CHARACTERIZATION OF LASER PLASMA IRRADIATION ON SOLID TARGET

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ABSTRACT

Plasma induced by focusing laser is very important phenomena to be applied in industries, medical and fusion research. A preliminary study leading to this research has been carried out. A Q-switch Nd:YAG laser with 1064 nm and 532 nm wavelength and 4 ns pulse duration was employed as a source of energy. The laser was focused using a single lens technique. Some variable were used in this laser plasma characterization studies including range of lenses with different focal length, different laser frequency and laser energy. In preliminary studies, the plasma generated at the focal region was detected and analyzed using video camera in conjunction of image processing system and interferometric technique. For laser irradiation on solid target, the pulsed laser was irradiated on aluminums, steels, burnt papers, silicon wafer and nanospheres. The interaction area was analyzed using metallurgical microscope and FE-SEM. The observation results show that the plasma was formed in an oval-like shape. The width and the length of the plasma were found linearly increased with respect to the lens focal length. The plasma temperature was found can achieve up to thousands of Kelvin when studied using interferometric technique. Besides that, solid material target show some physical changes due to shock wave induced by the pulsed laser.
CHAPTER I

INTRODUCTION

1.1 Research Background

Laser induced plasma (LIP) as well laser material interaction (LMI) offer great applications in fundamental and advanced research, renewable energy, industries and medical. In fundamental research, the laser is studies on the properties of laser beam and plasma generation. The factors that influence plasma formation in liquids environments and on solids were also investigated. For advanced research the laser plasma were used to study our space and galaxies. In the other hand, the laser induced plasma is broadly used to generate renewable energy especially in laser fusion research. In industries the laser is used as a tool to machine material such as aluminum, steel, glasses, polymer, semiconductor and nano-size material. For example, the lasers are used to cutting, carving, drilling, fabricating, micromachining, welding and marking. They are used because of precision, non-contact machining process, cleanliness and able to machining up to micron-scale piece of material.
1.2 Literature Review

In general, lasers are widely used to induce changes to the target material including solids, liquid, gas and plasma. We can cut, drill and weld metals and semiconductors only by controlling the properties of the laser beam. The main and very important criteria in controlling the laser beam are the optical system. The optical system may consist numbers of lenses, mirrors, polarizer, beam splitter, filter and so on. They are aligned in such way that can produce different properties of laser beam than from the output laser device. The changes of the laser beam (by specially aligning this optics) can induce different phenomena and changes to the target material. Consequently the properties of the interaction area of the material will also change. For example, in micromachining the depthness and dimension of the target area are very important. In addition the lasers offer very high accuracy, precision and cleanliness that are very hard to achieve by conventional method.

1.2.1 Laser Induced Plasma

The first demonstration of laser action by Maiman was achieved in 1960 by using ruby laser, a crystalline solid system (Koechner, 1976). Thus the demonstration has brought about a rapid growth in laser development and laser application. Hence, the study of laser produced plasma becomes one of the fastest growing fields in present-day physics. It has brought about numerous innovations in materials treatment, such as quality change, welding, drilling and related high-power beam weapons; the most exciting goal is the safe production of clean nuclear fusion energy with inexhaustive and low-cost fuel.

High power laser such as Q-switched Nd:YAG laser is usually used as a source in order to induce plasma. Laser induced optical breakdown was first demonstrated by Damon and Tomlinson in 1963, and since then many researchers have studied this phenomenon using a range of Q-switched lasers (Noriah Bidin, 1987). This nanosecond
long pulse laser beam will generate an optical breakdown when it is focused by lens. When focused to a small spot, usually less than 50 microns (μ) in diameter, Q-switched Nd:YAG lasers can produce adequate irradiance to induce optical breakdown.

One of the study of Q-switched Nd:YAG laser induced plasma has been reported by Kamarulzaki (Mohd. Kamarulzaki, 2000). In this study, the laser beam is brought to focus by lens. The focused beam generates an optical breakdown at the focal region. The optical breakdown is adequate to initiate plasma in the focal region through the mechanism of electron avalanche or cascade (Larsson et. al, 2001). The image of plasma formation was grab by using a high-speed photography system in conjunction with image processing system (Khairunnadim, 2000). Such of plasma formation in air was also been reported by Ahmad Hadi and Noriah (Ahmad Hadi Ali and Noriah Bidin, 2004).

Extended studies of plasma sizes induced by pulsed Nd:YAG laser and focused by different optical techniques and laser energy were also reported by Ahmad Hadi (Ahmad Hadi, 2004). In the same year, De Giacomo and De Pascale reported on the plasma formation some millimeters away from the target area by using 400 mJ Nd:YAG laser (De Giacomo, 2004). Then in 2005, Robledo-Martinez et. al. investigated the electrical size of laser plasma in a uniform electric field (Robledo-Martinez et. al. 2005). The dynamics of laser-produced plasma (LPP) and its shockwave-induced density jump (SIDJ) were investigated in low-pressure ambient air during the laser pulse using an optical interferometer (Tao et. al. 2006).

The advances of laser induced plasma studies were carried out by Nick Glumac and Greg Elliott (2007). They studied the effect of ambient pressure in the range of 0.1 to 1.0 atm on the size, temperature, electron number density, and fraction of laser energy absorbed in a laser-induced plasma in air. An analysis studies were conducted by Hongchao to determine the electron density temporal and spatial evolution of laser induced plasma in air from 18 ns and up to 100 ns of plasma lifetime by using mach-Zehnder interferometer (Hongchao et. al. 2009). In 2010, Fei Wand et. al. using acoustic
emission sensor to research the time-of-flight of the shock wave induced by laser-plasma in air for real time non-destructive evaluation (NDE) of laser shock processing (Fei Wang et. al. 2010).

1.2.2 Laser Plasma Irradiation on Solid Target

The interaction of a pulsed laser beam with solid materials is very practical in scientific research experiment as well as in manufacturing industry (Navarrete et. al. 2003). It offers wide potential application in different areas of research relevant to material treatment, physical analysis, photo deposition, depth profiling and many other areas (Colac, 2002). In industry laser is extensively used to cut and drill solid targets (Chwan & Hong, 2003). Lasers provide high accuracy, precision, cleanliness and the most important is it provides un-contact processes with the target material (Evgueni and Suwes, 2006).

Lasers such as Nd:YAG pulsed laser is generally used for this kind of operation. The laser pulse duration ranging from nanosecond to femtosecond provides laser peak power of up to tens of gigawatts (Torrisi et. al. 2001). It is easily could be achieved by producing laser pulse energy up to multi-kilojoules in a single shot or multishot pulses. This high peak power irradiance of laser pulse can induce an optical breakdown when brought to focus by lens (Walther et. al. 2002). This process of optical breakdown occurred in a very short time and can be observed by the formation of bluish spark at the focal region (Ahmad Hadi Ali and Noriah Bidin, 2004). The optical breakdown is adequate to initiate plasma through the mechanism of electron avalanche or cascade (Nadja and Natalie, 1998). After a free electron has been produced, the plasma grows as a cascade or avalanche when photon causes free electrons to accelerate and collide with atom (Tran, 2006).
When high peak power of laser pulse is focused through a lens on the metal surface, the beam makes contact with the surface consequently heating the metal. This results in the ablation of the metal target (St-Onge et. al. 2002). The temperature at the heated region can achieved up to thousands of Kelvin. Laser pulse affecting the metal surfaces could lead to phase transformation and structural changes as a result of physical and chemical processes. Laser metal surface interaction depends on the laser beam parameters; such as laser pulse power density, intensity, wavelength, beam divergence, beam diameter, incident angle and processing time. In addition the metal parameters are also important such as microstructure, chemical composition, thermal conductivity, phase, surface morphology and absorption (Balchev et. al. 2006). These processes also affected by ambient atmosphere where the laser metal interaction occur.

Laser plasma irradiations on solid targets such as aluminum, steel, glasses and semiconductor were extensively studied by researchers (Yilbas et. al. 2009). Fundamental studies on laser interaction with aluminum based on the energy distribution of aluminum plasma, laser ablation of aluminum, plume characteristics, vapor plasma formation and spectroscopic diagnostics were conducted (Torrisi et. al. 2006). In industries, the applications were found in very large scale machining processes such as laser plasma welding, cutting, drilling of aluminum (Ardian et. al. 2008).

1.3 Problem Statement

Based on the past researcher studies, there is some gaps/problem during investigating the laser matter interaction such as:

(i) The type of laser need to be changed based on the material used. This is mainly caused by the wavelength, energy and pulse duration of the laser that can induce different effect on the target area.

(ii) Lack of optical system was reported to change the properties of laser beam.
(iii) The laser beam only can induce changes in area down to micron sizes on target material such as aluminium, ceramics, steel, copper and semiconductor. A nano scale laser material interaction is needed especially for the nano structure material.

1.4 Research Objectives

This study embarks on the following objectives:

i. Induce plasma using pulse laser on air using multiple optical techniques and methods.

ii. Irradiates laser plasma on solid targets such as aluminum, steel, glasses and semiconductor.

iii. Analyze and characterize the plasma formation and solid material properties using multiple analyzing and diagnostic equipments.

1.5 Hypothesis

Based on fundamental waves and optical law, the precisely aligned optical system can change the properties of the laser beam. In addition, the best quality of interaction area on material is based the properties of the laser beam. So, it is hypothesized that the properties of the plasma formation on the focal region, on the solid target and interaction area on the solid target is strongly affected by the properties of the laser beams radiations and the optical system.
1.6 Scope and Delimitation of Studies

The scope of the study is confined under the Q-switched solid-state pulsed laser and optical system with variable target material.
CHAPTER II

LASER MATERIALS INTERACTIONS

2.1 Introduction

The physical process during laser beam interaction with material is very crucial to understand. When laser beam or laser pulse is incident on the surface of material, various phenomena occurs included absorption, refraction, reflection, scattering and transmission. One of the most important factors in laser material interaction (LMI) is the absorption of the laser radiation. The absorption of the laser radiation in the materials results in various effects such as heating, melting, vaporization and plasma formation. The extent of these effects depends on the characteristics of the laser beam (electromagnetic radiation) and the thermo-physical properties of the material. The laser parameter includes wavelength, frequency, intensity, coherence, polarization, pulse period, energy and power. In the other hand, the materials parameters include thermal conductivity, absorptivity, specific heat, latent heat and density.

2.2 Lasers

The most important parameter in the LMI is the radiation source itself, laser. Laser is an acronym for Light Amplification by Stimulated Emission of Radiation. The laser is
essentially a coherent, directionality, convergent and monochromatic beam of electromagnetic radiation with wavelength ranging from ultraviolet, UV to infrared, IR. Laser beam is transverse electromagnetic waves that have many applications in every field of fundamental and applied science, engineering, medicine and electronics.

2.2.1 Mechanism of Laser Operation

Basically, there are three processes required to produce the high-energy laser beam; that are population inversion, stimulated inversion and amplification.

a. Population Inversion.

Population inversion is a necessary condition for stimulated emission. Population inversion corresponds to a non-equilibrium distribution of electrons such that the higher energy states have a larger number of electrons than the lower energy states. The process of achieving the population inversion by exciting the electrons to the higher energy states is referred to as pumping. For a material in equilibrium, the distribution of electrons in various energy states is given by the Boltzmann distribution law:

\[ N_2 = N_1 \exp \left[ -\frac{(E_2 - E_1)}{kT} \right] \]  \hspace{1cm} (2.1)

Where \( N_1 \) and \( N_2 \) are the electron densities in states 1 and 2 with energies \( E_1 \) and \( E_2 \) respectively. \( k \) and \( T \) are the Boltzmann constant and absolute temperature respectively.

b. Stimulated Emission

Stimulated emission results when the incoming photon with frequency \( f \), such that \( hf = E_2 - E_1 \), interacts with the excited atoms of active laser medium with population inversion between energy level \( E_2 - E_1 \). This incoming photon or
stimulating photon triggers the emission of radiation by bringing the atom to the lower energy state. The emitted radiations have the same frequency, direction of travel and phase relationship as that of the incoming photon. As a result producing a stream of photon, called stimulated emission.

c. Amplification

The amplification of light can be achieved by stimulated emission of radiation. Amplification of laser light is accomplished in resonant cavity which consists of active material in between of a 100% reflective mirror at one end, whereas partially reflective mirror at the other end to allow amplified laser output.

### 2.2.2 Properties of Laser Radiation

Laser light is characterized by a number of unique properties including monochromaticity, collimation, coherence, brightness, focal spot size, transverse modes, temporal modes and frequency multiplication.

- **a. Monochromaticity** - The laser beam consists of very closely, discrete and narrow spectral lines.
- **b. Collimation** – Related to the directionality of the beam. Highly collimated beams are said to be highly directional, means the laser beam can be focused on a very small area even at longer distance.
- **c. Coherence** – The light waves have constant phase relationship.
- **d. Brightness** – Also known as radiance is defined as the amount of power emitted per unit area per unit solid angle. High brightness characteristics are influenced by operating the laser in Gaussian mode with minimum angle divergence angle and high output power.
e. Focal spot size – The spot radius is the distance from the axis of the beam to the point at which the intensity drops by $1/e^2$ from its value at the center of the beam. Focal spot size determines the irradiance, which is important in material processing.

f. Transverse mode – represented as the transverse electromagnetic mode, $\text{TEM}_{mn}$. The fundamental mode, $\text{TEM}_{00}$, has Gaussian spatial distribution and is the most commonly used mode in laser machining applications.

g. Temporal modes – The output laser beam can be either continuous CW or pulsed beam mode.

h. Frequency multiplication – The frequency of the laser beam can be multiplied by using frequency multiplier materials. An IR 1064 nm Nd:YAG laser can be frequency-doubled (second harmonic generation, 532 nm green visible), frequency-tripled (third harmonic generation, 355 nm UV) and frequency-quadrupled (fourth harmonic generation, 266 nm UV).

2.3 Absorption of Laser Radiation

Laser radiation is essentially electromagnetic waves, which are associated with electric ($\mathbf{E}$) and magnetic field vectors ($\mathbf{B}$). Absorption of light can be explained as the interactions of the electromagnetic radiation with the electrons of the contact material. The laser radiation can only interact with the lightweight electrons of the atoms of the material because the much heavier nuclei are not able to follow the high frequencies of the laser. When the electromagnetic radiation passes over the electrons, it exerts a force thus sets the electrons into motion by the electric field of the radiation (von Allmen, 1987).

$$F = e\mathbf{E} + \varepsilon_0 \varepsilon \left( \nabla \times \mathbf{H} \right)$$ (2.2)
The absorption of laser radiation in the material can be expressed by the Beer-Lambert law (Steen, 1991):

\[ I(z) = I_0 e^{-\mu z} \quad (2.3) \]

Where \( I_0 \) is the incident intensity, \( I(z) \) is the intensity at depth \( z \), and \( \mu \) is the absorption coefficient.

For opaque material, the absorptivity \( A \) is related to the reflectivity \( R \) by (Duley, 1983):

\[ A = 1 - R \quad (2.4) \]

The reflectivity and absorptivity of the material is greatly influenced by the wavelength and temperature (Duley, 1983).

Other parameters that influence the absorptivity of the material include the angle of incidence of the radiation and surface condition of the material. One way that can be utilized for the coupling of the laser radiation on to the reflective material is by applying antireflective surface coatings, and also by irradiating laser at certain suitable angle.

Laser energy absorbed by the material during LMI is converted into heat by degradation of the ordered and localized primary excitation energy. The typical energy relaxation times are of the order of \( 10^{13} \) s for metals and \( 10^{12} - 10^{6} \) s for nonmetals. The light energy conversion into heat and its subsequent conduction into the material establish the temperature distributions in the material. Depending on the magnitude of temperature rise during the heat conductions, various physical effects in the material including heating, melting and vaporization of the material. In addition, the rapid ionization of vapor during laser irradiation may lead to generation of plasma. Moreover for the thermal effects, the LMI may associate with photochemical processes such as photoablation of the material.
2.4 Thermal Effects

When laser beam with intensity $I_0$ is irradiated on a material’s surface, it results in the excitation of free electrons (in metals), vibrations (in insulators) or both (in semiconductors). This excitation energy is rapidly converted into heat depending on the type of materials. Followed by various heat transfer processes such as conduction into the materials, and as well convection and radiation into the surroundings. The generation of heat at the surface and conduction into the material establishes temperature distributions in the material depending on the thermo-physical properties of the material and the laser parameters such as wavelength, energy and time duration.

If the intensity of the laser beam is sufficiently high, the absorption of the laser energy may result in the phase transformation such as surface melting and vaporization. These phase transformation are associated with thresholds laser intensities $I_c$, referred to as melting and evaporation thresholds, $I_m$ and $I_v$. The processes of material heating, melting and evaporating are the efficient material removal mechanisms during LMI such as in laser machining process.

2.4.1 Heating

In order to understand the effects of laser irradiation on materials, it is necessary to evaluate the spatial and temporal variations of temperature distributions. The simplified thermal analysis based on one-dimensional heat conduction equation with simplified assumptions (Carslaw and Jaeger, 1959):

i. Material is homogeneous. The thermo-physical properties are independent of temperature.

ii. The initial temperature of the material is constant.

iii. Heat input is uniform during the irradiation time.
iv. The convection and radiation losses from the surface are negligible.

The temperature at the surface during heating and cooling can be expressed by (Narendra and Sandip, 2008):

\[
\Delta T(0, t)_{t < t_p} = \frac{H}{k} \left( \frac{4\pi t}{h} \right)^{1/2}
\]

\[
\Delta T(0, t)_{t > t_p} = \frac{H}{k} \left[ \left( \frac{4\pi t}{h} \right)^{1/2} - \left( \frac{4\pi (t - t_p)}{h} \right)^{1/2} \right]
\]

(2.5) (2.6)

Where \( T \) is the temperature at location \( z \), after time \( t \), \( \alpha \) is the thermal diffusivity, \( k \) is the thermal conductivity, \( H \) is the absorbed laser energy, and \( t_p \) is the irradiation time (pulse on time). For example, laser irradiation on copper with intensity \( I_0 = 10^{10} \) W/m\(^2\) and \( t_p = 1 \) \( \mu \)s, the important characteristics can be listed as (Wilson and Hawkes, 1987):

i. At the surface \( (z = 0) \), the temperature increases with increasing irradiation time, reaches maximum corresponding to pulse time, \( t_p \), and then rapidly decreases.

ii. At certain depths below the surface \( (z > 0) \), the temperature increases with increasing irradiation time, reaches maximum and then decreases. However, the maximum temperature does not reach exactly at the pulse time, \( t_p \), but at the longer time \( (t > t_p) \).

2.4.2 Melting

When laser irradiates a material, it is heated, and then the surface temperature may reach the melting point or the boiling point at sufficiently higher laser power densities, \( I_0 > 10^5 \) W/cm\(^2\). The corresponding laser power densities are often referred to as the melting and boiling thresholds. Each laser irradiation is characterized by the maximum depth of melting \( z_{max} \) corresponding to the cessation of laser power (where the surface temperature
has not yet reached the boiling point). At constant pulse time, the maximum depth of melting increases with increasing laser power density. In addition, at constant laser power density, the maximum depth of melting increases with increasing pulse time (valid before the initiation of surface evaporation) (Narendra and Sandip, 2008).

2.4.3 Vaporization

The depth of melting cannot increases to infinitely large value with increasing laser power density and pulse time. This is because the location of the melting point in the temperature verses depth plot is limited by the maximum achievable surface temperature. Once the surface temperature reaches the boiling point, the depth of melting reaches the maximum value $z_{\text{MAX}}$. Further increase in the laser power density or the pulse time cause the evaporative material removal from the surface without further increase in the depth of melting. The maximum depth of melting $z_{\text{MAX}}$ at which the surface reaches the boiling point can be calculated as follows (Wilson and Hawkes, 1987):

$$I \sigma_{\text{fc}} \left( \frac{H z_{\text{MAX}}}{\lambda k_2 \sqrt{\pi}} \right) = \frac{T_b}{T_m}$$

(2.7)

where $T_b$ and $T_m$ are the surface temperature that reaches boiling and melting point respectively.

Once the vaporization is initiated at the surface of the material, the continued laser irradiation will cause the liquid-vapor interface to move inside the material. This is accompanied with the evaporative removal of material from the surface above the liquid-vapor interface. Thus the velocity of the liquid-vapor interface into the material during laser irradiation $V_s$ and the depth of vaporization can be calculated by simple energy balance (Steen, 1991):
\[ V_c = \frac{H}{\rho (c_T s + L_p)} \]  \hspace{1cm} (2.8)

And

\[ d = \frac{\frac{H}{\rho (c_T s + L_p)}}{m} \]  \hspace{1cm} (2.9)

Where \( L_p \) is the latent heat of vaporization and \( \rho \) is the density. The mass of material removed per unit time \( m \) and the depth of vaporization \( d \) will be \( V_c \rho \) and \( V_d \rho \) respectively.

Two important parameters in analysis of thermal effects are the cooling rate \( \dot{T} \) and the temperature gradient \( \Gamma \). An important relationship in the solidification theory that relates these parameters is (Flemings, 1974):

\[ \dot{T} = GR \]  \hspace{1cm} (2.10)

Where \( R \) is the solidification rate. When the laser power is switched off (cessation), the depth of melting reaches a certain magnitude of \( z_{MAX} \). As solidification begin, the depth of melting decreases and eventually becomes zero corresponding to completion of solidification at the surface.

### 2.4.4 Important Considerations for Thermal Analysis

In practice, there exist some complex parameters which play important roles during LMI.

i. **Laser beam shape.**

In practice, the laser power density, or intensity, can be distributed in several distinct shapes. The most common is the distribution of energy in Gaussian beam as given by (Narendra and Sandip, 2008):

\[ J(r) = I_0 \exp \left( -\frac{2r^2}{\alpha^2} \right) \]  \hspace{1cm} (2.11)
Where \( r \) is the radius of the beam, \( I_0 \) is the intensity of the beam at \( r = 0 \), and \( w \) is the radius of the beam at which \( I = I_0 e^{-2} \). Figure 2.1 shows the Gaussian intensity distribution and Figure 2.2 shows the laser beam propagated in Gaussian mode.

![Gaussian Intensity Distribution](image1)

Figure 2.1: Gaussian intensity distribution (Ahmad Hadi Ali, 2004).

![Laser Beam Propagation](image2)

Figure 2.2: Laser beam in the form of Gaussian beam or Gauss mode after being focused by lens. At a focal point, \( z = 0 \), the beam waist is \( w_0 \) and at Rayleigh region \( z_0 \) the beam waist is extended to \( w_0 \sqrt{2} \) (Ahmad Hadi Ali, 2004).
ii. **Pulse shape.**

The pulse shape of laser beam gives rise to the complexity for thermal analysis. For analysis, it is important to define the temporal shape of the pulse. There are various single pulse shapes such as rectangular pulse, triangular pulse and smooth pulse. Rectangular pulses are generally characterized by the width of the pulse; whereas triangular and smooth pulse is characterized by the width of full width half minima (FWHM). The pulsed heating of the material is associated with temperature fluctuations (heating and cooling) during each pulse and time interval following the pulse (time between the adjacent pulses).

### 2.5 Vapor Expansion and Recoil Pressures

Surface vaporization is initiated when the laser intensity becomes sufficiently high, \( I_0 > 10^5 - 10^8 \) W/cm\(^2\). The vapor plume consists of clusters, molecules, atoms, ions and electrons. In the steady state evaporation, the vapor particles escape from the surface at temperature \( T_s \). Initially, the vapor particles escaping from the surface have a Maxwellian velocity distribution corresponding to the surface temperature. The velocity vectors of the vapor particles are all pointing away from the material’s surface. Then, due to collision among vapor particles, the velocity distribution in the vicinity of the vaporizing surface approaches equilibrium. This equilibrium region is known as Knudsen laser and is often treated as discontinuity in the hydrodynamic treatment. The velocity of the vaporization front is given by:

\[
V = \frac{k_B}{\mu L_v \frac{4\pi m}{n}} \tag{2.12}
\]

Where \( I_0 \) is the absorbed laser power density, \( m \) is the mass of the molten molecule, \( k_B \) is the Boltzmann constant and \( L_v \) is the latent heat of vaporization.
The evolving vapor from the surface induced recoil pressure $p_s$ at the evaporating surface, given by (Anisimov 1968);

$$\frac{p_s}{2s/S} = \frac{1.69}{\sqrt{2/2} \cdot (1 + 2 \cdot b^2)} \left( \frac{b}{L} \right)^{1/2}$$

(2.13)

Where $Q_0$ is the incident laser power, $S$ is the laser spot area, and $b^2 = \frac{K_0 T_e}{m_e L'}$. The evaporation-induced recoil pressure plays an important role in the removal of material in molten state during LMI. The melt expulsion is a dominant material removal mechanism at low power; whereas surface evaporation becomes dominant at high powers.

2.6 Plasma Formation

When the material is irradiated with sufficiently larger laser intensity $I_c$, significant surface evaporation takes place. Once the vaporization is initiated, interactions between the vapor and the incident laser beam then ionizing the vapor. This highly ionized vapor is termed as plasma (Figure 2.3). Under dynamic equilibrium, the degree of ionization $\xi$ in a gases environment can be expressed by the Saha equation:

$$\frac{\xi^2}{1 - \xi} = \frac{g_i N_e}{g_a N_g} \left( \frac{2 \pi m_e k T}{h^2} \right)^{3/2} \exp \left( \frac{E_i}{k T} \right)$$

(2.14)

Where $\xi = N_e/N_g$ and $N_g = N_e + N_a$. The $N_e$ and $N_a$ are the number densities of electrons and atoms/molecules respectively, $g_i$ and $g_a$ are the degeneracy of states for ions and atoms/molecules, and $E_i$ is the ionization energy.
In general, there are two types of laser induced breakdown, either complete or partial ionization, which is resulting in dense plasma formation. They are the cascade or avalanche ionization, and the multiphoton ionization. The first, which is cascade ionization, there exist free electrons that are often termed as “seed” or “priming” electrons at the focal region. These seed electrons then absorb laser energy by inverse bremsstrahlung absorption process. When the energy acquired by the free electrons exceeds the ionization potential of the molecules, ionization of molecules is initiated by collisions. The ionization of molecules generates new free electrons. These free electrons then absorb photon energy and ionize the molecules again resulting in avalanche ionization or breakdown as shown in Figure 2.4. The breakdown is occur if the free electron density in the plasma reach above $10^{18}$/cm$^3$. Thus it can say that plasma formation is a threshold phenomenon.

Second, in multiphoton ionization, each electron is independently ionized. So they do not require seed electrons, no collision and no molecules or particle-particle interactions. But under certain irradiation regimes, both the mechanisms (cascade and multiphoton ionization) may be significant. In such cases, the multiphoton absorption not only provides the seed electrons for the cascade ionization, but also contributes and accelerates the cascade process.
The generation of plasma can greatly influence the interaction of laser radiation with material. In LMI, plasma is generally considered to form near the evaporating surface of the target material. It remains confined to this region during laser irradiation with intensities just above $I_p$. The confinement of stationary plasma near the evaporating surface is referred to as plasma coupling. The plasma coupling is particularly important in conditions where normal laser irradiation is not strongly absorbed by the target material. Such conditions exist during irradiation of infrared laser on highly reflecting materials. This plasma coupling increases the absorptivity of laser radiation by the material.

When the laser power density is increased significantly beyond $I_p$, the dynamic interaction of the plasma with the laser radiation causes rapid expansion and propagation of the plasma away from the evaporating surface. Eventually, the plasma gets decoupled from the surface; consequently transfer of energy to the dense phase ceases. The laser radiation is then essentially absorbed in the plasma. This condition is referred to as plasma shielding where the decoupling of the plasma ceases the interaction of the laser radiation with the target material via plasma.
Figure 2.4 Initiation, electron avalanche growth and plasma formation by optical breakdown. The dominant mechanism of initiation of ionization by a Q-switched pulse is thermionic emission (Ahmad Hadi Ali, 2004).
2.7 Ablation

Ablation is generally referred to as material removal processes by photo-thermal of photo-chemical (bond breaking) interactions.

In photo-thermal (vibrational heating) process, the absorbed laser energy gets converted into thermal energy in the material. The subsequent temperature rise at the surface may facilitate the material removal due to generation of thermal stresses. When the laser energy is sufficiently large, the temperature at the surface exceeds the boiling point causing rapid ionization. These processes of material removal by thermal stresses and surface vaporization are generally referred to as thermal ablation.

In photo-ablation, the energy from the incident photon causes the direct bond breaking of the molecular chains in the materials. Consequently resulting in material removal by the molecular fragmentation without significant thermal damage on the material. This suggests that the process in photo ablation, the photon energy from the laser must be greater than the bonding energy.

2.8 Laser Shock Processing

Laser shock processing is a relatively novel process of surface modifications of materials especially in laser material interaction. When a material is irradiated laser beam of a very high intensity \( I > 10^9 \text{ W/cm}^2 \) and short pulse with typically 1-50 ns, the LMI at the very thin surface layer result in the generation of plasma. The volume of expansion of the plasma induces shock waves in the ablated target.

When target material is irradiated with laser beam, confined ablation occurs which involve three basic steps. During laser on time (pulse duration), plasma generated by the LMI induces a shock wave which propagates into the target and the confining
medium. The second step immediately begins after the laser is switched off. During this time, the plasma maintains the pressure which subsequently decreases due to adiabatic cooling. The target acquires an impulse momentum due to induced shock wave. Third step; for longer time, the complete recombination of the plasma takes place and the additional momentum to the target is due to the “cannon-ball-like” expansion of the heated gas inside the interface.

2.9 Interferometric Technique

Since the discovery of waves properties of light by Thomas Young through his excellent Young’s double slit experiment, many scientists had found numerous benefits from the interference phenomena (Al-Azzawi, 2007). Interference is the superposition of two or more waves from a coherence source and can be identified by the dark and bright fringes on observation screen. A slight change in optical path will result in phase change of the waves. This will affect the fringes pattern, in term of fringes shift of the interference pattern.

Interference is the superposition of two or more coherence waves. When two coherence waves, as example a laser light interfere to each other, a series of interference fringes will formed as shown in Figure 2.5. This phenomenon can be observed at a screen, recorded by a camera and also detected by using photo detector placed at the interference fringes.

![Figure 2.5](image)

Figure 2.5 Interference of two coherence waves.