Beam-Plume Interaction in Laser Materials Processing †

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Abstract

The paper describes the energy dissipation mechanism during beam - plume/plasma interaction. From spectroscopic and other optical measurements of Ti-plume induced by pulsed YAG laser shot, it has been concluded that major energy dissipation processes in plume are; 1) Absorption of photons in a plume/plasma by Inverse Bremsstrahlung, and 2) Rayleigh scattering of incident beam by ultra fine particles formed in the plume. Both processes have strong dependence on wavelength of radiation and the paper gives the generalized idea of energy loss of laser beam in laser induced plume/plasma.

KEY WORDS: Laser, Beam, Plasma, Plume, Interaction, Laser Materials Processing, Laser Processing, Absorption, Scattering

1. Introduction

The laser processing technology is principally an extremely high speed and high precision process, which is a general feature of materials processing by high power density beams. This leads to the difficulty of realizing adaptive control. In fact, there is no fully automatic laser materials processing method at present. One of the reasons is that there are so many physical and chemical phenomena which have not been understood scientifically in laser materials processing, because the phenomena occur within a very narrow region with steep gradients of physical and chemical properties as well as within an extremely short period. Therefore, comprehensive understanding of phenomena is absolutely necessary for future automatic control of laser materials processing.

When a laser beam is irradiated on a solid target with considerably high power density, a blight flame called laser induced plume or plasma is generated. It has been well known that this laser plasma interferes the effective energy transfer of the incident beam to the target surfact. This phenomenon is generally called plasma absorption and many people who are engaged in laser materials processing believe that the plume is a high temperature and high density plasma which strongly absorbs the incident beam by the plasma electron oscillation. However, this is almost impossible in ordinary laser materials processing.

The plasma oscillation is one of the fundamental properties of plasma and is a measure whether the incident electromagnetic wave can propagate or not through the plasma. The frequency is expressed as follow:

$$\omega_{pe}^2 = \frac{n_e e^2}{\varepsilon_0 m_e} \tag{1}$$

where, ω_{pe}: plasma electron frequency
n_e: electron number density
m_e: mass of electron
e: electronic charge
ε_0: dielectric constant

There are two kinds of plasma oscillation, i.e., plasma electron oscillation and plasma ion oscillation. Both frequencies are only determined by the number density of ionized particles and their masses. Because of the mass difference between the electron and positive ion, the plasma electron oscillation is always higher in frequency than the plasma ion oscillation and it is usually sufficient to consider only the plasma electron oscillation. **Figure 1** shows the relation of frequency vs. electron number density in a plasma. In the frequency range higher than the plasma frequency, the incident electromagnetic wave can propagate in the plasma, whereas it is reflected in the frequency range lower than the critical frequency. If the external wave has the same frequency of that of plasma, the wave is resonantly absorbed by plasma. As seen in the figure, the electron number densities equivalent to the plasma frequencies for CO_2, Nd:YAG and Excimer (ArF) lasers are 10^{25}, 10^{27} and 10^{28} numbers/m^3. These values are extremely

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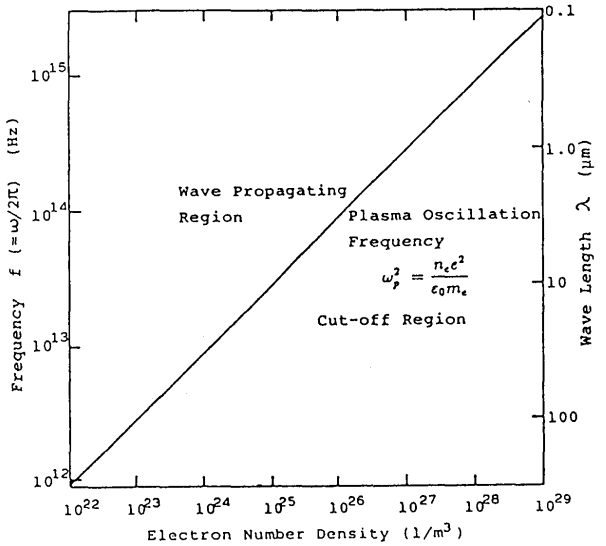
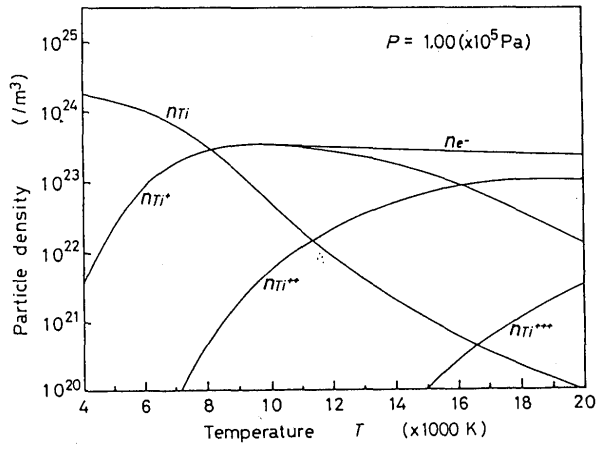
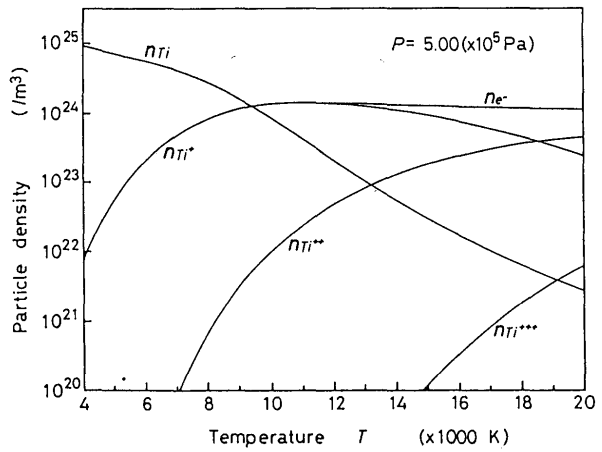


Fig. 1 Plasma electron frequency as a function of electron number density and equivalent number density of plasma oscillation to incident laser wavelength



(a) P=1.00x10⁵Pa



(b) P=5.00x10⁵Pa

Fig. 2 Number densities of Titanium plasma calculated by Saha's equation at 0.1 and 0.5 MPa

high ones which can be only achieved in very high pressure plasmas or solid conductors. **Figure 2** shows the calculated number densities of Titanium plasma species in 1 and 5 atmospheres obtained by Saha's equation under the assumption that the mixed gas of Ti atoms and other ionized particles is an ideal gas. The maximum electron densities are 10^{23} for 1 atm Ti-plasma and 10^{24} for 5 atm and they are much less than the equivalent electron number densities of plasma oscillation to the incident laser beams. It is also noted that the calculated number density of electron in metallic plasma is almost constant in wide range of temperature. It is, therefore, necessary to consider the photon - plasma interaction in the wave propagation region.

In order to know the quantity of absorption of laser beam in the plasma, it is necessary to know the plasma temperature as well as number densities of ionized particles. However, systematic temperature measurements of laser induced plume have not been well conducted. Only a few exception is seen in literatures. Peeble and others [1] reported that the plume temperature induced by pulsed YAG laser shot on Aluminium was 3.4×10^3 K in wide range of power density. Matsunawa and others [2] conducted a spectroscopic measurements of Titanium plume generated by pulsed YAG laser and suggested that the plume temperature might be slightly higher than evaporation temperature because the all resonant spectral lines whose lower energy was in the ground state were strongly self-absorbed by neighboring Ti atoms. In case of the CO_2 laser induced plasma, on the other hand, Kosuge and other [3] obtained the Fe plume temperature as high as $(1.8 - 2.2)\times10^4$ K from spectroscopic analyses. Herziger [4] has reported that the electron energy in laser induced Fe plasma is about 1.1 eV which is equivalent to 1.3×10^4 K in an equilibrium plasma.

In order to understand the beam energy dissipation process in a laser induced plume, the authors conducted spectroscopic measurements to determine the temperature of plume induced by a pulsed Nd^{3+}:YAG laser as well as other optical measurements such as scattering of incident beam in a plume, high speed shadowgraph photography, and so on.

2. Measurements of Temperature and Electron Number Density of Laser Induced Plume

Figure 3 shows the measured temporal intensity of an atomic spectral line of Ti under the different power densities. There found a distinct difference in temporal change of line intensity depending on the power density at the target surface. In relatively lower power density range, the intensity of spectral line is rather flat and the emission of

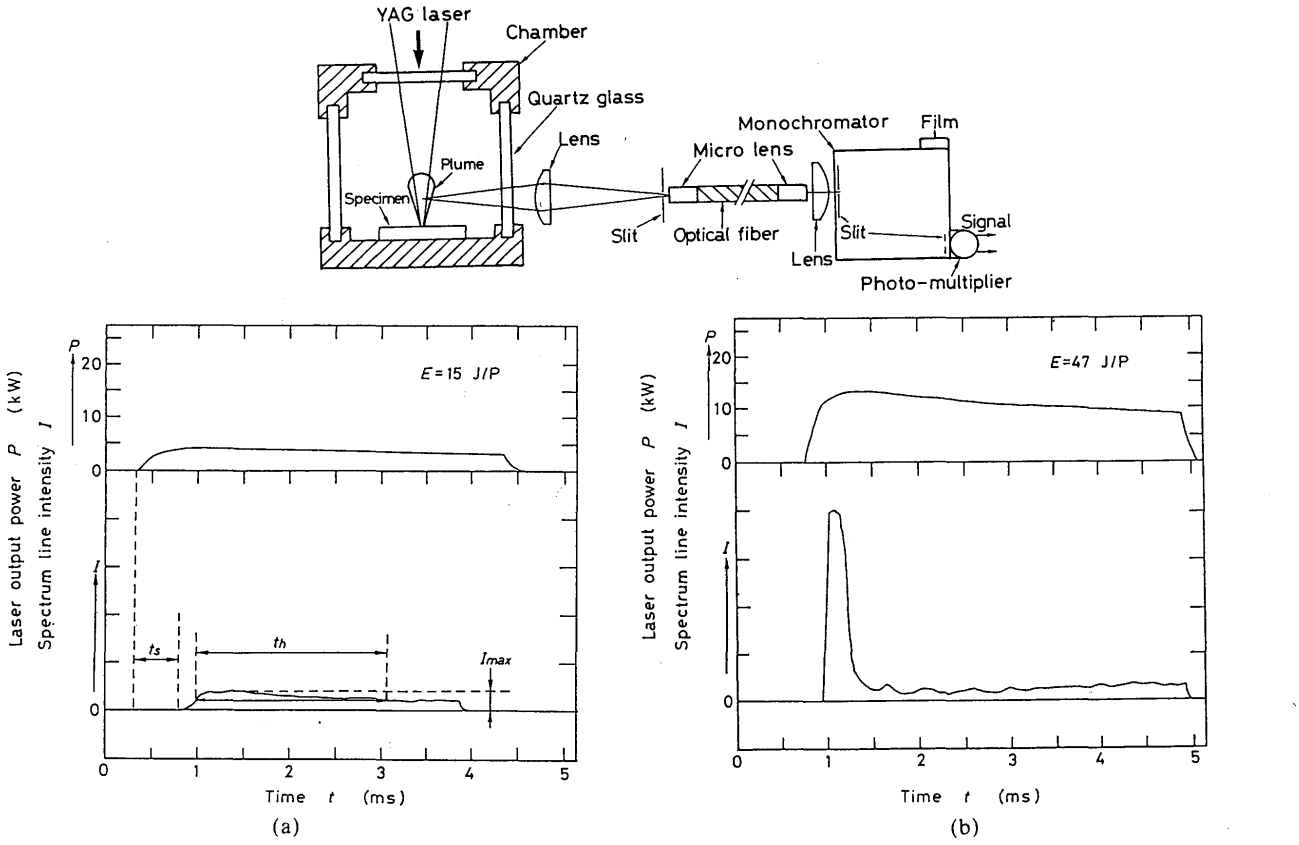


Fig. 3 Temporal change in intensity of atomic spectral line of pulsed YAG laser induced Ti-plume at different power densities

light continues quite long until the laser power decays to a certain value. While, in case of higher power density condition, the intensity of line spectrum quickly increases just after the evaporation and reaches to the maximum value and decays repidly in spite of evaporation still being continued. Namely, the plume is in excited state at the beginning of vaporization and is in non-excited state in the latter half of evaporation.

Temperature measurement of Ti-plume was conducted under the laser irradiation conditions of peak power density of 1.2×10^9 W/m^2 for 3 ms (15 J/s) on the pure Titanium target in the 1 atm Argon atmosphere. (Fig. 3 (a)) **Figure 4** shows the Boltzmann plot of measured relative intensities of spectral lines of different wavelength. The temperature was determined by the following relation.

$$In\left(\frac{I_{nm}\lambda_{nm}}{g_nA_{nm}}\right)=-\frac{E_n}{kT}+In\left(\frac{N_0hc}{Z(T)}\right) \qquad (2)$$

where, N: atomic number density
E_n: excited energy at n-th level
λ_{nm}: wavelength emitted by n-m transition
I_{nm}: spectral line intensity of
A_{nm}: transition probability from n-th to m-th level
g_n: statistical weight at n-th level
$Z(T)$: partition function of atom at temperature T

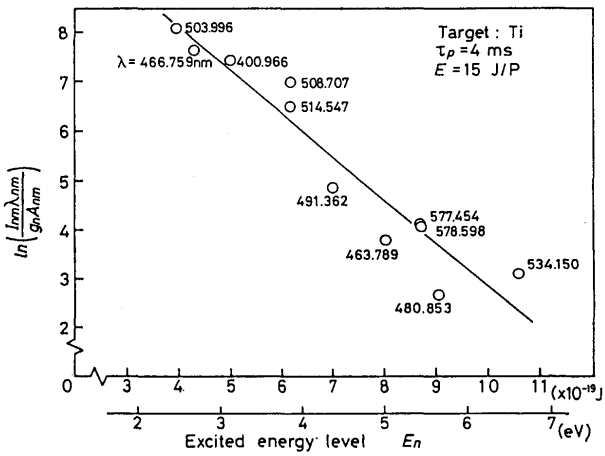


Fig. 4 Boltzmann plot of atomic Ti spectral line intensities to determine plume temperature using 11 atomic lines

k: Boltzmann constant
h: Planck constant

Namely, the temperature was obtained from the gradient of Boltzmann plot by the least square regression analysis. The obtained plume temperature was $(8.3+1.3)\times10^3$K.

The number density of plasma species was determined by the following spectroscopic analysis. Namely, the intensities of spectral lines emitted from neutral atoms and singly ionized ions were compared choosing 11 atomic and

2 ionic spectral lines. Each intensity is expressed by the following equations;

$$I_a = N_a \frac{g_a}{Z_a} A_a h\nu_a \exp(-\frac{E_a}{kT}) \quad (3)$$

$$I_i = N_i \frac{g_i}{Z_i} A_i h\nu_i \exp(-\frac{E_i}{kT}) \quad (4)$$

where, ν: frequency of spectrum ($\nu = c/\lambda$).

Combining these equations with Saha's equation, one obtains the equation of electron number density as follow;

$$N_e = \frac{I_a g_i A_i \nu_i}{I_i g_a A_a \nu_a} \frac{2(2\pi mkT)^{\frac{3}{2}}}{h^3} \exp(\frac{E_a - E_i - V}{kT}) \quad (5)$$

The electron number density calculated from equation (5) was 5.9×10^{23} numbers/m^3 which was equivalent to a thermal Ti-plasma of ideal gas at 2.5 atm. The number density of neutral Ti-atom calculated from Saha's equation was 1.0×10^{24} 1/m^3 and thus the ionization degree ($= n_i/(n_0 + n_i)$) of Ti-plume was only 38 %. Namely, the plume induced by a conventional pulsed YAG laser is no more a fully ionized plasma but a weakly ionized metallic gas.

The above pressure was obtained under the assumption of plume being an ideal gas. However, there is no evidence that a laser induced plume is an ideal gas. Matsunawa and others [2,5] measured the plume velocity, its radius and evaporation loss of the target during pulsed YAG laser irradiation of 3 ms in 1 atm, and estimated that the plume pressure was 2.4 atm. under the assumption that the plume is consisted of ideal gas of evaporated atoms at boiling temperature. This value was equivalent to that of the present study. However, the measured plume velocity was subsonic, i.e., 25 m/s, and no shock wave was observed. Considering the relaxation time of collision between plume species and surrounding atmosphere at 1 atmospheric pressure, the static pressure of plume should be the same with the ambient pressure. However, the measured electron number density can never be achieved in an ideal plasma of 1 atmospheric pressure as seen in the previous Fig. 2(a). This discrepancy may be explained that a laser induced plume during meterial processing is not an ideal gas but an ionized gas in which Van der Waals' effect is predominant. In a Van der Waals' gas, molecules are more condensed than those in an ideal gas in the same pressure.

3. Beam Energy Absorption in Plume by Inverse Bremsstrahlung

As mentioned in **1.**, it has been estimated that the all laser beams used for materials processing can propagate in the laser induced plasma. However, the plasma is not a perfect transparent medium but may absorb a part of incident energy. A possible absorption mechanism is the Inverse Bremsstrahlung (photon-electron interaction). The absorption coefficient of Inverse Bremsstrahlung is given as follow from the theory of plasma physics.

$$K_a = \frac{z^2 e^6 n_e^2 \, ln\,\Lambda}{3\omega^2 c \varepsilon_0^3 (2\pi m_e k_B T)^{\frac{3}{2}} \sqrt{1 - (\frac{\omega_{pe}}{\omega})^2}} \quad (6)$$

where, n_e: electron number density,
n_i: ion number density,
z: charge number,
e: electronic charge,
c: velocity of light,
ε_0: dielectric constant,
m_e: mass of electron,
k: Boltzmann constant,
T: temperature,
ω: angular frequency of incident wave,
ω_p: angular frequency of plasma oscillation,
$ln\,\Lambda$: Qoulomb logarithm.

As seen in Equation (2), the absorptivity is proportional to the product of $n_e n_i$ and inverse proportional to ω and $T^{3/2}$. That is, the absorption becomes less as the wave frequency is higher and plasma temperature increases, while it becomes higher as the number densities of electron and ion increase. At the same time, the absorption becomes infinity when the incident wave has the same frequency of the plasma oscillation.

Putting measured values into eq. (6), the absorption coefficient of YAG laser beam in the Ti-plume becomes 6.1 1/cm which is equal to that 6 % of the incident beam is absorbed during the beam propagation through 1 cm length of plasma. In the same temperature plasme, the CO_2 laser is strongly absorbed, i.e., 100 times higher, because of the 10 times higher frequency (longer wavelength) than that of YAG laser beam.

4. Scattering Loss of Beam Energy in Laser Induced Plume

The calculated absorption rate of YAG laser by Ti-plume seems to be too low compared with the actual heat input to the target material measured by Matsunawa and others [2]. The absorbed energy by Ti target was about 50 % of the incident energy, while the energy lost by Ti-plume was 30 to 40 %. Thus, some other mechanism of beam energy dissipation in the plume must be considered. They conducted the simultaneous optical measurements of plume under the relatively high power density condition as shown in **Figure 5.** The results are shown in **Figure 6.** Transmittance of the probe laser (Fig. 6(b)) drops sharply

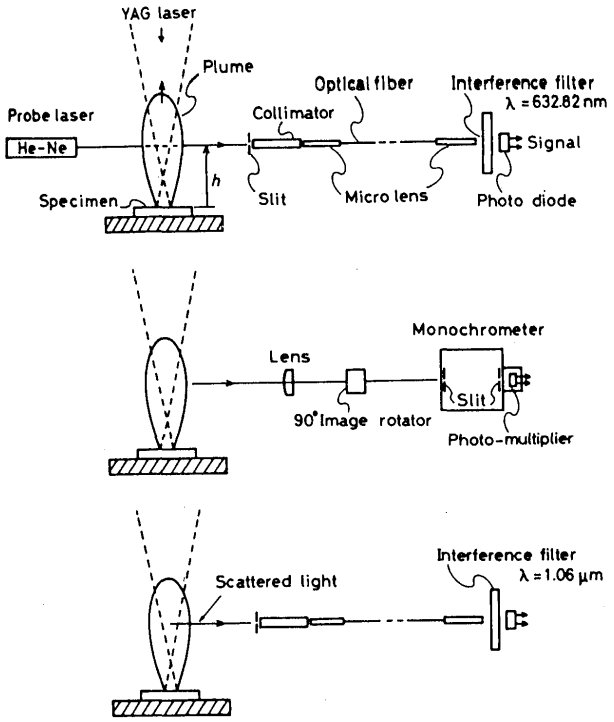


Fig. 5 Simultaneous optical measurement methods of temporal change in transmission of probe laser, intensity of stomic spectral line and scattering of incident YAG laser beam to right angle

at a certain time after YAG laser initiation and it keeps low level until the YAG laser output power decays, which means that evaporation of target material takes place continually for most of the lasing time. On the other hand, the intensity of line spectrum (Fig. 6(c)) quickly increases just after the evaporation reaching to the maximum value and decays rapidly as described in Fig. 3 (b). While, the scattered intensity of incident YAG laser beam to the right angle (Fig. 6(d)) begins to increase remarkably after the line spectrum intensity reaches to the maximum and keeps high value until the incident laser beam power decays. Matsunawa and others has clarified that the scattering is caused by the ultra fine particles (UFP) formed in the plume by the condensation of evaporated atoms.[2] The size of UFP is a function of ambient pressure as seen in **Figure 7,** which shows that the average size is much less than the wavelength of incident beam. The fact indicates that the phenomenon observed in Fig. 6 (d) is caused by Rayleigh scattering by UFP. It has been experimentally verified that the scattered intensity of incident beam is greatly reduced in lower ambient pressures because of forming smaller UFP.[2]

As well known, the intensity of Rayleigh scattering by a spherical particle much smaller than the incident wavelength is given by the following equation;

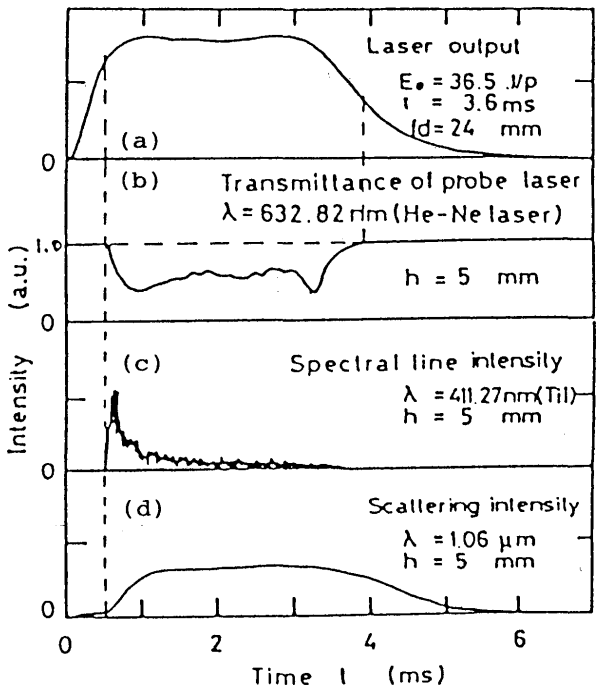


Fig. 6 Measured temporal change in transmission of probe laser, intensity of atomic line spectra and scattering of incident YAG laser beam to right angle

$$\frac{I_{sca}}{I_{inc}} = \frac{2\pi^2 V^2}{r^2 \lambda^4} \left(\frac{\varepsilon - \varepsilon_0}{\varepsilon_0}\right)^2 (1+\cos^2\varphi) \tag{7}$$

where, V: particle volume,
r: distance from particle,
φ: angle of scattering,
ε_0: dielectric constant of medium,
ε: dielectric constant of particle,
λ: wavelength of incident beam.

The equivalent absorption coefficient of Rayleigh scattering by many particles distributed randomly in the space is given by:

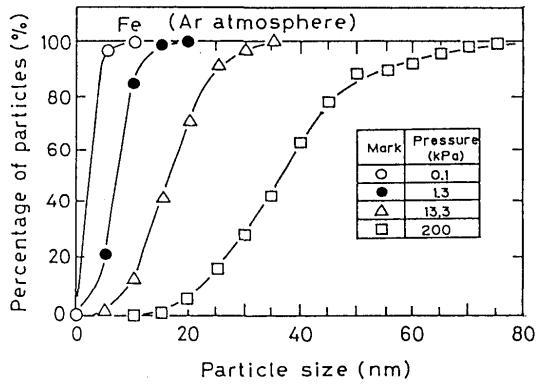


Fig. 7 Size distribution of ultra fine particle formed in YAG laser induced plume and its dependence on ambient pressure

$$K_{sca}=\frac{8\pi^3NV^2}{3\lambda^4}\left(\frac{\varepsilon-\varepsilon_0}{\varepsilon_0}\right)^2 \quad (8)$$

where, N: number density of particle.

Namely, the scattering loss is inversely proportional to the 4th power of wavelength. This means that the shorter wavelength is more dominantly scattered by particles than the longer wavelength, if the particle size is the same. Therefore, it will be reasonable that the incident YAG laser beam is strongly scattered in the plume which suppresses the efficient energy transfer to the target surface. However, the quantitative evaluation of scattering loss in the plume has not been clarified at present.

5. Dependence of Wavelength on Energy Dissipation in Laser Plume

As described previously, there will be two major loss mechanisms of energy dissipation in the laser induced plume. One is the photon absorption by electrons in the plasma by Inverse Bremsstrahlung and another is the beam scattering by UFP formed in the plume by Rayleigh scattering. Boss losses are strongly dependent on the wavelength of incident beam as described in equations (6) and (8).

Figure 8 shows a schematic of beam energy dissipation in the laser induced plume as a function of wavelength under the conditions of constant plasma temperature and particle size in every wavelength. The figure indicates that the beam energy loss is mainly governed by Inverse Bremsstrahlung in longer wavelength, while it is significantly influenced by Rayleigh Scattering by ultra-fine particles formed in a plume in shorter wavelength.

As stated in Section 3, the absorption coefficient by Inverse Bremsstrahlung is the function of number density of ionized species, plasma temperature and wavelength. **Figure 9** is the calculated result of absorption coefficient as a function of plasma temperature at one atmospheric

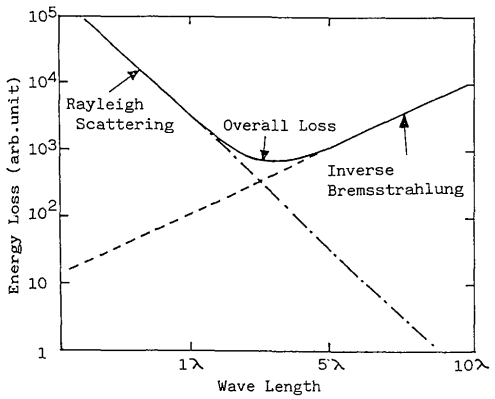


Fig. 8 Schematic illustration of energy dissipation of incident beam in plume by Inverse Bremsstrahlung and Rayleigh scattering

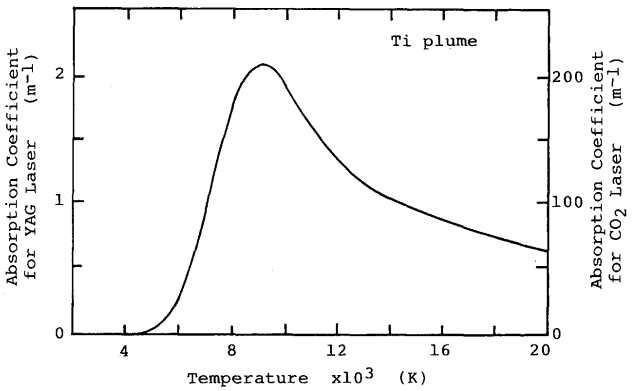


Fig. 9 Effect of plasma temperature on absorption coefficient by Inverse Bremsstrahlung

pressure (0.1 MPa) under the assumption that the Ti-plume is an ideal gas over the boiling point. The absorption coefficient becomes maximum in the temperature range of 8000 K for both wavelength of CO_2 and YAG lasers though the absolute values are different each other in the magnitude of 100 times. It is interesting to note that all published data of plume temperature, though the data numbers are limited and target materials are different each other, are much over 10^4 K for CO_2 laser processing, while they are much less than 10^4 K for YAG laser processing. This may be attributed that in case of YAG laser beam the absorption of photon by electron is not high which yields low temperature plasma, while in case of CO_2 laser beam the absorbed photon energy heats up the plasma until the thermal balance between the absorption of photon energy in the plasma and the heat loss from plasma by convection and conduction is achieved. Namely, if the plasma temperature is low, it absorbs the incident energy which rises the temperature, while if the plasma temperature is too high which reduces the absorption, but the heat loss from plasma is enhanced due to the steep temperature gradient. That means a kind of self regulation or minimum energy principle is achieved.

As to the loss of incident energy by scattering, it is necessary to know the size and density of ultra fine particles as well as their dielectric constant. However, a detailed process of condensation of evaporated atoms in a plume has not been well understood. Therefore, it is difficult to deal this problem quantitatively at the present stage. It is necessary to conduct further systematic studies on size and density of ultra fine particles in a plume induced different wavelength laser as well as clarification of fluidmechanical structure of each plume.

6. Summery

The above stated results and their physical interpreta-

tions are only the early stage of understanding of a part of so many complex phenomena taking place in laser materials processing. It is necessary to conduct more detailed observations to increase the accuracy of models as well as to get the deep insight of phenomena. In particular, the evaporation phenomena play the important roles in materials processing by high power density beams and therefore it will be necessary to establish a vaporization theory under the intense heating and also to construct mathematical and physical modeling of heat and mass transfer including strong evaporation.

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