Chapter

Laser Machining

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Abstract

The increasing demands of materials with superior properties are given priority by most of the industries in recent years due to their higher performance levels. Machining of hard materials is a challenging task since it involves higher cutting forces and rapid tool wear. This leads to complexity in shaping these difficult-to machine materials such as advanced composite and ceramics. There have been many alternative techniques developed to overcome the shortcomings of conventional machining processes. Laser beam machining (LBM) is one of the advanced non-contact machining processes that employ monochromatic light with high frequency for machining using thermal energy. The highly energized photos are focused on a material cause heating, melting and vaporizes the material which is effectively used to remove unwanted portion of a material. Due to higher coherency of laser beam, materials can be machined very precisely than conventional machining processes. Generally, the laser-based material processing is suitable for a brittle type of material with minimum conductivity. However, this laser machining can be used for all kinds of materials in most cases. This chapter provides the principle of laser and its types, mechanism of material removal using laser, applications, advantages, and limitations of LBM.

Keywords: laser, monochromatic, machining, laser ablation, stimulated emission

1. Introduction

The growing product development for advanced applications such as aerospace, automobiles, electronics and medical devices requires materials with high strength-to-weight ratio. Advanced materials with superior properties are being developed by researchers around the world for meeting the growing demand. The materials such as nickel, titanium and their alloys, ceramics are known not only for high strength-to-weight ratio but also for higher level of corrosion resistance, prolonging capacity at higher temperatures with superior mechanical strength comparing to other engineering materials [1]. These materials have greater properties such as higher density and melting point, ductile, higher hardness and strength, hence conventionally machining these materials is very challenging. Despite, it can be machined using conventional techniques, but higher cutting forces and rigorous tool wear attributes to huge cost in shaping these materials to the requirement. Hence there were many unconventional machining processes (UMPs) developed to replace conventional machining processes. One of the UMPs is laser beam machining (LBM) which is extensively used machining those difficult-to-machine materials. LBM is considered suitable for machining hard materials LBM is characterized by independency to hardness property of work material. LBM is gaining attention among the researchers and industry people because of its advantages such as higher light intensity with low power requirement, good focusing property within short duration of pulse, uniform heat distribution, eco-friendly nature which results in accuracy in machining, narrow heat affected zone, increased productivity and reduced manufacturing cost [2]. The upcoming sections describes in detail about the principle of laser and its types, mechanism of laser machining, advantages, applications and limitations of using LBM.

2. Principle of laser

The principle of Light amplification by stimulated emission of radiation (LASER) was first hypothesized by Albert Einstein in the year of 1917 but it took almost half a century to construct a working laser. Around 1960, a first experimental setup of working industrial laser is developed. In many cases, the laser is different from the normal light in a way that it carries photons of higher frequencies. However, in some cases, the infrared laser has photons with low frequency than normal light. The frequencies of all the photons contained in a laser light are all same hence laser is characterized by coherence. The photons carried by a light can stimulate the electrons in an atom therefore it emits same frequency photons [3]. Based on this principle, laser produces high energy coherent light. Since laser is the fundamental part of any laser-based system, it is essential to understand the principle of laser light production.

Stimulation and amplification is the process (called as lasing) by which laser system converts electrical energy into a light of high intensity energy. The medium by which the lasing process carried out is called lasing medium. In any model of an atom, positively charged nucleus is surrounded by negatively charged electrons rotating at some specified path called orbits. The diameter and geometry of the orbit vary based on many parameters including number of electrons, surrounded magnetic field, structure of electrons and the existence of neighbor atoms. Every electron presents in the orbital connected with a distinctive energy level. An atom is said to be at ground level when it is at absolute zero temperature in which all the electrons reside in their lowest potential energy. Energy from any exciting sources such as electronic pulsation at higher temperature, chemical reaction or photon can be absorbed by an electron at ground level. After absorbing the energy, it excites to a higher energy level as schematically shown in **Figure 1**. Thus the movement of electron from lower to higher energy level is accomplished. Upon reaching higher energy levels, electron attains an unstable energy band. Immediately within very short time (tens of nanosecond) it starts moving back to ground state by releasing

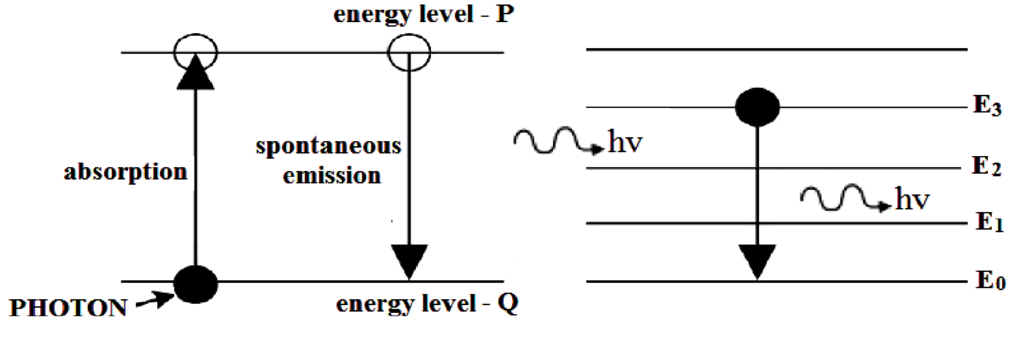

Figure 1.
Excitation between energy levels.

a photon and this process is termed as "spontaneous emission." The frequency of emitted photon would be equal to the frequency of exciting photon.

Sometime, when the electrons put into a meta-stable band due to energy change, the electron stays in the higher energy level itself for a short time (micro to milli-seconds). The state by which more number of electrons stays in meta-stable energy level compared to the atoms in the ground level of a material is called "population inversion." These electrons are stimulated by suitable energy or frequency photons to come back to ground state. Photons emission due to this stimulated return of electrons is termed as "stimulated emission." In this way, the emitted photons along with one original photon temporarily having some spatial phase would create coherent laser beam. From the schematic representation of stimulated absorption, spontaneous emission, and stimulated emission as shown in **Figure 2**, position of electrons in various energy levels are shown.

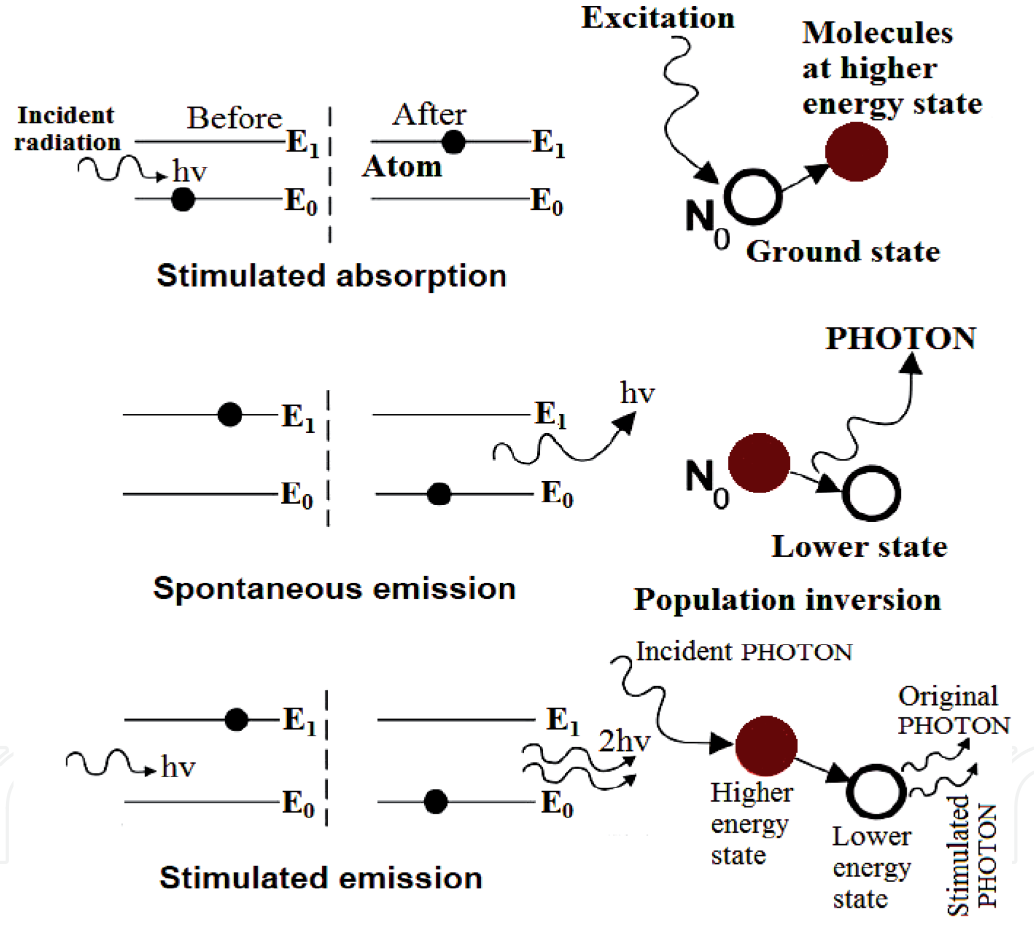

Figure 2.
Excitation between energy levels.

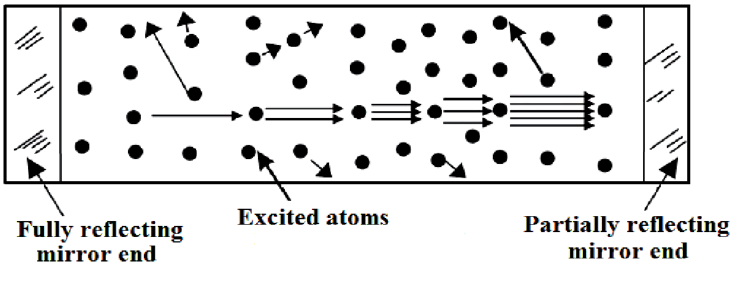

Figure 3.
Excitation between energy levels.

The working of laser is schematically represented in **Figure 3**. A lasing medium contained by a cylindrical glass container is closed using completely (100%) reflecting mirror on one end and partially reflecting mirror on the other end. When the glass vessel is exposed to a light using flash lamps, the photons of light excites the atoms of lasing medium thus population inversion is obtained. Further due to stimulated emission, photons are emitted. These stimulated photons in the longitudinal direction form a high intense, coherent and highly directional laser beam. Most of the stimulated photons would not be in the longitudinal direction and these photons usually generate waste heat and finally lost.

3. Properties of laser

The distinctive properties of laser are coherence, highly monochromatic, intensive radiance and directionality. These optical properties can be quantified for analyzing the laser properties.

3.1 Coherence

The relationship between magnetic and electronic components of electromagnetic wave refers to coherence property. The light beam is said to be coherent when these components are properly aligned as shown in **Figure 4**. There are two terms of coherence for a laser as spatial coherence and temporal coherence. Coherence is said to be spatial when the correlation of phases happens at different points in a space at a single point of time whereas in temporal coherence, correlation happens at single point in a space over a time period. **Figure 5** shows the concept of coherence. Temporal coherence can be quantified through two important measures such as coherence length and time. This property can be improved by run the laser in single longitudinal and transverse mode.

3.2 Monochromatic

It is the most important property of laser and it can be measured by spectral line width. When the range of emitted frequencies is small by a light source, it is said to be high monochromatic. Laser beam normally have very few or single spectral lines with highly narrow widths as shown in **Figure 6**. Monochromaticity is most important because wide range of applications depends on this property such as interferometry, velocimetry, holography, separation of isotope and communications which require laser beam content. But this property is a not decisive factor for machining.

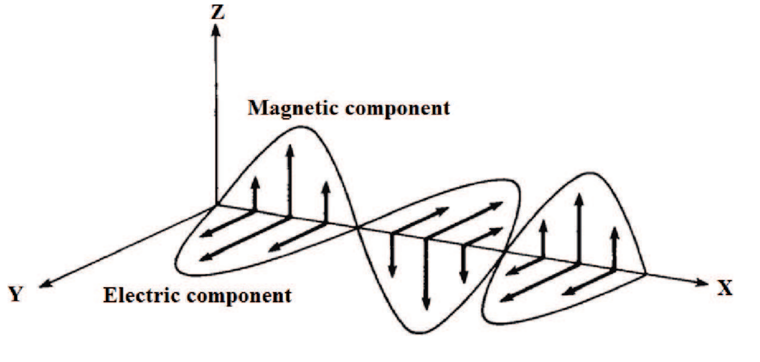

Figure 4.
Components of electromagnetic wave.

DOI: http://dx.doi.org/10.5772/intechopen.93779

3.3 Low-diffraction or collimation

Directionality is a property by which a light beam bends after passing sharp corners of objects. Diffraction or scattering of light at sharp edges increase the distance

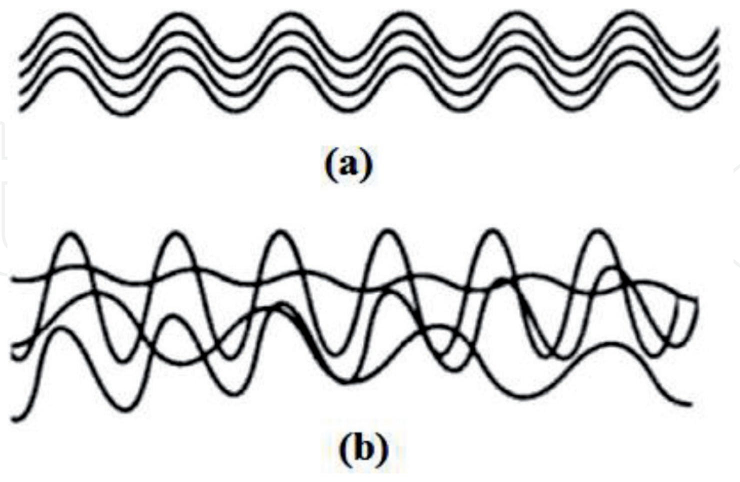

Figure 5.
Schematic of spatially and temporally (a) coherent light and (b) incoherent light.

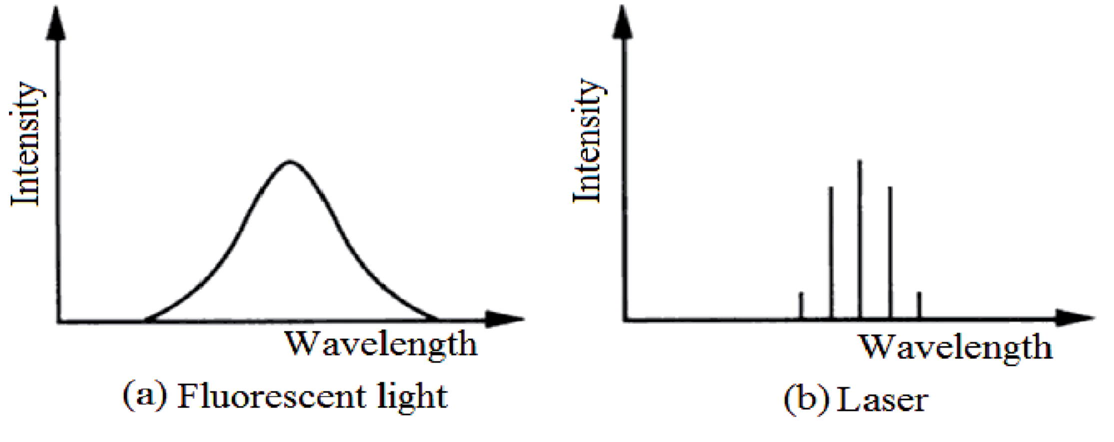

Figure 6.
Monochromaticity.

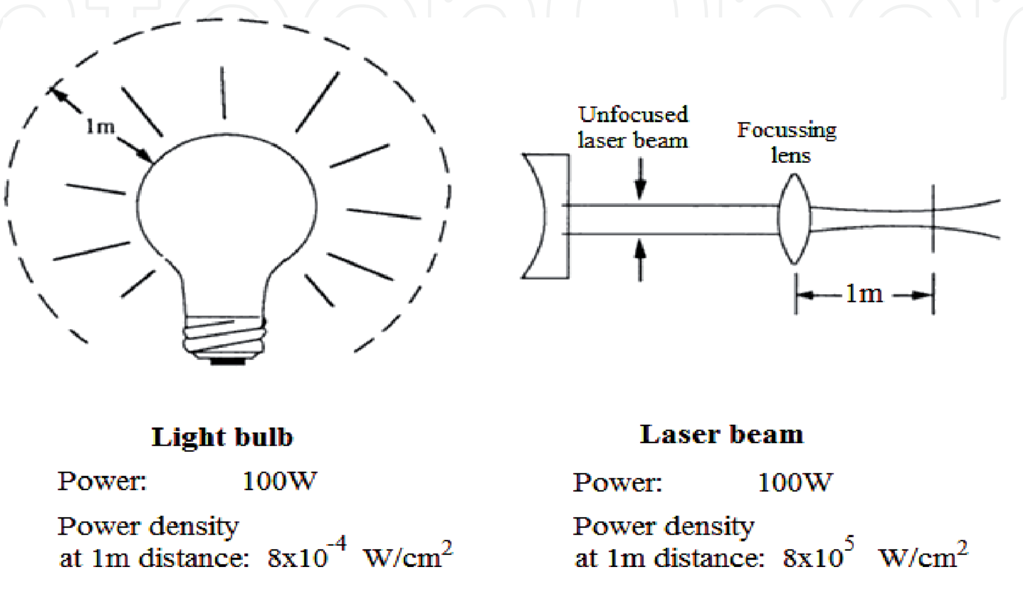

Figure 7.
Comparison of radiation from normal light bulb and a laser beam.

from light source therefore certain amount of energy is lost. But laser beams possess very low-diffraction property hence higher energy transfer can be effectively achieved. This directional characteristic is useful when directing the laser beam for machining applications.

3.4 Intensive radiance

The intensive radiance of a light is defined as the amount of power emitted per unit area for a given solid angle. The unit for radiance is watts per square meter per steradian. The angle by which a light beam is focused as a cone is called a solid angle. Since the intensity of photons is high in laser beam, it can have high output powers. Laser light source possess extreme amount of intensive radiance and transmitted through a small solid edge angle. This property makes it very convenient to be used for machining operations. **Figure 7** gives the comparison of power density transmitted by normal light source and a laser [3].

4. Types of laser

Lasers are classified based on the state of lasing medium used and the temporal mode. Based on the physical nature lasers are classified into solid-state lasers, gas lasers, semiconductor, and liquid dye lasers [4]. Based on temporal mode, further laser is categorized into two modes namely continuous wave (CW) and pulsed mode. Continuous mode emits the laser beam continuously without interruption whereas pulsed mode emits the laser beam periodically. **Tables 1** and **2** shows the important laser types along with their wavelengths.

In solid-state layers, the lasing medium is doped with very small number of impurity ions. Maimam has developed the first solid-state laser during 1960 which was a ruby laser. There are a number of laser types developed in the solid-state category in which Nd:YAG is majorly used for LBM applications. Solid-state lasers such as Nd:YAG, ruby and Nd-glass are highly used for machining metallic materials. Nd:YAG lasers can also be used to ceramic materials. Gas lasers are grouped

Solid-sate lasers.		Gas lasers	
Lasing medium	**Wavelength (nm)**	**Lasing medium**	**Wavelength (nm)**
Ruby	694	ArF	191
Alexandrite	700–820	KrF	249
Ti-sapphire	700–1100	XeCl	308
Nd-YLF	1047	XeF	351
Nd:YAG	1064	Argon	488, 514.5
Nd:glass	1062	Krypton	520–676
Er-YAG	2940	HeCd	441.5, 325
—	—	Copper vapor	510.6, 578.2
		Gold vapor	628
		HeNe	632.8
		CO_2	10,600

Table 1.
Solid-sate and gas lasers with their wavelengths.

Semiconductor lasers		Liquid dye lasers	
Lasing medium	**Wavelength (nm)**	**Lasing medium**	**Wavelength (nm)**
AlGaInP	630–680	Stilbene	403–428
AlGaAs	780–880	Coumarin 102	460–515
InGaAs	980	Rhodamine 6G	570–640
InGaAsP	1150–1650	—	—

Table 2.
Semiconductor and liquid dye lasers with their wavelengths.

into three categories based on the composition such as neutral atom, ion, and molecular. Gas lasers generally can be of CW or pulsed mode lasers and available with axial flow, transverse flow and folded axial flow in construction. CO_2 laser is the most commonly used gas laser for machining plastics, ceramics, nonmetals and sometimes organic materials also.

Semiconductor lasers, though made of solid materials the working principle are different from solid-state lasers. It is based on radiative recombination of charge carriers. Unique characteristic of a semiconductor laser is that they are capable of producing wide beam divergence angles around 40°. Comparing to other types of lasers, liquid-state lasers are easier to fabricate. Main advantages of liquid-state lasers are ease cooling and replenishment in laser cavities. Spectral properties of liquid organic molecules enable liquid dye lasers to get tuned within wide range of wavelengths from 200 nm to 1000 nm. The detailed working principles of these lasers are beyond the scope of this chapter and can be found in any standards texts.

5. Material removal using laser

5.1 Construction of LBM

Laser beam machining is a nonconventional, advanced machining process wherein there are essential parts required to construct a complete LBM setup. A pumping medium or lasing medium that contains large quantity of atoms is a primary component to produce laser light. For exciting the atoms in lasing medium, a flash lamp or flash tube is needed and it should be connected to the controlled high voltage power supply. Based on the type of operating mode (either pulsed mode or CW) a capacitor can be integrated to the power circuit. A typical solid-state LBM setup is schematically shown in **Figure 8**.

5.2 Mechanism of material removal in LBM

Laser based machining processes is identified as a material removal technique in industrial application. Materials removal is accomplished by the interaction between the laser beam and work material. It is severely a localized thermal process. Higher amount of light energy is received by base material and then higher heat is created between the locality of interaction while hitting the laser source on the base material. Due to highly elevated temperature at the beam spot, the material becomes soft, melt, burn and vaporized. Additionally, the interaction of laser beams and work material is associated with the material removal by photochemical process which is often called photo ablation. **Figure 9** schematically represents the effects of laser beam-work material interaction [5].

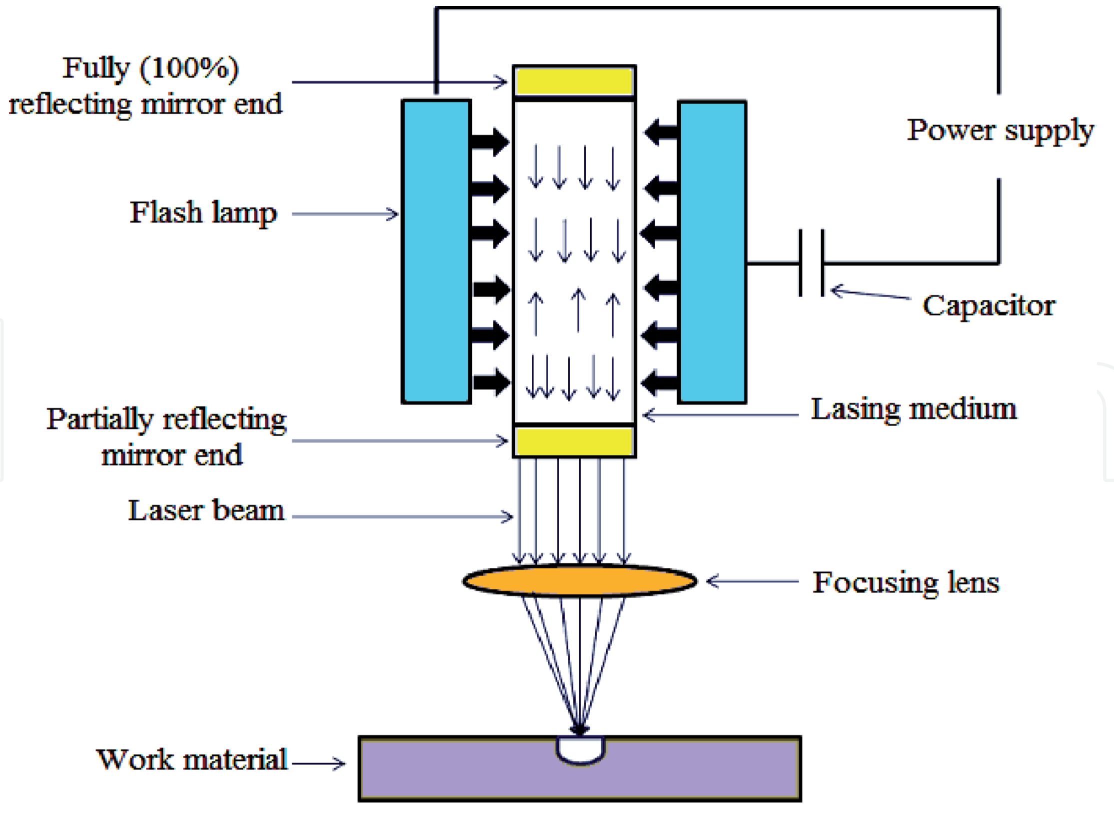

Figure 8.
Laser beam machining setup.

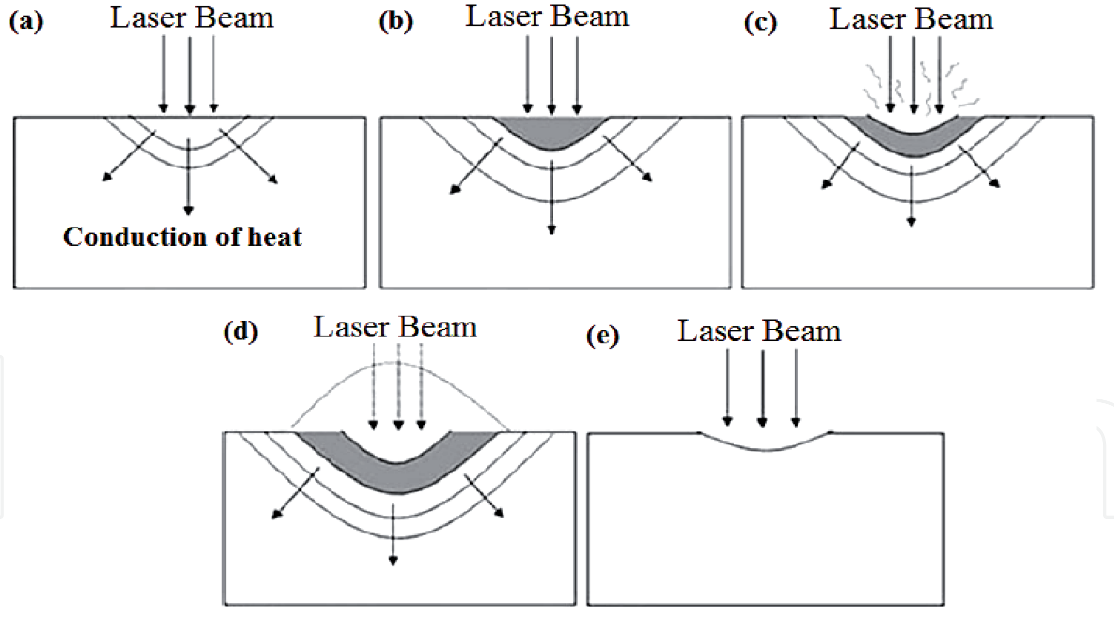

Figure 9.
Laser beam-work material interactions: (a) heating, (b) melting of surface, (c) vaporization of surface, (d) formation of plasma, and (e) ablation.

The parameters of LBM such as intensity of laser light, distribution of beam, spot size, scanning speed, and relative motion between laser beam and work piece can be changed according to the requirements for different work materials. As presented in the introduction section, lasers are replacing conventional machining processes due to many advantages. Many developments have been made in the laser technology to shorten the pulse time for different machining processes. Longer pulse duration increases the heat affected zone (HAZ) and leaves high thermal

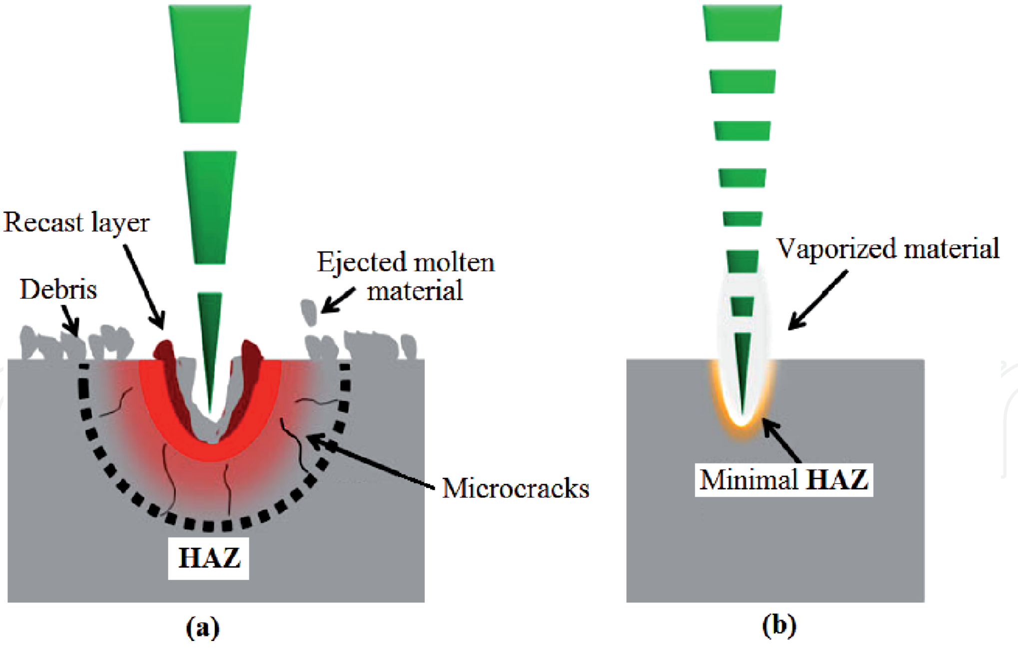

Figure 10.
Difference between the effects of (a) long-pulsed and (b) short-pulsed lasers.

stresses resulting in crack and void formation, and surface debris. Short pulse duration leads to lesser thermal conduction thus resulting in precise machining operation and good surface finish. **Figure 10** shows the difference between the effects of long and short pulse durations [6].

5.3 Types of LBM techniques

Machining using laser is generally categorized into three types namely one-dimensional, two-dimensional and three-dimensional machining processes. In one dimensional machining process, the laser beam will have no relative motion with the work piece material. In this relatively stationary arrangement, the erosion front is located at the work piece and focused laser beam removes the material in the path it propagates through which is a straight line. Hence one-dimensional LBM process is generally used for drilling applications. In contrast, the work piece also will move along with laser source in two-dimensional LBM process. The erosion front placed on the beam edge and the material removal happens in a two-dimensional plane

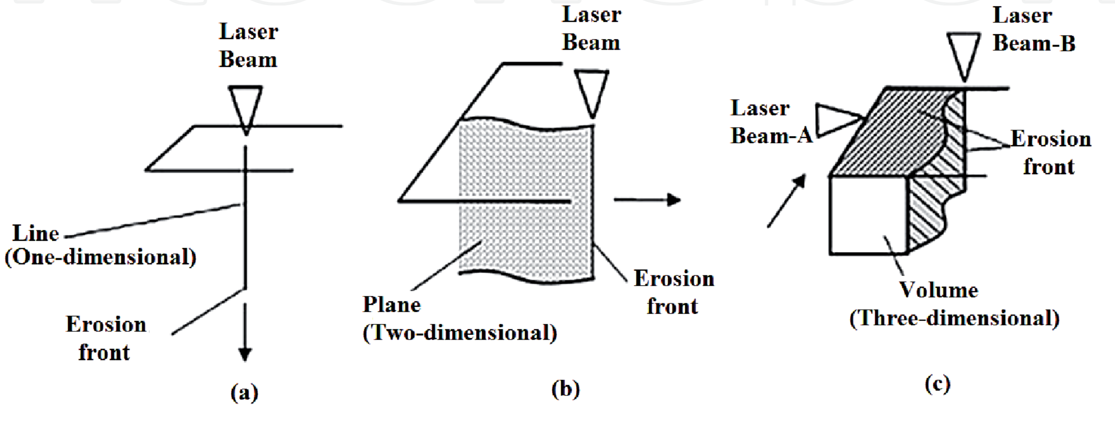

Figure 11.
Schematic of (a) one-dimensional (drilling), (b) two-dimensional (cutting), and (c) three-dimensional (milling) machining operations.

resulting in a creation of two-dimensional surface as shown in **Figure 11**. Two-dimensional LBM is most suitable for cutting operations. Three-dimensional LBM uses two or more sources of laser beams. Each laser beam forms two-dimensional surfaces according to their relative motion with the work piece. When the surfaces formed by each laser beams intersects a three-dimensional space is created that defines the shape of material to be removed. Three-dimensional LBM process is generally used for milling process. For better understanding of different types of LBM processes a schematic representation is given in **Figure 11** [7].

6. Applications

In general, the use of lasers found in many applications includes chemical, biochemical, optics, medical, military operations, polymer sciences, nuclear physics [8–12] and so on. In manufacturing, lasers are successfully applied for material removal, metal joining, cladding and alloying processes. Specifically, this chapter discusses the material removal applications of lasers. Drilling, grooving, cutting, three-dimensional machining operations such as lathe and milling operations, micro machining and laser assisted machining processes are the extended applications of lasers in LBM [3].

6.1 Drilling using LBM

One of the major advantages in drilling using lasers compared to conventional machining process is the aspect ratio (max 1:20) and small size of the hole drilled. Both continuous and pulse laser are used for drilling operations in which pulsed laser gives lesser plasma generation. The types of drilling operations that can be performed using LBM are single-pulsed drilling, percussion drilling, trepanning and helical drilling. When laser beam is focused into the material, the temperature is created by absorbing the photons. The material melts and vaporizes when the temperature exceeds the melting temperature of the material. If the radiation of laser is set lesser than particular threshold (106 W/cm^2 for steels), the material melts but not vaporizes and using a jet of gas the molten material is ejected [13]. The single pulse drilling process makes either through or blind holes with less than 1:15 aspect ratio. This is a rapid drilling process mainly suitable where production rate is more important than quality. Single pulse drilling is mostly adapted in automotive industry for processing connecting rods and filters. Percussion drilling uses pulsed-lasers' focus on the same spot to produce a hole while maintaining a balance between throughput and quality. Due to major advantages like its precision and quick processing capability, percussion drilling is adapted in making holes in the blades of turbine-airfoil. Though it has major advantages, there are drawbacks reported such as dross, spatter, and tapering.

Trepanning technique is another hole making technique where the material removal is performed on the circumference of any circle to make holes of higher diameters. It is considered to be a standard technique for making holes around 500 micrometers diameter. The nanosecond pulsed laser source is utilized for material removal around the circumference hence the drawbacks of percussion drilling remains in this application also. Trepanning technique reduces the taper effect and produces more jagged edge quality. To overcome the drawbacks of trepanning a relatively new technique called helical drilling is introduced. Helical drilling follows multitude ablation steps. The advantages of helical drilling over trepanning using percussion drilling are improved circularity of drilled holes, minimized loads on opposite walls and more importantly reduced recast layers or sometimes completely

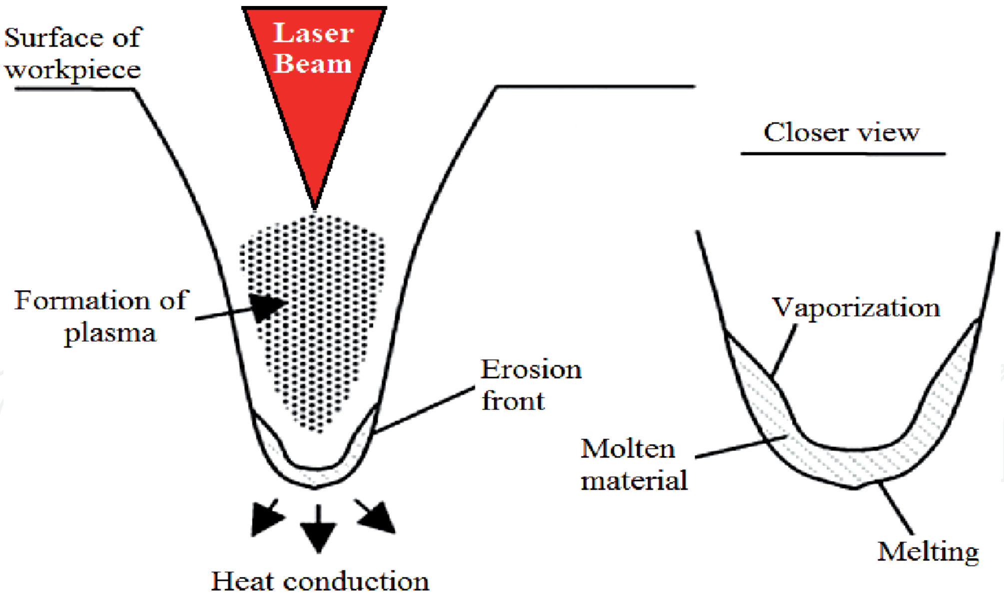

Figure 12.
Schematic of laser drilling.

avoided. Helical drilling is more preferred in the case of laser beam diameter is very near to helical diameter at focus point. Energy balance is important in laser drilling among the energy released by laser beam, energy absorbed by material, energy lost to the surrounding and the energy utilized for melting (phase changing) the material as shown in **Figure 12**.

6.2 Cutting using LBM

Cutting is an essential operation in any material removal processes. A relative motion between work piece and the laser beam is required to produce a two-dimensional working plane where the material removal takes place. During relative motion of laser beam and work piece, a kerf is produced which removes the material in its path. Complex two-dimensional shapes can be cut from the flat work piece

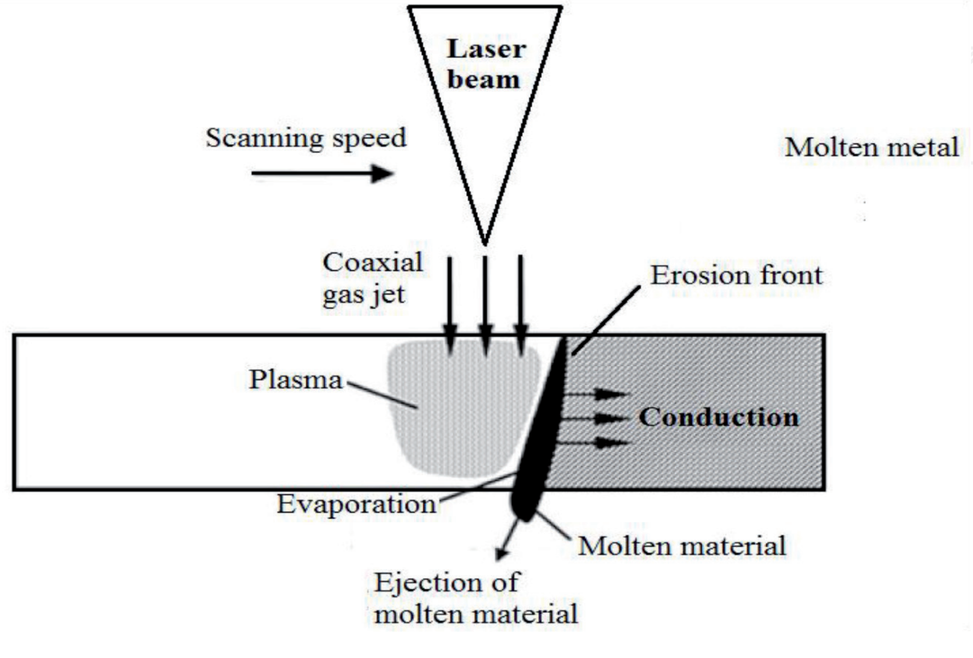

Figure 13.
LBM for cutting operation.

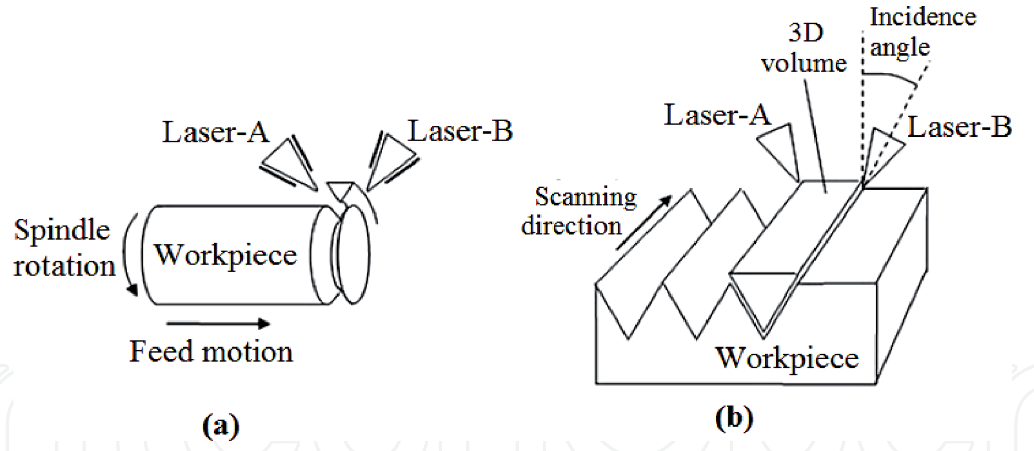

Figure 14.
Three-dimensional LBM for (a) lathe operation and (b) milling operation.

materials where mechanism of material removal is similar to drilling operation. In contrast to the drilling process, the erosion front is located at the front of line of laser beam as shown in **Figure 13**. However, the temperature field and erosion front is fixed based on the coordinate moves along with produced laser source that ensures steady state process. The erosion front molten material is flushed away using a gas jet during the cutting process.

6.3 Three-dimensional LBM

Three-dimensional LBM uses two or more number of laser beams simultaneously focused to obtain an intersected volume for material removal. To precisely create such volumes with relative motions, highly accurate optical manipulating systems are therefore necessary. Recent systems equipped with optical scanning systems have high level of control over the motion of laser beams which enables efficient and effective machining operations. The material removal using these tools is referred as 3-dimensional (3D) laser material processing. In general, the 3D laser material processing is grouped into various categories such as laser beams along with 3D LBM, 5-axis heads along with 3D processing workstation and 3D remote laser processing. **Figure 14** illustrate the graphical picture of two-beam laser machining processes for lathe and milling operations. Each beam creates a groove like volume of material removal when they intersect with some incidence angle. The incidence angle may be changed and dynamically varied along with relative motion to get intricate shapes of machining.

LBM is successfully adapted in micromachining field due to its high flexibility to automation and high degree of radiance. Laser beam micromachining is capable of producing parts with sizes ranging from micro to sub-micro scales. It usually employs the pulsed lasers with an average power of less than 1 kW. The pulses of femtosecond duration are widely used for micromachining. Micromachining can be performed on wide range of materials such as metals, glasses, diamond and other difficult to machining materials. Laser-assisted manufacturing (LAM) is another technique helps to enhance the maximum productivity, quality with minimized machine tool vibrations, machining forces and tool wear. LAM is also an effective technique to machine brittle materials without cracks and failure. This hybrid machining process, laser beam is focused on the work piece just before the cutting tool engages. Scanning of laser initially heats up the work therefore helps in plastic deformation rather than brittle deformation during machining. The LAM processes are suitable for brittle and hard type of material such as ceramics, nickel alloys and the higher amount of silicon element material.

7. Advantages

LBM is an excellent manufacturing technique to process wide ranges of difficult to machine materials especially ceramics and advanced composite materials. LBM technique is capable of machining intricate shapes that cannot be reached or processed by conventional machining processes. LBM is an alternate to conventional machining processes due to many advantages as follow:

- Due to precise machining capability, LBM can produce excellent surface finish therefore post processing can be eliminated.
- LBM is a clean manufacturing technique due to less environment pollution and no requirement of chemicals or solvents for machining.
- LBM can be easily automated for higher productivity and to achieve high speed machining.
- It uses no cutting tool therefore no cutting forces involved during machining. This phenomenon helps to avoid heavy construction of machine tools, physical damages, vibrations, frequent tooling requirements.
- Degree of accuracy in machining complex geometry is high.
- LBM depends on thermal and few optical properties of work material rather than mechanical properties such as hardness and brittleness. As a result, most of the materials with any degree of mechanical properties with lower diffusivity and conductivity can be machined.
- Wide range of materials from plastics to diamond can be machined.
- Residual stresses caused due to HAZ are very less in LBM.
- Machining micro features with large aspect ratio is possible with LBM.

8. Limitations

There are many issues and limitations associated with the aforementioned LBM technique. The major issues are produced accuracy, achieved surface quality and rate of material removal. The erosion front is the main factor decides the amount of material removal in LBM technique. In one-dimensional machining, the speed of propagation in erosion front in the straight line decides the rate of material removal. In another hand, the scanning speed plays a significant role in metal removal during the two-dimensional machining processes. Similarly, the laser scanning speed is produced the intersecting surfaces for volume formation and the decisive factor for material removal rate during the 3D machining processes. Controlling the LBM parameters for a balanced and effective machining is a real challenge faced by industries. Secondly, the dimensional accuracy is affected by the kerf shape of laser which leads to tapered holes instead of narrow holes. Surface quality is the other important aspect of machining, which is measured by surface roughness, formation of dross and the HAZ. Since LBM is completely thermal based machining process it also has several limitations such as,

- Minimum amount of metal removal
- Investment cost is high
- Highly skilled operator is required
- Maintenance cost is high
- Power consumption for LBM is high
- Transparent and greatly reflective materials cannot be machined using LBM
- Applications related to machining thicker materials are very limited

9. Conclusions

The chapter presented an overview of the LBM technique and the principle of laser production, properties, types of lasers, and its application in machining field. The advantages and limitations are also discussed at the end. Based on the discussions from the presented sections, the following conclusions are made regarding LBM.

- LBM is an effective technique for processing complex geometries of different materials with superior properties. While this technique is mostly advantageous in the field of machining, it also possesses few disadvantages such as low energy efficiency, low material removal rate which affects productivity, quality concern due to diverged or converged laser beam.
- LBM depends upon many important parameters such as wavelengths of lasers used, scanning speed, type of laser beam (pulsed or CW), pulse duration, assist gas and its flow, material properties and physical dimensions to assess some of the performance characteristics like surface quality, thermal stresses due to HAZ, formation of dross and defects.
- Excellent flexibility to automation of LBM enables it to be used in advanced machining applications like micromachining with superior level of accuracy.

Acknowledgements

The authors wish to thank the Ministry of Science and Technology, Taiwan ROC for the financial support to carry out this work.

Conflict of interest

The authors declare that they have no conflicts of interest in the work.

DOI: http://dx.doi.org/10.5772/intechopen.93779

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