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A Review on Lasers Assisted Machining Methods – Types, Mode of Operations, Comparison and Applications

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***Abstract*: Materials having high hardness and difficult to cut are becoming more popular in distinct industries such as automobile, aerospace, medical, construction, nuclear, sports and others. Because, hard and difficult to cut materials offered high strength to weight ratio, high resistance against wear, high yield strength, high resistance against corrosion, and ability to retain high strength at elevated temperature. However, the machining of hard and difficult to cut material poses a serious challenge owing to severe tool wear and higher cutting force involved. To overcome this, Laser assisted machining (LAM) has shown to be one of the most promising technologies for cutting difficult-to-cut materials. Hence, the aim of current review paper is to provide an overview on LAM, historical background, basic phenomena of laser generation, properties of lasers, generalized concept of laser- material interaction, types of lasers, distinct modes of laser operations and applications. Finally, the recent advances in laser assisted machining are discussed.**

***Index Terms*—Non Conventional Machining; Laser Beam Machining; Monochromatic; Continuous Wave; Single Pulse**

I. INTRODUCTION

In current machining environment, various manufacturing industries are facing vicious challenges in the global market. The demand for higher quality of machining at lower cost in less delivery time leads to put a great effect on the various manufacturing industries.

To meet with these customer requirements and considering all current limitations of the conventional machining method, there has been a major focus on advanced machining methods [2].

The selection of the best non-conventional machining process among the available methods is very tedious and important task.

There are various prominent non-conventional machining methods which are acquired by the manufacturing industries for better machining purposes. Non-conventional machining methods have a wider area of applications than the conventional methods which can resolve the machining issues more efficiently [3]. The common parameters to be taken into consideration for adopting a particular process are (a) Physical characteristics of the substrate (b). Size and shape of the workpiece to be produced (c) Types of cutting operation such as hole making, cutting etc. (d). Process capability (surface finish, tolerance, rate of metal power requirement) etc. (e) Cost analysis.

Furthermore, parametric combinations can also be identified using this process planning. Based on the selection process flow chart, there are various non-conventional machining processes that can be selected as per the industrial requirement as shown in Figure 1**.**

The non-conventional machining refers to the removal of the excess material in terms of chips or debris of having small dimensions/size. These techniques help in removing excess material which involves various energies like thermal, mechanical, electrical, and chemical or the combination of the above. Then on conventional method produces high surface modification properties with a high material removal rate (MRR) as compared to other conventional methods.

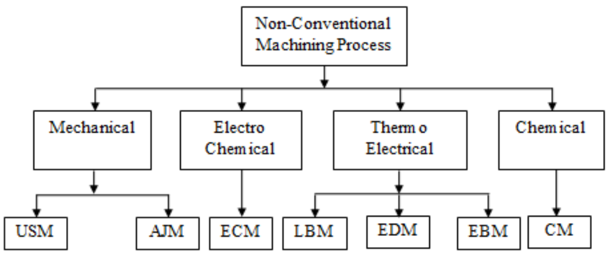

Figure 1. Various Non-Conventional Machining Processes

Among them, laser based machining methods (LBM) are more widely and popularly used for its accuracy and efficiency to machine hybrid GFRPs. Laser assisted machining (LAM) method is widely applicable in various fields like laser cutting, welding, drilling, cladding and engraving etc. They have several industrial applications, mainly in aero-space, medical treatment, astronautics, military, computer &electronics and other micro mechanical industries. High precision, flexibility and high degree of freedom in the machining environment are the special features of laser based processes. Therefore, the problems like large cutting forces, elevated cutting temperature, poor surface finish and lesser tool life has been resolved using the LAM method LAM methods works on the principle of lasers therefore it is essential to study the history, basic nature, working principle and different types of lasers used.

A. Laser Assisted Machining

The material scientists and researchers worldwide are developing advanced and difficult to cut materials, but the machining of these materials is a tedious task by using conventional machining methods. Therefore the demand for laser assisted machining methods is increasing day by day. Laser basically termed as "**L**ight-**A**mplification-by-**S**timulated-**E**mission-of-**R**adiation". Due to its electro-

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optical nature laser generally emits coherent beam of radiation. Albert Einstein in 1916 first postulated the concept of developing the induced emissions and momentum conversation by which the lasers can produce the coherent radiation. Since then the improvement in the laser technology grows with time. Its accuracy and cost effectiveness were clearly the possible reasons for the expansion in its application. Further, with the technological improvement there has been tremendous scope in the continuous use of lasers in the manufacturing field.

- **History of Laser Generation**

Lasers with stimulated emission and its negative absorption were discovered in 1928 by R.W. Landenburg. Therefore, V.A Fabrikant in 1940 illustrated the possible existence of property named population inversion in lasers. Table 1 shows the discovery of the laser with advancement in its technology.

TABLE 1: ADVANCEMENT OF LASER GENERATION [4]

Year	Year wise advancement in Lasers Technology
1887	H. Hertz discovered the photoelectric effect accidentally which leads to introduce the concept of photons by Albert Einstein.
1901	Planck solved the scientific challenge called related to spectral energy densities at high frequency of divergence.
1905	Electromagnetic energy was quantify by Einstein
1913	Born invents quantification of the energy levels of electrons. Further Einstein proves the compatibility between the photons & black bodies which leads to the idea of stimulated emission.
1949	The first optical pumping and population inversion was developed by Kastler and Brossel.
1950	Device which amplifies the microwave by stimulated emission of radiation was developed by Weber. The device can amplify electromagnetic waves in the microwave region.
1954	Stimulated emission of microwaves was further amplified with the help of ammonia having wavelength of 13 mm.
1958	Schawlow and Townes used electromagnetic waves in only one dimension. This results in the more powerful magnification of the wave when used in closed cavity.
1960	Optical laser effect using ruby laser having 694.3 nm was experimented. Later it became common for using various application in the industries
1961	First helium-neon laser gas was developed by J. Bennet and Herriot at 1.15 µm, which can emit colors from green to orange and red.
1962	Invention of first red colored helium and neon laser
1965	Invention of the first semi-conductor laser came into existence.
1966	First colored pulsed lasers (red, orange, yellow) were introduced.
1970	Colored laser of continuous wavelengthwas developed.
1974	At Avcoeverest labs first halide gas eximer was introduced by Ewing, and Brau.
1977	Later Madey's group at Stanford University introduced first laser with free electrons.
1977	Further chemical oxygen iodine laser (COIL) was developed by Dermott, Pehelkin, Benard and Bousek,
1980	A great achievement was encountered when first X-rays report was formulated through the laser technology by Geoffrey Pert's Group at Hull University, UK.
1984	Demonstration of first X-ray laboratory report was done by the Matthew's Group
1999	Invention of the All Gas Phase Iodine Laser (AGIL)
2001	Discovery of State of solid Heat Capacity Laserby Lawrence Livermore National Laboratory and so on.

Later, microwaves through special fibres during the world war initiated the utilization of monochromatic light source which leads in the further development of laser technology [5]. As discussed above, the first basic laser was developed in 1961. Since then the discovery in lasers and its improvement is endless. Laser works on some basic principle. It is utmost essential to be familiar with the basic principles along with various properties of lasers so that one can understand its advanced utilization and application in the future manufacturing industries.

B. Basic Phenomena of Laser Generation

Laser works on a very basic principle of energy transfer. But to know this concept, first it is essential to know the formation and structure of matter, its light absorption and emission phenomenon. Basically matter is made up of atoms. They store and releases energy from one energy level to another. According to the theory of quantum mechanics, each electron stays at a certain energy level, which leads to different energies at various levels. Electrons are responsible for this energy transition by releasing and absorbing energy from lower level to a higher level and vice versa as shown in Figure 2.

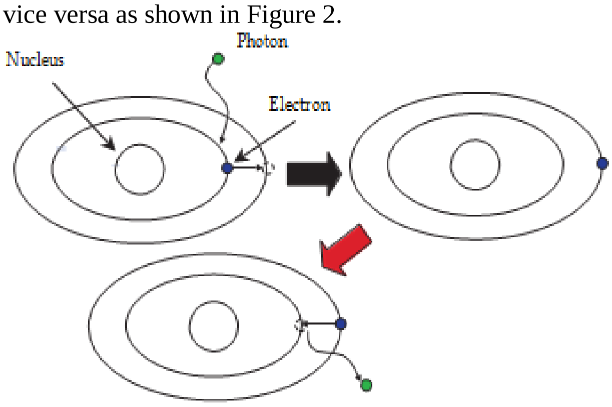

Figure 2: Energy Generation in Absorption and Emission of Photon [6]

During this transition, the energy of the travelling photon is always equal to the difference in energy between the two atomic levels [7].

When an atom is at the lowest energy level it is said to be at the ground state, likewise jumping of electron to the higher energy level by absorbing the required amount of energy is called an excited state. The Spontaneous and Stimulated Emission process is shown in Figure 3.

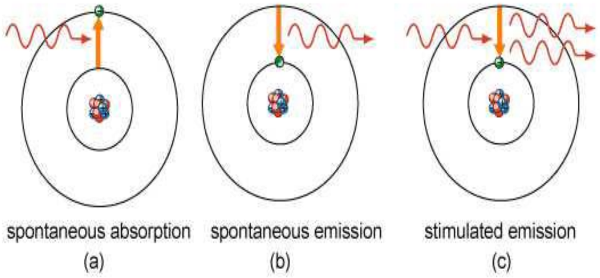

Figure 3: Spontaneous and Stimulated Emission [8]

This energy transfer is basically split into three categories;

- Spontaneous absorption: Whenever an electron absorbs a photon from a lower energy state and reaches to the higher energy state, it is said that spontaneous absorption has been occurred as given in figure 3. (a).
- Spontaneous Emission: When an electron emits a photon spontaneously from a upper energy level to an energy level at the lower stage, it is said that spontaneous emission has been occurred as shown in figure 3. (b).
- Stimulated Emission: When the different emitted incident photons have the same phase and wavelength, they correspond to the energy difference of two energy levels. This results in the photon stimulation an atom and results in the stimulated emission of radiations as shown in figure 3. (c).

Whenever an atom or a molecule gets excited either by electrical or heating method, electron starts moving from the ground molecular state to higher orbitals. Similarly, after losing energy it falls back to its ground molecular state with the energy difference equals to the energy levels of two states as mentioned in Figure 4. Therefore, the energy becomes equals to $E_{photon} = E_2 - E_1$.

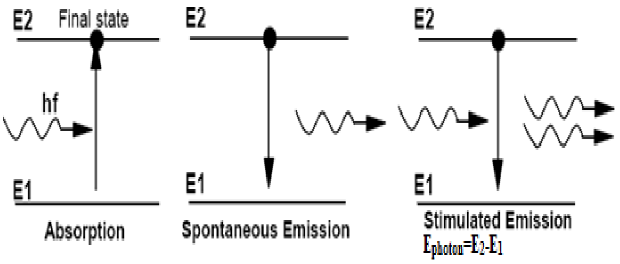

Figure 4: Two Level Energy Level Distribution System (Mishra, 2005) [9]

Therefore, the major characteristic of the laser is to emit the monochromatic emission of radiations that too with high coherence within space and time. The laser beam thus produced has following major properties which are different from the common light as shown in Figure 5.

- It is different from the ordinary light which is made up of different wavelengths.
- It is monochromatic in nature with single wavelength.
- The light is coherent in nature, i.e. the light comprises of same wavelength and polarization.
- The ray produced by the stimulated emission is very narrow and collimated.
- The Light is of high intensity in nature than the ordinary light.

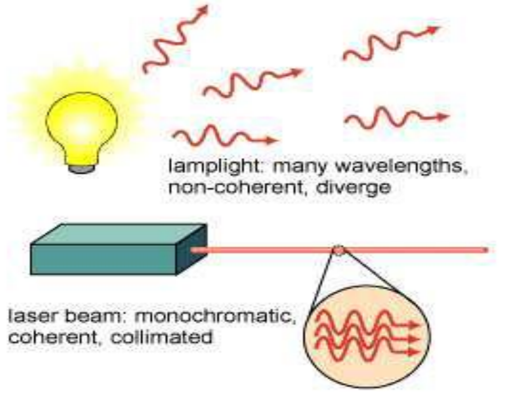

Figure 5: Monochromatic, Coherent and Collimated beam of Radiation [8]

Another phenomenon which called population inversion is also an important term related to the generation of the laser. In this, firstly an atom absorbs the energy and reaches the excited state. After staying momentarily, it falls to the intermediate metastable state. At this stage the atoms stays for longer time than at the ground level state. Due to this there is large proportion of atoms at the metastable state than at the ground level and such phenomenon is called population inversion as shown in Figure 6.

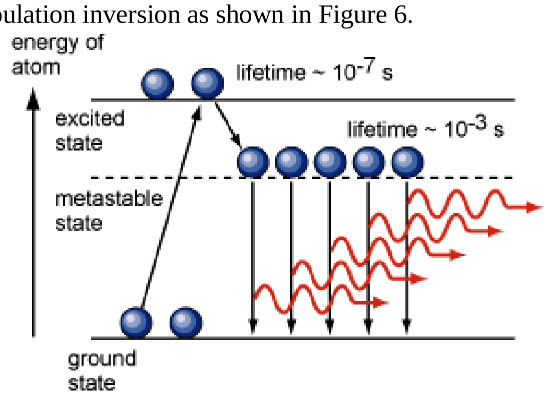

Figure 6: Population Inversion [8]

This property of the population inversion is very important for the generation of the laser, as it ensure the number of the atoms which return back from the meta-stable state to the ground state during stimulated emission should be more than it transmits from the ground to the meta-stable stage during an absorption phase. Due to this phenomenon there will be an increase in the number of photons which further intensify the laser output.

C. General Properties of Lasers

There are basically three general properties of the lasers without which the laser beam cannot be generated. These properties are;

- **Monochromaticity**

Ordinary light contains radiations of electro-magnetic nature which particularly includes radio-waves, micro-waves, infrared, X-rays, visible rays, UV rays and gamma rays etc. All these are collectively known as

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electromagnetic spectrum, which comprises wide range of wavelength. The distinct properties of laser are shown in **Figure 7**.

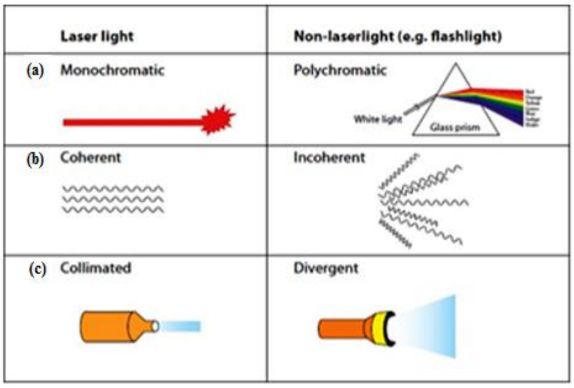

Figure 7: Properties of Laser Beam [10]

When the wavelengths are different the generation of laser beam is not possible and that property is known as poly-chromaticity. On the other hand, if the light emits only one single defined wavelength of very narrow band width, it is called as monochromaticity as shown in Figure 7 (a) [10].

- **Coherence**

Coherence is the property of laser in which the wavelength of the light should be in phase with respect to time and space, then only the laser beam can be generated. Stimulated beam of emission is responsible for the property of coherence. Figure 7 (b) shows the coherent and incoherent beam of light [10].

- **Collimation**

Collimation refers to the directional behaviour of the laser as given in **Figure 7 (c)**. Beams which are highly focused and directional can be considered as the collimated beams. This property of the beam focused on very small area from the far distance, which results in the less energy loss in the intensity of the beam. So with no divergence, there is a narrow beam of light which is parallel and highly focused at one place only and leads to the higher intensity of laser beam providing much more efficiency than the divergent laser beams [11].

D. Basic Construction and Working of Laser

Lasers basically consist of three major parts, first is the laser source or medium like electron, atom etc. secondly its pumping medium which is used to excite the laser source. Medium from lower energy level to higher energy level and lastly the optical devices (front and back mirrors) which are used by radiation of beam to pass either once completely or reflect back partially or fully depending upon the medium used as shown in Figure 8.

As mentioned earlier the mirrors or the reflectors are placed in such a manner that they must face each other. These two mirrors as a whole are called the optical resonators. The mirror placed at the front is reflective partially and only reflects a portion of beam striking on it, while some part of the total energy escapes through it. The back or rear mirror is fully reflective (100 % reflective) which reflects the total laser energy impinges on it. The energy or pump source provides the excitation to the source medium and results in the spontaneous and stimulated emission which give rise to the phenomenon called population inversion. Lastly, a portion of high intensity non divergent monochromatic light of same wavelength with coherent nature escapes from the front mirror and a laser beam is produced [9].

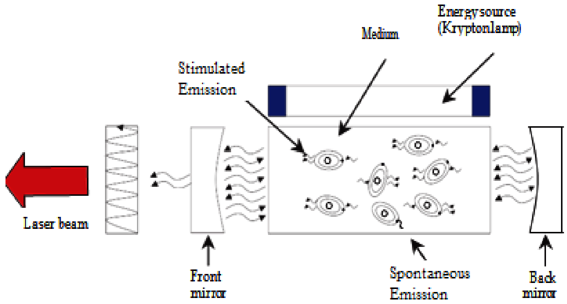

Figure 8. Construction and working Principle of Laser [6]

E. Generalized Concept of Laser- Material Interaction

After studying the basic principle of the laser and its working, it is important to understand the laser-material interaction phenomena. It is a generally a heat transfer concept of material in which laser beam impinges on its workpiece surface material. Whenever the incident ray strikes on the material surface, the beam scattered into majorly three different parts;

- Reflection
- Absorption
- Transmission

Out of which the absorption part is important in context of the machining of the material by laser. When the incident radiation strikes the surface of the work-piece, a part of the beam is absorbed, some part is reflected back by the surface and rest is transmitted through the material. All the properties of the incident radiation depend on the property on the material as shown in Figure 9[11].

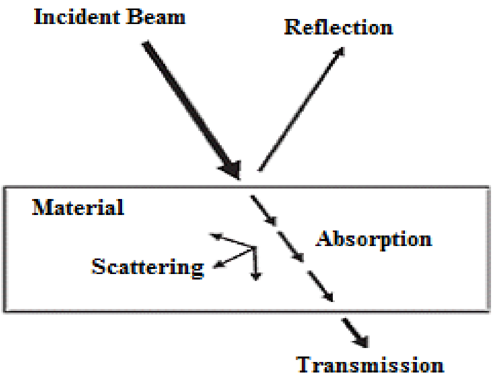

Figure 9. Laser Material Interaction [11]

Apart from laser material interaction, there are various other aspects also which arises during this phenomenon which greatly affects the material surface when machined by the laser beam. Heating, melting, surface vaporization, plasma formation, ablation are various aspects.

Figure **10 to 11** shows various aspects of laser material interaction [9]; [11].

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- **Heating**: It is the mechanism which maintains the temperature at the sufficient level. Whenever the laser strikes the surface of the workpiece, the temperature starts to increase with increase in the intensity of the laser beam due to the phenomenon of heat conduction. This temperature reaches at certain maximum depth of the surface and then starts decreasing after a certain depth as explained in Figure 10, after this stage the melting of the surface started.

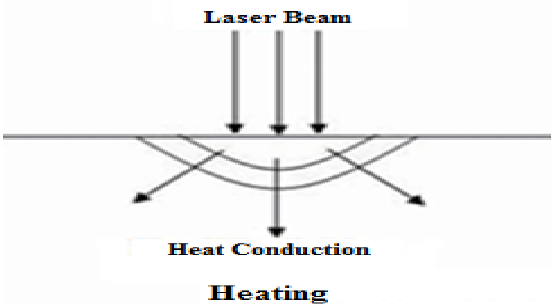

Figure 10.Heating Process

- **Melting:** It is also known as the fusion process which results in the phase transition of the substance. High intensity laser beam when heated to a certain level starts getting melted. Due to this process, the viscosity also decreases as shown in Figure 11.

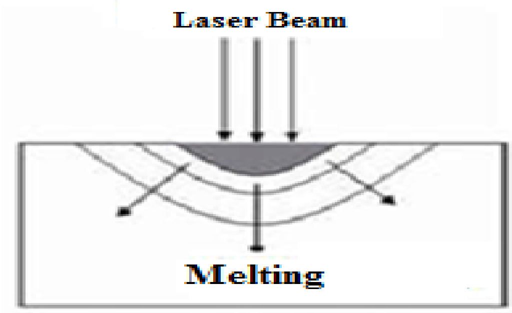

Figure 11. Melting Process

- **Surface vaporization:** This process is the further development of the melting process. It is also a phase transition process from liquid to vapors. With increase in the melting due to high intensity of laser beam, the depth is not increased to infinite value and is limited to certain extent. Due to this, whenever the temperature touches its boiling point, the surface vaporization gets started in the form of evaporation or boiling as shown in Figure 12.

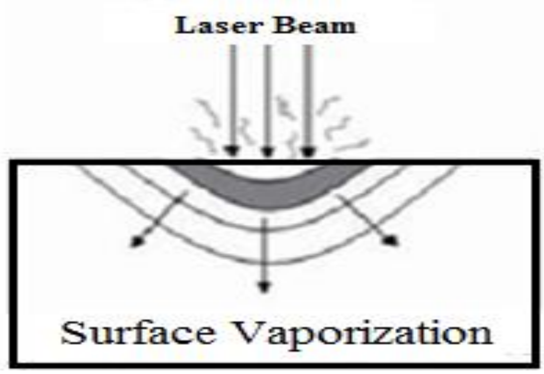

Figure 12. Surface Vaporization Process

- **Plasma formation:** Formation of plasma occurs due to the interaction between high intensity of laser with the workpiece surface. Plasma formation started with the production of electron, followed by the surface vaporization and its ionization as discussed earlier with its breakdown in the plasma propagation. When the surface vaporization takes place, its ionization interaction gets started with the high laser beam intensity. So, vapor with high ionization is termed as plasma formation as shown in figure 13.

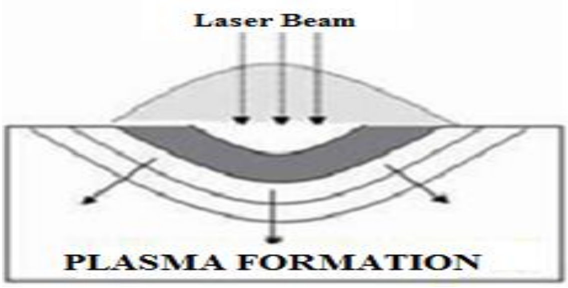

Figure 13.Plasma Formation Process

Ablation: Whenever the material gets removed from the surface of an entity by plasma formation, evaporation, vaporization and other erosive processes with the help of thermal or chemical technique, ablation occurs. The Ablation occurred due to laser is very much affected by the material properties and its capacity to absorb energy during the process. Figure 14 shows the laser ablation process.

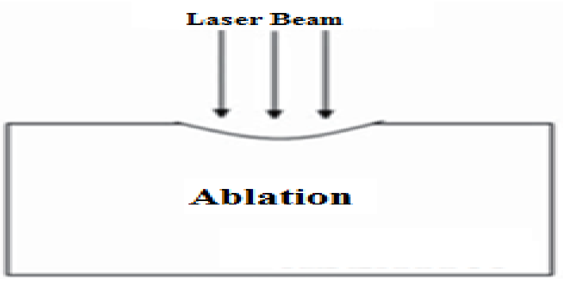

Figure 14. Ablation Process

II. TYPES OF LASERS

Due to very high monochromaticity and greater precision, different types of lasers are being used for various machining purposes as shown in Figure 15. Lasers are being categorized according to the usage and its versatility which is being demanded by today's manufacturing industries at large scale. Some of the most prominent lasers which are used for the industrial needs are; gas lasers like CO_2 and excimer lasers, chemical lasers like hydrogen and deuterium, solid state lasers like Nd:YAG etc., metal vapor lasers like helium cadmium and semiconductor lasers like gallium nitride, AlGaAs etc.

The laser action is being initiated with the help of the active electrons and ions and is responsible for the transition in the energy levels [12].

- **Gas lasers:** Coherent light is produced by a gas when the discharge electric current flows through the medium. It was the first continuous laser light to operate on the conversion of electric energy into the light energy with visible red light as the primary output.

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- **Chemical lasers:** In a chemical laser, chemical reaction is the medium to obtain the laser beam output. It has a continuous wavelength with its power almost reaches to the level of megawatts. Drilling and cutting are the major operations that are done using the chemical lasers.
- **Solid state lasers:** A laser which uses solid gain medium like ruby etc other than liquid medium such as gas or dye is termed as solid state laser. Host material such as glass is used as laser medium in which dopant like chromium, ytterbium etc. is added which emits infrared light at a particular wavelength.

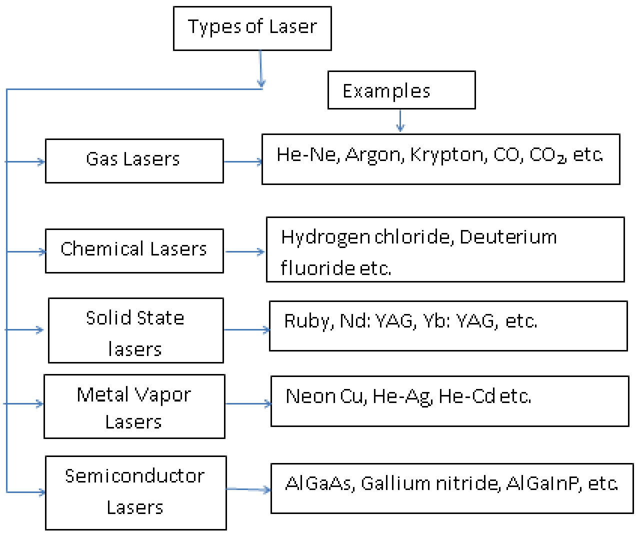


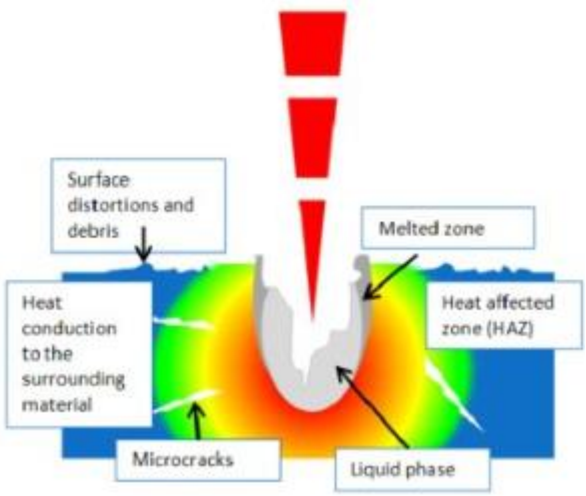
Figure 15. Types of Commonly Used Lasers [13]

- **Metal vapour lasers:** Like solid state lasers, metal vapour laser use vaporized metal as a gain medium. It was first developed by Silfvast in 1966. Further, the gain medium is put in the cavity with the heater to form vapors. Then the vaporised metal with the help of current, pumps the vapour into the medium, which helps in the generation of the laser beam. Various examples of metal vapour lasers are He-Cd, He-Hg etc.
- **Semiconductor lasers:**It is generally termed as diode laser. It is a semiconductor device in which the laser beam is created at the junction of the diode. Its function is to directly convert electrical energy into the light energy. It allows the recombination of the electrons with a hole due to the voltage driven in doped p-n junction transition. This allows the fall of the electron from the higher energy level to the lower level, results in generating radiation in the form of emitting photon. Stimulated generation of beam is produced which generates light of same wavelength, coherence and phase. Further the range of the diode laser varies from infra red to ultra violet (UV) spectrum. The basic application includes communication through fibre optics, reading of barcodes, pointers, DVDs etc. [13].

A. Different Modes of Laser Operations

The various modes of operations on the basis of desired applications in a laser beam machining processes are broadly categorized as continuous wave, single pulsed, Q-switched pulse, repetitively pulsed and mode locked [12] [14].

- **Continuous Wave (CW):** It is the operation of continuous wave mode in which the laser is being pumped continuously with the stable average beam power. This results in the constant emission of light as the medium is being pumped continuously without any delay. He-Ne laser is one of such example.
- **Normal mode (Single Pulsed):** As the name suggest, the mode of operation is referred to as long pulse or normal mode when the laser is generally having the duration of pulse from few hundred microseconds to milliseconds.
- **Q-Switched Pulsed:** Q-Switched laser uses laser media of Q-switch cells which allows to stores the potential energy to the maximum level. When the optimum gain condition reaches, the laser emission occurs in a single pulse, which emits the highest peak ranges from 10^6 to 10^9 watts. This is the reason that Q-switch laser pulse is also known as giant pulse formation with extremely high peak power. This process remains continued until the pumping is switched off. Further to achieve strong, single and short pulse this technique is used very often for industrial purposes.
- **Repetitively Pulsed:** When the pulse operation of laser beam is operating at a fixed rate of pulse ranges upto as high as 20,000 pulses per second on a repetitive basis then it is called repetitively pulsed laser.
- **Mode Locked**: Ultra short laser pulse is generated using the mode locking operation. In this pulse operation phases of various frequency modes are synchronized or locked together. These phases will interfere with each other to generate a very high frequency beam effect. This effect ranges from 10^{-15} femto to 10^{-12} pico seconds. This mode locking pulsating laser beam can deliver very high power when compared to the Q switched pulse laser which can reach upto the range of 10^{12} watts. The schematic diagram of long pulsed and short pulsed fibre laser is depicted in **Figure 16.**



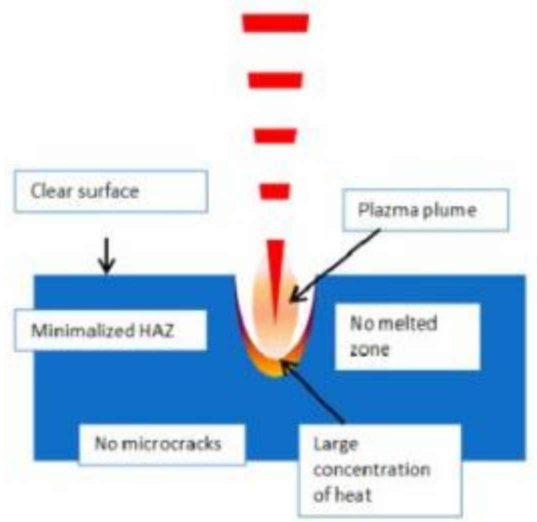


Figure 16(a) Long Pulsed **(b)** Ultra Short Pulsed Fibre Lasers [13]

Figure **16 (a)** and **(b)** shows HAZ formed by long and short type of pulsed laser. It has been revealed that the HAZ is more prominent for the long pulses because of the comparatively longer duration of time period of laser radiation on the material surface which allows the transmission of additional heat, results into huge thermal stresses and ultimately leading into micro cracks, debris at the surface due to solidification of molten material. Whereas, laser having shorter pulse has small HAZ because of the short time duration of thermal transportation from laser pulse onto the material surface, leaving behind a much accurate, aesthetic and precise structure.

These long and short pulsed lasers are much used in High power diode lasers (HPLD). Table 2 shows comparison of some of the different types of important industrial lasers. HPLDs are very compact and are of portable type with highest quantum efficiency upto 50%. HPLDs have longer life and run on low running cost than the other laser systems. HPLDs are used for soldering, glazing, marking, micro welding and engraving etc [16-25]

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TABLE 2. COMPARISON OF DIFFERENT TYPES OF LASERS [15]

Lasers Types	Features	Main weakness	Applications
CO_2 Laser	*Highest average power (25KW) *Good beam mode Efficiency is high (15%)	*The beam cannot be delivered by utilizing optical fibers	Marking of non-metallic materials, sheet metal cutting, welding etc.
Nd-YAG Laser	*Transmittable beam through optical fibers * Pulsed beam having high peak power	*Sensitive surface colour *Need high safety Poor beam mode.	Multi axis robotic welding, machining and paint stripping, drilling and metal marking etc.
Excimer Laser	*Peak power is maximum *Very short pulse UV wavelength	*Having high cost to run and install *Need high safety	Micro-machining, Chemical and physical vapor deposition, surface cleaning etc.
HPLD	*Size is small and portable *Long life up to 100000hrs Low voltage device *Very less maintenance Quantum efficiency is maximum (up to 50%)	*Beam mode is poor *Need high safety *Cost is high Limited power	Glazing, soldering, micro-welding and engraving.

B. Applications of Various Lasers

Laser due to its unique features and properties other than ordinary light has a broad range of applications in different industrial areas like cutting, scribing, marking, welding, and engraving etc. Various important and considerable applications of lasers beam machining are given in Table 3.

TABLE 3.TYPICAL APPLICATIONS OF LASER BEAM MACHINING [26-28]

Materials	Applications
Ceramics, silicon and plastic	Via drilling and interconnect drilling
Inorganics, metal and plastic	High volume via turning quartz, drilling and oscillators,
Metal, silicon, ceramic, plastic	Via drilling & interconnect drilling
Metal, plastic, oxides silicon	Thin film, bulk machining resistor and I.C. engine.
Metals, plastic, oxide silicon	Thin film, Bulk machining resistor and IC repair
Silicon	Existing trimming
Metals, plastic, ceramics and inorganic	Balloons, Micro-office drilling, angioplasty devices etc.
Plastic	Orifice drilling
Metals	Diagnostic tools and stents
Silicon, plastic, glass, ceramics	Air bearing, wire stripping and heads micro via drilling
Plastic	Wire stripping
Metals, plastic, ceramics	Disk texturing servo etching micro via drilling

C. Recent Advances in Laser Assisted Machining

To fulfill the present demands of the various manufacturing industries numerous efforts have been made in the past by different researchers. These efforts are categorized as:

- **Laser Drilling:** It is the process through holes or popped holes of smaller diameter of 0.002” (~50 µm) can be created by using pulsing focused laser energy repeatedly on to material. The steps involved in laser drilling includes heating of solid, change of phase, formation of plasma and ejection of vapor melt from irradiated region.
- **Laser Cutting:** Technology which cut materials with the help of laser beam is termed as laser cutting. Sheet metals are cut and shaped according to its desired size with the help of high power lasers machines.

However, this process requires appropriate range and selection of the cutting parameters to obtain desired quality of cut surface.

- **Laser Welding:** When pieces of different metals or thermo-plastics are joined using laser beam, the process is termed as laser welding. During welding a rigorous source of heat is provided narrow and deep welding. This process is commonly used in large volume of applications with the help of automation, majorly in the automotive industries.
- **Laser Bending:** whenever a material is bent with help of laser irradiation, laser bending is occurred. The bending process is slightly different from the laser welding such that the in this shallow depth of the phase change is required at the surface level where as deep penetration is required in the laser welding process into the material substrates
- **Laser Engraving:** Laser engraving technique is used to remove the material surface at the micro level to a very precise level. In this technique, laser strikes on the surface to eradicate the material by vaporization and other erosive processes to get the desired pattern or shape [29-43].

III. CONCLUSION

Among the various non-conventional machining methods available, a variety of laser assisted machining methods like laser welding; drilling, bending, cutting, and engraving are widely used for difficult to cut materials. These lasers based techniques are utilized for different and unique purposes on various materials. High precision, flexibility and high degree of freedom in the machining environment are the special features of laser based processes. Therefore, the problems like large cutting forces, elevated cutting temperature, poor surface finish and lesser tool life has been resolved using the LAM methods. Also, recent advancement in laser assisted machining methods fulfills the present demands of the various manufacturing industries with less production cost and more productivity.

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