Bending of Shock Wave Plasma Induced by Q-Switched Nd:YAG Laser at Low Pressures

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A Q-switched Nd:YAG laser (8 ns, 53 mJ) was focused on copper near the edge of the target at 2 Torr air pressure in order to observe bending in the laser plasma. It was shown that the bending of the secondary plasma edge extended into the shaded area, with the plasma emission front moving at a speed comparable to the emission front speed in the forward direction, confirming the role of the shock wave in the generation of the secondary plasma. This conclusion was also corroborated by a similar experiment on the bending of the shock wave induced by the laser bombardment at 1 atm.

Key Words: Shock wave plasma, Confined laser plasma, Bending of laser plasma

1. Introduction

The observation of laser induced shock wave was first reported by Basov et al.1 in an experiment applying a high power Nd glass laser (6 J, 15 ns) on a carbon target in air at a pressure of 2 Torr. By means of a shadow photograph recording technique synchronized with a probing ruby laser, they clearly found that a strong and near spherical shock wave with a wave front propagating with a velocity of 500 Mach at 1 cm from the target. In a subsequent experiment using schlieren and interferometer, Basov group further showed that ionization took place mostly just behind the shock wave.2) Further confirmation and more detailed results regarding the shock wave characteristics have also been reported by Bobin et al.3, Hall4 and Emmony and Irving,5) using different laser system and different target materials. In all of these experiments laser with a pulse energy higher than several hundreds mJ was used.

The role of shock wave in the generation of the secondary plasma induced by the laser with relatively lower pulse energy was first suggested by Kagawa et al.6) from an experimental result employing N2 laser on metal targets at reduced surrounding air pressure. They also demonstrated that the secondary plasma has some characteristics favorable to spectrochemical analysis.6-9) This so-called shock wave induced plasma model has since been reexamined and confirmed in a series of experiments using N2 laser,7-10) TEA CO2 laser,11,12) XeCl Excimer laser13) and Nd:YAG laser, operated in the normal oscillation mode14,15) and in the Q-switched mode.16) All of these experiments were performed at reduced gas pressures. The most important characteristics revealed by those experiments consists of the typical hemispherical shape of the plasma with a thin emission shell at the plasma front, which moves with a propagation length proportional to t 0.4, in excellent agreement with the shock wave characteristics predicted theoretically by Sedov.17) It was further demonstrated that ionic emission was generally insignificant compared to neutral atom emission.13) Although those results have provided relatively solid and comprehensive support for the model, additional evidence on some unique aspect concerning interaction of shock wave with an object will be highly desirable because the excitation mechanism of the secondary plasma has not been established. In addition to our shock wave model, other models such as the recombination model18) and the gas reservoir model19) have been proposed to interpret the secondary plasma.

We report in this paper the result of an experimental observation of bending phenomena occurring when the Q-switched Nd:YAG laser beam with relatively low pulse energy was focused on copper near the edge of the target. It will be also shown that the bending of the secondary plasma is a clear manifestation of shock wave characteristics.

2. Experimental Procedure

The experimental arrangement is shown in Fig.1. The laser radiation from a Nd:YAG laser (λ = 1.064 nm) operated in a Q-switched mode was focused by a multi-coating lens (f = 100 mm) through a window onto the surface of the sample. The laser was operated manually. The shot-to-shot fluctuation of the laser was estimated to be approximately 3 %. The energy of the laser radiation was fixed at 53 mJ with the aid of a filter. The surrounding air pressure was set at 2 Torr for secondary plasma generation.
In all of the experiments, a copper plate (Rare metallic Co., 99.99%, 0.2 mm thickness) was used as a sample. In each experiment, the sample was placed in a small, vacuum-tight metal chamber (11 cm x 11 cm x 12.5 cm), which could be evacuated with a vacuum pump and filled with air at desired pressure. The air flow through the chamber was regulated by a needle valve in the air line and another valve in the pumping line. The chamber pressure was measured precisely with a digital Pirani gauge (Diavac Limited, PT-1DA). The sample, together with the whole chamber and multi-coating lens, could be moved in two dimensions, using a step motor for movement in the laser beam direction and micrometer for movement perpendicular to the laser beam direction. The sample was rotated after each irradiation shot to secure uniformity of the emission intensity. In addition to the window for the YAG laser radiation, two optical windows were positioned around the laser plasma for visual and spectral observation. The windows were sufficiently large to ensure that the plasma light was not obstructed by the walls when the position of the chamber was moved.

In this experiment, the plasma was confined by using two parallel glass plates, so that the plasma expansion was limited within a narrow space. The width of the glass plates was 2.5 cm with 6 mm separation. The laser-induced plasma was imaged 1:1 by the aid of a quartz lens onto the entrance slit of the monochromator (SPEX M-270, Czerny-Turner configuration, focal length 270 mm with 1200 grooves/mm). The slit, both for entrance and exit of the light was set at 1 mm in height and 100 μm in width. The electrical signal from the photomultiplier (Hamamatsu 1P-28) was fed to a digital storage scope (HP-54600B). A part of the laser beam was detected by a PIN photodiode and the output was used as a trigger signal for digital storage scope. Data collection was carried out by using a printer.

In order to detect the density jump due to shock wave propagation induced by laser bombardment at 1 atm, a shadowgraph technique was employed using a He-Ne laser as a probe light. This probe light was sent into the second channel of the digital storage scope.

3. Results and Discussion

Figure 2 (a) shows the feature of the confined plasma obtained by ordinary irradiation method as illustrated in Fig.3 (a). Visual inspection of the secondary plasma also reveals a uniform distribution of green color which arises from copper atoms. Figure 2 (b) shows the plasma generated by the bombardment of laser focused near the edge of the sample block (at 3 mm from the edge). It is clearly seen that the secondary plasma curves around to the back side of the block, a position which corresponds to the shaded area when seen from the primary plasma. The feature of the bending plasma was illustrated in Fig.3 (b).

As already reported in the previous paper, when high power TEA CO2 laser (500 mJ, 100 ns) was focused onto the target with an obstacle placed in front of it, reflection and diffraction of the secondary plasma was clearly observed. We have argued that this phenomenon should be viewed as an evidence to support of the shock wave excitation model. Similar phenomenon was also observed when the Nd:YAG laser pulse with relatively low pulse energy of around 50 mJ was employed in the confined configuration, although it could not be clearly observed in the free expansion set up. In our previous paper, it was concluded that the characteristic of the secondary plasma confined in the space consisting of two parallel glass plate can be interpreted by the shock wave excitation model as in the case of free expansion plasma. The occurrence of bending effect observed here under confinement also becomes strong evidence to support the idea that at the initial stage of the laser ablation shock wave is induced to excite the secondary plasma. It is supposed that the shock wave started near primary plasma expands with time with hemispherical shape until it collides with the glass plate, and the reflected shock wave turn into two dimensional shock wave propagating in the space consisting of two parallel glass plate.

The speed of the plasma front was measured at points p and q on the x-axis as illustrated in Fig.3 (b). The result showed that the speed at point p and q were 7.5 km/s (Mach 22) and 5.1...
km/s (Mach 15), respectively. In order to obtain the speed arriving time of the front emission was measured at different two points with a separation of 1 mm. In the shaded region, the front speed of the secondary plasma was also measured at point r and s in the y direction as shown in Fig. 3 (b) and the result were 5.5 km/s (Mach 16) and 3.74 km/s (Mach 11) respectively. In other words, the plasma emission front kept moving at high speeds after bending to the back side. These observation unambiguously proved that the phenomenon was not due to diffusion process occurring in the surrounding gas, showing that the bending took place even in the secondary plasma, as in the case of ordinary shock wave.\(^{21}\)

In the previous experiment we succeeded in detecting the coincidence between the front of the emission of the secondary plasma and the density jump due to shock wave using He-Ne laser as a probe light.\(^{14}\) But this detection was possible only when the surrounding pressure is higher than 100 Torr. In this experiment we failed to detect the density jump. It was probably due to the rather low pulse energy and low surrounding air pressure. It is supposed that the main feature of the propagation and the bending of shock wave taking place in the confined region was the same regardless of the pressure of the surrounding gas. Nevertheless, the small magnitude of density jump occurring at low pressure did not allow its detection in the experiment. Therefore, instead of detecting the density jump due to the shock wave induced at low pressure, we performed the experiment at 1 atm under the same experimental configuration. Namely, by employing the confined shock wave induced by the laser bombardment at 1 atm, the bending phenomenon was confirmed. In this case, the size of the laser plasma itself is very small (2-3 mm), but the shock wave expands in the surrounding gas in the confined space consisting of the two parallel glass plate. For detecting density jump due to shock wave, the probe light was directed to various points a, b, c, d, e, f, g, h, i as denoted in Fig. 3 (c).

Figure 4 is an example of the signal of the probe light obtained at 1 atm due to the density jump induced by shock wave arriving at a position 4 mm from the target in the forward direction of the confined plasma expansion. The feature of the shock wave propagation and the bending are illustrated in Fig. 3 (c). The front speed of the shock wave in the shadow region was 1.36 km/s (Mach 4) at point e and decreases to 0.6 km/s (Mach 1.7) at point i.

Figure 5 shows how the shock wave front moves with time in log-log plot for two cases, one is for the forward direction and the other is for the shadow region. Points a, b, c and d are obtained in the forward direction and points e, f, g, h and i are taken at the shadow region as denoted in Fig. 3 (c); the distance was measured from the primary plasma.

![Fig. 2 Confined plasma photographs taken under laser irradiation of 53 mJ at 2 Torr air pressure. The glass width and its separation used for this experiment are 25 mm and 6 mm respectively: (a) confined plasma induced by ordinary irradiation method, (b) when laser was focused near the edge of the sample.](image)

![Fig. 3 Illustration of the confined plasma: (a) when the laser was focused on the center of the sample surface at air pressure of 2 Torr, (b) when the laser was focused near the edge of the sample at air pressure of 2 Torr, (c) shock wave expansion when the laser was focused near the edge of the sample at air pressure of 1 atm.](image)
The relationship between the propagation time (t) and the propagation length (r) from the source of the explosion can be derived for two dimensional shock wave using the method of dimensional analysis.\(^{16}\) This relation is expected by the following equation.

$$r = \left( \frac{E_0}{\rho \alpha} \right)^{\frac{1}{\gamma}} t^{\frac{1}{\gamma}}$$  \hspace{1cm} (1)

where \(E_0\) is the initial explosion energy, \(\rho\) is the density of the surrounding gas at the shock front, and \(\alpha\) is a constant involving \(\gamma\) (the ratio of the specific heat of gases). The slope of the curve for shadow region was found to be about 0.5 close to the value given in equation (1). The slope of the curve for forward direction, however, is a little bit higher than that for shadow region. The slightly higher point of \(e\) compared to that of \(a\) is most probably due to the fact that the shock wave moves faster along the sample surface at its initial stage than in the forward direction.

According to our shock wave model the secondary plasma is produced in the following process.\(^{16}\) Right after the cessation of the primary plasma, atoms gush out from the primary plasma at supersonic speeds, pushing the surrounding gas like a piston. This expansion of the propelling atoms, being impeded by the surrounding gas, give rise to a compression process. As a result of this compression, a blast wave is generated in the surrounding gas with its wave front almost coinciding with the front of the propelling atoms. Due to this compression process, the kinetic energy of the propelling atoms is converted into thermal energy in the plasma, by which atoms are excited. It is supposed that during the expansion process of the secondary plasma shock wave acts as something like a wall on which atoms are stagnated being pushed from back side with the propelling atoms coming successively from back side. It is naturally supposed that when bending takes place in the shock wave, the front of the secondary plasma would also follows the bending. Therefore, the bending effect strongly supports the shock wave model for explaining the excitation process of the secondary plasma.

4. Conclusion

We have demonstrated in the experiment that the secondary plasma displaying edge bending phenomenon was characterized by comparable propagation speeds above the sound speed both along the forward plasma expansion direction as well as in the shadow region covered by the bending plasma. It is argued that this characteristic can not be attributed to the diffusion process in the surrounding gas. The experimental result also confirmed that similar bending phenomenon took place in the laser induced shock wave at 1 atm. These observation are consistent with our shock wave model for laser induced secondary plasma at reduced air pressure in which case the atoms gushing out from the target are excited at a region just behind the shock front.

References

21) J. J. Glass: Shock Waves and Man (The University Toronto Press, 1974).