBM can be used for different purposes such as drilling (1D), cutting (2D) and turning or milling (3D) [Steen (1991)].

1.2.1 Classification of Laser Beam Machining

Figure 1.6: Classification of Laser beam machining

Laser drilling is one dimensional LBM process in which the laser beam remains stationary relative to the workpiece. It is used for generating thousands of closely spaced holes in the turbine blades and combustion chambers. The erosion front is located at the bottom of the drilled hole and propagates in the direction of light source in order to remove the material. This is sometimes also known as percussion drilling. In this process, a sequence of pulses is used to drill a hole and the molten material is solidifies again.
between successive pulses. Some part of the energy is used for re-melting of this material. During the percussion drilling process, plasma formation may occur when material is vaporized. The direction of the plasma is difficult to control which results into problem of dimensional inaccuracies. The percussion drilling process is shown in Figure 1.7. Laser drilling in has several advantages like high production rate, applicable to both conductive and non-conductive materials, no mechanical damage, e.g. tool wear as it is a non-contact processing, improved product quality, low material wastage, low production cost, small heat-affected zone (HAZ), and ecologically clean technology [Panda et al. (2011)].

However, laser drilling holes are inherently associated with a number of defects such as circularity of holes, spatter thickness, recast layer formation and hole taper [Choudhury et al. (2012)]. The percussion drilling is used to drill the small holes of diameters in the range 0.125mm - 1.2mm with the depth to diameter ratio, 100:1. The holes greater than 1.2 mm diameter, cannot be drilled by percussion drilling due to low power density of focused laser beam.

![Figure 1.7: Laser percussion drilling](image)

Hence larger size holes are trepanned (cut) along the periphery of the hole. This process is known as trepan drilling and is shown in the Figure 1.8. In this process the laser beam is focused on the workpiece and the molten material is removed with the help of coaxial gas jet. The CNC table provides the required profile movement while laser beam remains stationary. Laser trepan drilling is also commonly used to generate holes in the difficult to
cut materials such as super alloys, titanium alloys, etc., with little defects as compared to the percussion drilling [Chien et al. (2007)].

Figure 1.8: Laser trepan drilling

Laser cutting is two dimensional, thermal energy based advanced machining process in which laser beam is focused at a particular spot and material gets melted. The molten material is removed from the molten pool with the help of a high pressure co-axial assist gas jet as shown in Figure 1.9. The most commonly used assist gas is oxygen (O₂) which gives highest cutting speed due to its exothermic nature. But it also leaves oxides on the cut edge and creates a largest heat affected zones (HAZ) as compared to other assist gases [Benedict (1987)].

The air is the least expensive gas and gives smaller HAZ as well as cutting speed as compared to O₂. Sometimes inert gases such as helium (He), argon (Ar), etc., are used as assist gases in the laser cutting. These gases give better surface qualities (smaller HAZ, better cutting edge surfaces, less recast layer thickness, less oxide layer thickness) but the cutting speed is also decreased. Laser cutting applications are blanking, cutting, marking, creating complex shapes and intricate profiles in different category of materials such as metals, super alloys, ceramics and composites [Benedict (1987)].

In order to make laser cutting process more applicable for bulk material removal processes, two or more laser beams can be used for removing the materials. Such types of processes are classified as three dimensional machining processes such as laser turning, laser milling and laser grooving. Unlike laser cutting techniques, each beam creates a
blind groove and material is removed when the two grooves intersects to each other [Chryssoulouris (1991)].

In the laser turning process, the material is removed either by helix removal or by ring removal as shown in Figure 1.10. The ring removal method uses two perpendicular laser beams, whereas in helix removal process; two inclined laser beams are used. In laser milling, two laser beams are positioned at an oblique angle from the workpiece surface to create converging grooves in the workpiece. The material volume removed is prismatic with rectangular cross section as shown in Figure 1.11. In laser grooving process, the laser beam is moved over the workpiece surface and co-axial or off axial gas jet is used to remove the molten material from the kerf as shown in Figure 1.12. Unlike laser cutting, the laser beam does not penetrate through the workpiece surface in laser grooving. Laser grooving is used in various manufacturing applications, such as the creation of micro channels for cooling systems and the creation of slots for assembly, while in the form of laser scribing it is used for marking part identity [Stournaras et al. (2009b)]. Laser scribing is a process for making a groove or line or line of holes either fully penetrating, or not, but sufficient to weaken the structure so that it can be mechanically broken. Laser scribing has wide applications in photo voltaic applications, semiconductor devices scribing, edge dislocations, ID marking, defect and shunt repairing and back-contact deposition [Li et al. (2009a)].

Laser scribing also relieves the stresses that are induced in the material during manufacturing. The scribe lines increase the surface resistivity of the material, resulting in reduced eddy current loss. Laser scribing of polycrystalline thin films used for solar cells can eliminate the frequently observed problem of ridge formation along the edges of scribe lines in the semiconductor films [Majumdar et al. (2003)].

Laser beam machining also has wide applications in micromachining with short and ultra short pulses. For micromachining, pulsed Nd:YAG, fiber and excimer lasers are most commonly used. Compared with the traditional laser, fiber laser has several advantages, such as single-mode output, high power stability, high wall-plug efficiency and compact rugged packet [Meng et al. (2009)].

Micromachining of materials (having overall size upto 1 mm) with laser beam requires a micrometer size spot and a very short interaction time. Q- switched Nd : YAG lasers with nano second and pico second pulses are better for this purpose. Nd : YAG lasers with
double and triple frequency have been applied in micromachining of different metals, non-metals and composites.

Applications of nano-machining are in the field of nano-technology, three-dimensional (3D) nano-scale devices, materials and structures. Nano-scale devices include quantum-wire, metal-semiconductor-metal photo detectors, quantum-dot, ring transistors, surface plasma mirrors, nano dot arrays, optical switches, nano-wire cross-bar structures,

organic light-emitting materials and devices, polymer gratings, integrated circuit devices, super-high-density information storage devices and photonic crystals [Ali et al. (2008)]. Laser micro machining is frequently used for the machining of different types of glasses
which are used for medical components and devices by a various industries, including telecommunication, medicine, entertainment, instrumentation, optical data memory/storage, and remote sensing and imaging [Tsenga et al. (2007)].

Laser micromachining has wide applications in the medical field for machining of implantable parts such as expendable rib cages, finger and toe replacements, spinal fusion cages, dental implants and cardiovascular stent. A typical shape of cardiovascular stent cut by laser micro machining is shown in Figure 1.13.

In a laser based hybrid machining process, two or more machining processes are combined. These processes are used for harnessing the advantages of individual processes and removing some of the disadvantages. The performances of these processes have been found better than the individual processes for same parameters settings [Dubey and Yadava (2008b)]. Most of the hybrid processes have been developed by combining the
conventional or unconventional machining processes with the LBM. Laser hybrid machining process are becoming very popular in the industries due to better performance characteristics and have been found superior to single non-conventional machining process in various applications. The different hybrid machining processes developed with LBM are shown in Figure 1.14.

![Diagram showing hybrid machining processes](image)

**Figure 1.14:** Laser and non-laser hybrid (a) conventional and (b) unconventional machining processes. LAT-laser-assisted turning; LAS- laser-assisted shaping; LAG-laser-assisted grinding; LA EDM-laser-assisted EDM; LA ECM- laser-assisted ECM; UA LBM-ultrasonic-assisted LBM; LAE-laser-assisted etching [Dubey and Yadava (2008b)]

### 1.2.2 Mechanism of Metal Removal in Laser Cutting

There are different mechanisms of metal removal in laser cutting such as vaporization, melt shearing (fusion), chemical degradation, controlled fracture, scribing and laser assisted oxygen (Lasox) [Steen (1991)]. In vaporization cutting, the laser beam is focused on the workpiece material which heats the materials up to the boiling point and vaporization of the material starts resulting in the generation of a keyhole. After that, the absorptivity of the laser beam increases suddenly due to increase in temperature of cutting zone and multiple reflections of laser beam in the key hole which finally deepens the keyhole or kerf. As the kerf deepens, more vapor formation takes place and the vaporized material is ejected out of the kerf stabilizing the molten walls of the kerf. Vaporization cutting is used for the cutting of those materials which do not melt and have low melting point such as wood, carbon and some plastics (acrylic and polyacetal).

The materials such as most of metals and thermoplastics having high melting and boiling points may not be cut by vaporization cutting as the cutting of these materials requires
very high heat for heating up to the boiling point. For the cutting of these materials, fusion cutting method is most commonly used. In fusion cutting, the laser beam is focused on the workpiece which heats the materials up to the melting point. The molten material is blown away from the melting pool with the help of high pressure, coaxial assist gas jet as shown in Figure 1.15. This method requires only around one tenth of heat as compared to the vaporization cutting [Steen (1991)]. The fusion cutting is divided into two categories depending upon the type of assist gas used, one that uses inert assist gas and the other that uses reactive assist gas such as oxygen for removing material.

In the second type of cutting method, the assist gas such as oxygen reacts exothermally with the workpiece materials and provides more heat for melting of material, i.e. acts as secondary heat source to the cutting process apart from removing the molten material. Sometimes such type of cutting is also known as reactive fusion cutting. The reactive fusion cutting gives higher material removal rate, high cutting speed and low dross while inert gas cutting gives better quality cut but reduced cutting speed and material removal rate.

![Figure 1.15: Laser fusion cutting [Powell et al. (2004)]](image)

Chemical degradation cutting method is used for cutting of thermosetting plastics. In this method, the laser beam breaks the chemical bonding and burns the material to a smoke. This process requires more heat as compared to fusion cutting. The cutting speed and maximum thickness of materials to be cut of thermosetting plastic that can be cut are lower than those of thermo-plastics [Powell et al. (2004)]. The cut quality obtained by chemical degradation cutting is better than fusion cutting process.

Laser scribing is the process by which very fast cutting speed may be achieved for the cutting of brittle and thin section ceramics used in the electronic industry. In the laser
scribing process, a line of holes either fully penetrating or shallow penetrating across the surface of the sheet, is made so that it may be mechanically broken along the line. In this process, low-energy, high-power density pulses are used to remove the material. The specimen cut by this method is free from debris and possesses low heat affected zone. It improves magnetic domain refinement, stress relaxation and inhibition of domain-wall movement in the fabrication of core laminations for motors and transformers [Majumdar et al. (2003)].

Brittle materials like glass and ceramics which are vulnerable to the thermal stresses can be cut with a controlled fracture mechanism using a fine spot of laser beam. The laser heats a small volume of the surface and tensile stresses are generated all around it due to the melting of the material. If there is a crack in this space, the induced stresses are concentrated around the crack which ultimately results in propagation of crack in the direction of heat source. And if this propagation of crack is controlled properly, the desired kerf may be obtained. As in this process, the surface is not melted, it requires very low power and the quality of cut is very good. By the introduction of high power excimer lasers working in ultraviolet region, a new method of laser cutting have been developed known as cold cutting (as in this process no heating takes place). The energy of ultraviolet photons is about 4.9 eV which is similar to the bond energy of many organic compounds or materials. When such high energy photons strike the materials, it may break the chemical bonds of the materials until the material dissociates into its chemical components. The material is removed in micro scales, layer-by-layer. This process is highly desirable in medical applications such as micro surgery and tumor ablation, and polymer processing applications.

In Lasox process, first the laser beam is used to heat the material above the ignition temperature to a larger area than the area of the impinging coaxial, oxygen gas jet. After that oxygen gas jet is impinged on the heated area and burning of material takes place which gives the required kerf along the movement of laser beam as shown in Figure 1.16. Lasox process can be used to cut thick workpiece. It may be used to cut upto 80 mm thick workpiece as compared to other laser cutting methods where the sheet cutting thickness is limited to 25 mm [Steen (1991)]. It has other advantages over the plasma and oxy-fuel cutting processes such as square cut top edges, reduced taper, little variation in the roughness over the smooth cut edge, high cutting speed, and less distortion due to the absence of hot gas jet.
Components of Laser Cutting Systems

The components used for laser cutting systems are broadly classified into four different categories: (i) beam generation unit (ii) beam delivery unit (iii) workpiece positioning systems (iv) auxiliary components. The components of laser cutting systems are shown in the Figure 1.17.

Beam generation unit is shown in Figure 1.4. In this figure, lasing medium is a collection of atoms, molecules or ions. The lasing mediums are solid (e.g. Nd:YAG), liquid (dye) or gas (e.g. CO$_2$, N$_2$, He, Ne, etc.) [Jain (2005)].

The types of lasers are classified depending upon the nature of the lasing medium. For example in CO$_2$ gas laser, the lasing medium is a combination of different gases such as CO$_2$, nitrogen (N$_2$) and helium (He). Excitation source is some external source which provides the energy to excite the ions, molecule and atoms in the lasing medium by direct or indirect means [Chryssolouris (1991)].

For gas and diode lasers, the energy is usually introduced directly by electric current flow, whereas, for solid lasers, an intense flash of white light produced by incandescent lamps introduces the excitation energy. The excitation for gas lasing medium is achieved into two stages. For example, in the case of CO$_2$ laser, only a small percentage of CO$_2$ gas molecules are excited by means of direct electrical discharge while most of the electrical energy is absorbed by N$_2$ gas molecules. The remaining CO$_2$ gas molecules are excited by
colliding with the N₂ gas molecules. Two optical mirrors are used in the beam generation unit which acts as an optical resonator or feedback system.

The photons moving along the optic axis interact with a large number of excited atoms, stimulate them and the stimulated photons are amplified by the optical resonators. The stimulated and amplified photons are reflected back and forth by the optical resonator and pass through the excited medium creating more photons. In each round trip, a percentage of these photons exit through the partially reflective mirror as intense laser beam [Majumdar (2003)]. The rest of the photons remain in the lasing cavity which is responsible to maintain the stimulated emission. A cooling unit is also used to remove the waste heat generated during the laser beam generation in order to avoid the thermal damages of different components of beam generation unit.

![Different components of laser cutting system](image)

**Figure 1.17:** Different components of laser cutting system

The beam delivery unit consists of several optical components which are used to focus the laser beam on a particular spot of the workpiece. The main components of beam delivery unit are mirrors, beam splitters, focusing lenses and fiber optic coupling. Mirrors are used to direct, reflect or bend the laser beam in the desired direction. For this purpose, generally metallic mirrors are used as these mirrors possess high reflectivity, minimal energy losses, and withstand high energy density without thermal damage due to their high thermal conductivity [Chryssolouris (1991)].
Copper is most commonly used for making the mirrors and it can withstand energy densities above 100 kW/cm² without any thermal damage. To enhance the optical properties of a mirror, a dielectric material is coated on the mirror. The diamond polished mirrors are used to achieve the flat surfaces of the mirrors. Beam splitter is an optical device which is used to reflect a portion of incident beam energy and to transmit the remaining incident energy. Beam splitters are used to distribute the incident laser power among the different workstations [Chryssolouris (1991)]. There are three methods namely reflection, interference and polarization which are generally used for splitting the laser beam. Focusing lens is used to focus the laser beam into a small area as well as to increase energy density of the laser beam. The common lens materials for CO₂ and Nd:YAG lasers are sodium chloride (NaCl), potassium chloride (KCl), zinc selenide, gallium arsenide, and germanium. The lens material must have high transmissivity or low reflectivity to the laser light wavelength. The energy density of the focused laser beam can be changed by changing the spot diameter of the beam for different applications. The spot diameter can be changed by changing the focal length of the lens as by increasing the focal length, the working distance as well as the spot diameter of the laser beam can be increased. For the laser cutting of thin workpieces, it is advisable to use minimal focal length in order to obtain maximum material removal rate with a narrow kerf. The spot diameter can also be decreased by increasing the unfocused beam diameter.

Beam delivery systems based on mirror-assembly have certain advantages such as geometric flexibility, integration of laser to multi degree of freedom devices such as robots, and movement of laser along the complicated and complex profile path. For such types of situations, fiber optic coupling can be used to transfer the laser beam between the laser output and laser head in place of mirror-assemblies. Optical fibers can be used for beam delivery into two modes: single mode (for TEM₀₀ beam mode transmission) and multiple-mode (for higher order transmission). The main problems in using the optical fibers are the limit of power that can be transmitted through them, a fraction of beam energy absorbed by the optical fibers and mode distortion during the transmission of beam [Chryssolouris (1991)]. The maximum power transmitted through the optical fibers depends upon the dielectric breakdown at the entrance of them. Beam power upto 100W for continuous mode and 500W for pulsed mode can be transmitted [Chryssolouris (1991)]. An assist gas supply unit is used to supply high pressure, coaxial gas jet which
removes the molten material from the melting pool and also prevents thermal damage of optical components.

Workpiece positioning units are used to control the relative motion between laser beam and workpiece. There are two approaches by which the movement of the laser beam and workpiece can be controlled. In the first approach, workpiece remains stationary, while the laser beam moves along the required path. In the second approach, workpiece moves along the cut profile, while the laser beam remains stationary. This method is most commonly used for different laser cutting systems and provides high degree language (G and M codes). In some systems, it can be downloaded directly from the systems using drawings according to the profiles, drawn at AutoCAD or COREL DRAW software. Recently a number of laser systems have been developed which are integrated with the multi-axis robotic manipulation of beam positioning systems. The multi-axis robotic systems are used due to some advantages such as high accuracy, high flexibility, high repeatability, smooth motion, better beam power control and reduction of floor space required to machine a large workpiece [Chryssoulouris (1991)]. The main limitation of such system is the inaccuracies in positioning and controlling the velocity of multi-axis robots.

The auxiliary components are those components which are not used directly in laser beam generation or for the positioning of the workpiece. Auxiliary components are used to support laser machining for its safe and efficient running. Laser head and some safety equipments are used as auxiliary components. Laser head is used to enclose the laser beam and to guide the co-axial assist gas jet with the laser beam. With the help of co-axial assist gas jet, pressure gradient is created to remove the molten material from the cutting front. The co-axial gas jet creates downward driving force which expels the molten metal from the bottom of the kerf as in the laser cutting. But off-axial gas jets are used to create upward driving force to remove the molten material as in the case of laser grooving. Most of the current laser systems use a co-axial gas nozzle with parallel and convergent flow passage. Lasers are hazardous for the health due to high energy density and radiation of infrared to ultraviolet electromagnetic waves. To avoid such types of hazardous effects, the beam delivery unit, workpiece, laser head and machining area should be completely enclosed. An exhaust system should also be used to remove the hazardous fumes and vapor generated during the laser cutting of materials. It is also advisable to use protective goggles for each operator during the operation.
Characteristics of Laser Cutting

Laser cutting is most commonly used laser beam machining (LBM) process due to its different advantages such as narrow kerf, small HAZ, high accuracy and cut edge quality, material versatility, high flexibility, no tool wear, non-contact nature, high production rates and better material utilization. Due to excellent cut quality and narrow kerf, laser cutting process can be applied for a very precise cutting of sheet metal. The intricate and complex profiles with very narrow kerf width can be created in any type of material by the laser cutting process [Grevey et al. (1994)]. The concentrated laser beam produces very little HAZ and laser cut specimens do not require further subsequent machining operations. Laser cutting can be applied to almost all categories of materials such as metals, superalloys, ceramics and composites. The laser cutting capability depends mainly on optical and thermal properties of the material rather than mechanical properties. The materials which exhibit high degree of hardness or brittleness and possess through favorable thermal and optical properties such as low reflectivity, low thermal conductivity and diffusivity are well suited for laser cutting process [Dubey and Yadava (2008b)]. As laser beam can be transferred from one place to another place with the help of optical fiber, it can be applied for cutting in inaccessible areas.

According to the different types of lasers are available in market, solid state Nd:YAG and gaseous CO\textsubscript{2} lasers are mostly used for cutting in industries due to their high powers and other suitable properties. The use of CO\textsubscript{2} lasers is not common in practice for cutting of highly reflective and thermally conductive materials such as copper, aluminum and their alloys due to its poor absorptivity. High reflectivity of these materials require high laser power when cut with CO\textsubscript{2} laser and there is possibility of damage to laser cavity, cavity optics or beam delivery optics due to reflected laser beams. Further, high thermal conductivity of aluminum alloys tends to produce large heat affected zone (HAZ), wider kerf and oxides on the molten materials in the cutting front. Although Nd:YAG lasers have low average power but when operate in pulsed mode, give higher peak power and beam intensity. Due to the shorter wavelength (1.06 \textmu m), it can be better absorbed by reflective materials such as copper, aluminum and their alloys as compared to the CO\textsubscript{2} laser. Pulsed Nd:YAG laser cutting becomes an excellent means of cutting due to good focusing characteristics, smaller kerf width and narrow HAZ [Chryssolouris (1991)]. Most of the organic materials such as plastics, wood based products, leather and natural rubber can not be cut by Nd:YAG laser as these materials are transparent to the Nd:YAG
laser light and most of laser light passes through the material without heating it. But CO₂ laser can be used for the cutting of these materials.

**Applications of Laser Cutting**

The main industrial application of the lasers at the present time is in the laser cutting of different materials. The applications of laser cutting in different fields are numerous. Laser cutting is the neatest and the fastest profile cutting method. Since the setup time is very less, the jobs can be completed in only few minutes. The ease of the profile cutting has opened up several interesting novelties in design. It is used in an economical way for the production of many components (10,000 pieces or more). Laser cutting is widely used in different technologically advanced industries such as automobile, aerospace, nuclear, medical, chemical, civil structures and household applications. Mild steel sheets are most commonly used for civil structures and house hold applications which are easily cut by laser cutting [Salem et al. (2008), Karatas et al. (2006), Yilbas (2008), Arif et al. (2009) and Malikov et al. (2009)].

Laser cutting is used for the cutting of titanium and its alloys which are most widely used for different industries such as aerospace, marine, chemical, food processing and medical due to their superior performance characteristics such as high strength and stiffness at elevated temperatures, high strength to weight ratio, high corrosion resistance, fatigue resistance, and ability to withstand moderately high temperatures without creeping [Biffi et al. (2011)].

Aluminium and its alloys cannot be cut easily by conventional cutting methods due to their thermal and electrical properties so that laser cutting is applied for the cutting of this type of materials. It is widely used in the market due to its unique properties such as their lightness, high strength-to-weight ratio and good corrosion resistance. These are most widely used in aircraft, automobile, ship building and chemical processing industries. In the coated form (alclad sheet), duralumin is used for the construction of ship frames, and when alloyed with nickel, it is used for making the pistons and piston rings of aircraft and automobile engines [Patnaik et al. (2011), Stournaras et al. (2009a) and Dubey et al. (2008b)].

Besides the metals, laser cutting is also applied for the cutting of superalloys which are commonly used for making the different parts such as aerospace parts, gas engine components, parts for nuclear power plant, ship building due to its good mechanical
properties at high temperature and corrosion resistance in hostile environments [Ahn et al. (2010), Thawari et al. (2005)]. Laser cutting process is also applied for nuclear power plant to dismantle and repair the plant with the help of high power lasers [Chagnot et al. (2010)].

Apart from these applications, laser cutting is applied for the cutting of difficult-to-cut materials such as ceramics and composites which have many applications in mechanical, electrical and engineering applications due to outstanding thermo-mechanical and thermo-chemical properties [Yilbas et al. (2012), Ji et al. (2008) and Sulaiman et al. (2006)]. The traditional methods of ceramic tiles cutting, such as diamond saw, water jet machining and ultrasonic machining, are very expensive and time consuming. Laser cutting is applied for the cutting of ceramic tiles [Black (1998a), Black (1998b) and Black (1997)].

Short and ultra short pulse lasers are used for the cutting of different parts at micro and nano levels. Short pulse Nd:YAG laser is successfully used in electronic industry to cut QFN packages (semiconductor packages which are plastic encapsulated packages with copper lead frame substrate) [Li et al. (2005a), Li et al. (2005b) and Li et al. (2007a)]. High quality femto-second lasers are used for the micro cutting of alumina ceramics which is used for the manufacturing of high power radio frequency electronic circuits and fabrication of multichip modules, mainly due to its high electrical resistance, high dielectric strength and high thermal stability [Wang et al. (2010)].

In the medical field, different surgeons use lasers for the cutting nickel-titanium shape memory alloys which are used for different medical applications such as wires for minimal invasive surgery, super elastic devices for cardio-vascular systems, and spinal cord [Pfeifer (2010)].

Bulk metallic glasses (BMGs) are disordered materials that lack the periodicity of crystalline structures. BMGs exhibit many exceptional physical, chemical and mechanical properties that differ markedly from those of crystalline metals. Thus, BMGs have attracted considerable attention as structural materials. Laser cutting with ultra short pulses is employed for the cutting of BMGs [Lin et al. (2012)].
The maximum cutting speed and the maximum thickness of the workpiece for the laser cutting of different materials such as metals, nonmetals, ceramics and composites have been tabulated in Table 1.2 [Chryssoulouris (1991)].

<table>
<thead>
<tr>
<th>Material</th>
<th>Types of laser used to cut</th>
<th>Laser power/Energy density</th>
<th>Maximum cutting speed</th>
<th>Maximum cut thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>CO₂</td>
<td>4000W</td>
<td>0.95 m/min</td>
<td>10 mm</td>
</tr>
<tr>
<td>St. steel</td>
<td>CO₂</td>
<td>100-850 W</td>
<td>0.94-2.6 m/min</td>
<td>1 – 9 mm</td>
</tr>
<tr>
<td>Aluminium</td>
<td>Nd:YAG</td>
<td>1250W</td>
<td>1.5 m/min</td>
<td>3 mm</td>
</tr>
<tr>
<td>Copper</td>
<td>Nd:YAG</td>
<td>120 W</td>
<td>0.05 m/min</td>
<td>3.5mm</td>
</tr>
<tr>
<td>Gold</td>
<td>Nd:YAG</td>
<td>190 W</td>
<td>0.015 m/min</td>
<td>3 mm</td>
</tr>
<tr>
<td>Hastalloy</td>
<td>Nd:YAG</td>
<td>120 W</td>
<td>0.02 m/min</td>
<td>8 mm</td>
</tr>
<tr>
<td>Titanium</td>
<td>CO₂</td>
<td>375 W</td>
<td>2.54 – 9.14 m/min</td>
<td>1.524 – 3.175 mm</td>
</tr>
<tr>
<td>ABS plastic</td>
<td>CO₂</td>
<td>400 – 1200 W</td>
<td>0.6 – 4.5 m/min</td>
<td>3.175 – 12.70 mm</td>
</tr>
<tr>
<td>Poly-carbonate</td>
<td>CO₂</td>
<td>400 W</td>
<td>0.82 – 4.80 m/min</td>
<td>3.175 – 12.70 mm</td>
</tr>
<tr>
<td>Poly ethylene</td>
<td>CO₂</td>
<td>400 W</td>
<td>0.4 -18 m/min</td>
<td>0.635-12.70 mm</td>
</tr>
<tr>
<td>Poly propylene</td>
<td>CO₂</td>
<td>400 W</td>
<td>0.5 – 3.4 m/min</td>
<td>3.175-12.70 mm</td>
</tr>
<tr>
<td>Poly styrene</td>
<td>CO₂</td>
<td>400 – 1300 W</td>
<td>0.55 – 50 m/min</td>
<td>0.635 – 7.50 mm</td>
</tr>
<tr>
<td>Aluminium oxide</td>
<td>Nd:YAG</td>
<td>50 MW/cm²</td>
<td>0.02 m/min</td>
<td>15 mm</td>
</tr>
<tr>
<td>PSZ</td>
<td>CO₂</td>
<td>2.6 kW</td>
<td>9.14–11.76 m/min</td>
<td>0.1016–0.254 mm</td>
</tr>
<tr>
<td>Quartz</td>
<td>CO₂</td>
<td>500 W</td>
<td>1.2 m/min</td>
<td>2 mm</td>
</tr>
<tr>
<td>Silicon carbide</td>
<td>Nd:YAG</td>
<td>6 MW/cm²</td>
<td>0.04 m/min</td>
<td>5 mm</td>
</tr>
<tr>
<td>Tungsten carbide</td>
<td>Nd:YAG</td>
<td>10 MW/cm²</td>
<td>0.045 m/min</td>
<td>5 mm</td>
</tr>
<tr>
<td>Silicon nitride</td>
<td>Nd:YAG</td>
<td>10 MW/cm²</td>
<td>0.05 m/min</td>
<td>3 mm</td>
</tr>
<tr>
<td>Zirconium oxide</td>
<td>Nd:YAG</td>
<td>5 MW/cm²</td>
<td>0.2 m/min</td>
<td>1.3 mm</td>
</tr>
<tr>
<td>Aramid/Polyester</td>
<td>CO₂</td>
<td>800 W</td>
<td>0.5 m/min</td>
<td>2 mm</td>
</tr>
<tr>
<td>Glass/Epoxy</td>
<td>CO₂</td>
<td>1000W</td>
<td>2 m/min</td>
<td>5 mm</td>
</tr>
<tr>
<td>Kevlar/Epoxy</td>
<td>CO₂</td>
<td>150-950 W</td>
<td>2.04 m/min</td>
<td>3.2 – 9 mm</td>
</tr>
<tr>
<td>Glass/Polyester</td>
<td>CO₂</td>
<td>800 W</td>
<td>0.5 m/min</td>
<td>2 mm</td>
</tr>
<tr>
<td>Graphite polyester</td>
<td>CO₂</td>
<td>800 W</td>
<td>0.5 m/min</td>
<td>2 mm</td>
</tr>
<tr>
<td>Wood (soft maple)</td>
<td>CO₂</td>
<td>250 W</td>
<td>1 m/min</td>
<td>13 mm</td>
</tr>
<tr>
<td>Wood (hard maple)</td>
<td>CO₂</td>
<td>250 W</td>
<td>0.28 m/min</td>
<td>22 mm</td>
</tr>
<tr>
<td>Wood (red oak)</td>
<td>CO₂</td>
<td>250 W</td>
<td>0.06 m/min</td>
<td>29 mm</td>
</tr>
<tr>
<td>Plywood</td>
<td>CO₂</td>
<td>400 W</td>
<td>Not found</td>
<td>19 mm</td>
</tr>
<tr>
<td>Paper</td>
<td>CO₂</td>
<td>185 W</td>
<td>330 m/min</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Glass</td>
<td>CO₂</td>
<td>1200W</td>
<td>Not found</td>
<td>5 mm</td>
</tr>
</tbody>
</table>
1.3 Working of Pulsed Nd:YAG Laser Cutting System

The basic principle of beam generation in Nd:YAG laser system may be illustrated from Figure 1.4. Two optical resonators/mirrors, one totally reflective and other partially reflective, are used in the beam generation system to direct the randomly moving photons. The output laser beam is obtained by partially reflective mirror. For a very good beam quality (minimum divergence and low mode number) usually a long resonator is selected, i.e. the distance between two mirrors is far apart [Manual SIL-200 (2003)]. But on the other hand, it results in an increase in scatter losses. An additional means of improving beam quality is to install a diaphragm in the resonator. The output characteristics of Nd:YAG laser can be changed by varying the pumping discharge waveform. For high pulse energy in a pulse time of one millisecond, a long flash pulse is used to obtain six to seven joule. Laser beam with output power of 10 to 1000 W can be obtained with peak power of about 400 kW. The basic components of Nd:YAG laser cutting system is shown in the Figure 1.18.

The laser beam emerging from the partially reflective mirror, reaches into a beam detector which converts the light intensity into a proportional electric signal by which electrical system is able to assess the energy of the laser pulses. A beam shutter is fitted after detector to prevent any undesired emergence of the laser radiation from the optical system. After the beam detector, the laser beam arrives to the beam expander which serves to reduce the spot diameter at the focal point of the lens. An adjustable expander is used to pre-focus or pre-unfocus the laser beam marginally. When the beam shutter is open, the beam reaches the bending mirror which is a path folding mirror. It bends the laser beam 90° to guide it towards the focusing lens. The focusing lens, which is convex in nature, focuses the parallel laser beam coming from the bending mirror onto the workpiece. The focused laser beam heats a particular spot and melts the material which can be removed with the help of pressurized co-axial assist gas jet. The assist gas also prevents the breakage of optical components used for focusing the beam. Generally oxygen is used as assist gas and is kept in a cylinder pressure at 40-80 kg/cm². The laser beam remains stationary while workpiece moves relative to the laser beam [Chryssolouris (1991)]. A CNC table is used to move the workpiece as per cutting shapes and profiles. The motion of the table in X and Y-directions is controlled by a CNC controller. The CNC system uses drawing software, known as Corel Draw, to draw the drawings of
profiles as per cutting dimension requirements in the computer provided with the laser cutting system.

The photograph and specifications of 200 W pulsed Nd:YAG laser cutting system (Model SLP-200) available in Machine Tools and Advanced Machining Lab of Motilal Nehru National Institute of Technology Allahabad (Uttar Pradesh) India, supplied by Suresh Indu Lasers Private Limited, Pune (Maharashtra), India, is shown in Figure 1.19 and Table 1.3, respectively [Manual SIL-200 (2003)].

**Figure 1.18:** Different components of Nd:YAG laser cutting system

**Figure 1.19:** Pulsed Nd:YAG laser cutting system (Model SIL-200) [Manual SIL-200 (2003)]
Table 1.3: Specifications of pulsed Nd:YAG laser cutting system (Model SIL-200) [Manual SIL-200 (2003)]

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Specifications</th>
<th>Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Average power</td>
<td>200 W</td>
</tr>
<tr>
<td>2</td>
<td>Wavelength of laser beam</td>
<td>1.06 µm</td>
</tr>
<tr>
<td>3</td>
<td>Source of pumping</td>
<td>Plasma flash lamp</td>
</tr>
<tr>
<td>4</td>
<td>Pulse width or pulse duration</td>
<td>0.1 - 25.5 ms</td>
</tr>
<tr>
<td>5</td>
<td>Pulse frequency or pulse repetation rate</td>
<td>1 - 50 pulse/s</td>
</tr>
<tr>
<td>6</td>
<td>Maximum cutting speed</td>
<td>5 m/min</td>
</tr>
<tr>
<td>7</td>
<td>X-Y movement of the working table</td>
<td>29 x 27 cm</td>
</tr>
<tr>
<td>8</td>
<td>Z movement of the nozzle</td>
<td>10 mm</td>
</tr>
<tr>
<td>9</td>
<td>Maximum thickness to be cut</td>
<td>7 mm</td>
</tr>
</tbody>
</table>

1.4 Scope and Objectives of the Present Work
Recent trends on LBC of thin sheets show that the pulsed Nd:YAG lasers are quite suitable due to their peculiar characteristics such as short pulse duration, low mean beam power and high laser beam intensity. The published literatures available on LBC show that the experimental works are mainly aimed at studying the effect of input parameter variations on output quality characteristics through unplanned experimentation. Only a few researchers have used scientific methods under the umbrella of design of experiments (DOE) for a planned study of LBC process. Unplanned experimental study includes a lot of undesired factors which affect the performance variations and finally leads to unreliable results. Also, the quality laser cutting of highly reflective and thermally conductive materials like aluminium and its alloys have not been studied systematically to fulfill the demand of complex shape generation in these highly demanding materials. The newly developed difficult-to-cut advanced materials like ceramics, composites and superalloys have high demand in industries but only a few researchers have applied scientific approach to improve the laser cutting quality of these materials.

Following are the objectives of the present work:

- To study the effect of laser cutting input parameters on highly reflective and thermally conductive material specially aluminium alloy shown by using pulsed Nd:YAG laser.
- To optimize the laser cutting parameters for minimum bottom kerf deviation (BKD) in cutting of an aluminium alloy sheet using Taguchi Method.
- To optimize the laser cutting parameters for minimum surface roughness (SR) in cutting of an aluminium alloy sheet using Taguchi Method.
To optimize the heat affected zone in laser cutting of duralumin sheet using hybrid approach of Multiple Regression Analysis (MRA) followed by Genetic Algorithm (GA).

To optimize multiple quality characteristics using hybrid approach of Taguchi method and Grey Relational Analysis (GRA) coupled with entropy measurement method. Two quality characteristics, BKD and SR optimized simultaneously using this hybrid approach.

1.5 Organization of the Thesis

First chapter of the thesis comprises of introduction about laser generation, laser beam machining (classification, mechanism of metal removal in laser cutting) and laser beam cutting (characteristics, working principle and applications). Towards the end of chapter 1, the scope and the objectives of present thesis work has been discussed. In the second chapter, a literature review of experimental investigations (conventional materials, advanced materials and difficult to laser cut materials) and theoretical investigations of laser beam cutting, modeling optimization tools in laser beam cutting and artificial intelligence applications in laser cutting have been discussed. Chapters 3 and 4 include the modeling and optimization of the single quality characteristic: bottom kerf deviation and surface roughness, respectively. Chapter 5 performs modeling and optimization of a single quality characteristics-heat affected zone-based on Artificial Intelligence. Chapter 6 performs multi-objective optimization of laser beam cutting for aluminium alloy sheets using hybrid approach of Taguchi method and grey relational analysis coupled with entropy measurement method. In chapter 7, the main conclusions derived from this research work has been discussed in detail and it also discusses the scope for further research in this area.