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The characteristics of confined ablation in laser propulsion*

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Compared with direct ablation, confined ablation provides an effective way to obtain a large target momentum and a high coupling coefficient. By using a transparent glass layer to cover the target surface, the coupling coefficient is enhanced by an order of magnitude. With the increase of the gap width between the target surface and the cover layer, the coupling coefficient exponentially decreases. It is found that the coupling coefficient is also related to the thickness of the cover layer.

Keywords: laser plasma, propulsion, confinement ablation
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1. Introduction

When is a target irradiated by a high-energy focused laser beam, the target surface absorbs energy from the laser, thus generates a plasma with supersonic expansion. If the target surface is covered with a transparent layer, the plasma expansion can be confined. The momentum transfer and the coupling coefficient can then be enhanced. Due to this advantage, the confined ablation can be used in laser ablation propulsion.[1,2] Since Kantrowitz proposed the concept of the laser ablation,[3] Azechi *et al* have first used an enclosed configuration to enhance the coupling coefficient.[4] Later, Fabbro *et al* introduced a transparent layer into the laser propulsion and investigated the physical processes.[5] All these experiments have confirmed that a confined ablation can efficiently enhance the coupling coefficient. In this paper, we present experimental results of the nanosecond-laser-pulses-ablated targets that are covered with a glass layer. Different from other experiments performed in vacuum, our experiments are carried out in atmospheric pressure. The dependence of the coupling coefficient on the laser intensity and laser energy is measured. Especially, the effects of the gap width between the glass layer and the target surface on the coupling coefficient are studied. It is demonstrated that the coupling coefficient strongly depends on the gap width. The effects of the thickness of the cover layer on the coupling coefficient are also investigated.

2. Experiment

The schematic of the experimental setup is shown in Fig.1. A pendulum is used to measure the target momentum and the coupling coefficient. The coupling coefficient is defined as the ratio of the target momentum to the incident laser energy. The laser pulses (532 nm wavelength, 7 ns duration) are focused perpendicularly on the target surface with a lens of $f/1.9$. The maximum laser energy on the target surface is approximately 900 mJ. The laser power intensity ranges from 0.45 to 11.37 GW/cm^2. In experiments, the laser system is operated in a single shot mode. In order to measure the target velocity, a He–Ne laser beam is focused along the target surface into a photodiode, which is placed on the other side of the target. Af-

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ter irradiation of a drive laser pulse, the target moves across the He–Ne beam. The time for the target to move across the He–Ne laser beam is recorded by an oscilloscope. By using the target thickness and the time moving across the beam, the target velocity can be deduced. Then the target momentum can be easily calculated from the target velocity and the target mass.

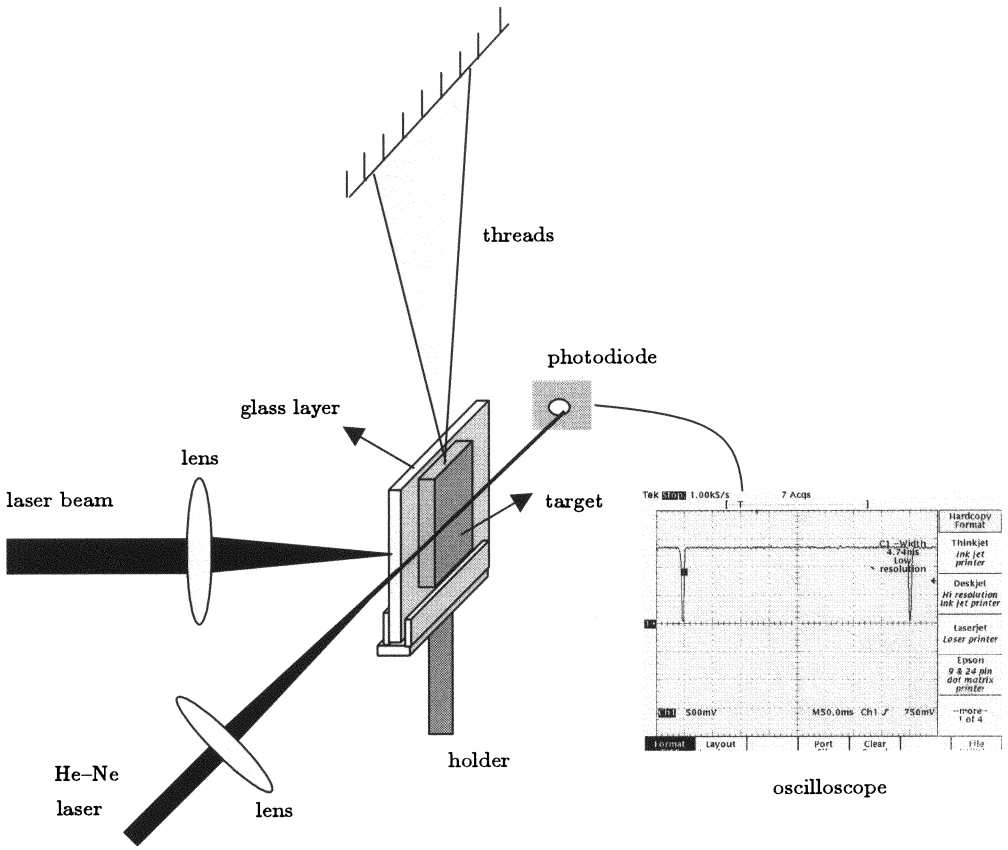


Fig.1. Schematic of the experimental setup.

The targets used in the experiment are aluminium plates with a size of 9 mm×11 mm×2 mm. A transparent glass layer with an available thicknesses is used to cover the target surface. For the direct ablation, laser pulses are directly focused onto the target surface. For the confined ablation, the target surface is covered with the transparent glass layer that is fixed on a holder, and the laser pulses are focused onto the target surface through the glass layer. In order to optically hold the target and the glass layer together, for some shots, some vacuum grease is placed on the glass-target interface.

3. Results and discussion

Figure 2 shows the dependence of the coupling coefficient on the laser intensity for the direct ablation and the confined ablation in atmospheric pressure. It is clear that with laser intensity increasing from 0.45 to 11.37 GW/cm^2, the coupling coefficient increases for all cases, in which the coupling coefficient of confined ablation is more dependent on the laser intensity. With the irradiation of 11.37 GW/cm^2, the coupling coefficient is about 18.09×10^{-5}N·s/J for the confined ablation, but only 1.79×10^{-5}N·s/J for the direct ablation. When the vacuum grease is used in the interface, the coupling coefficient can be enhanced only at a high laser intensity.

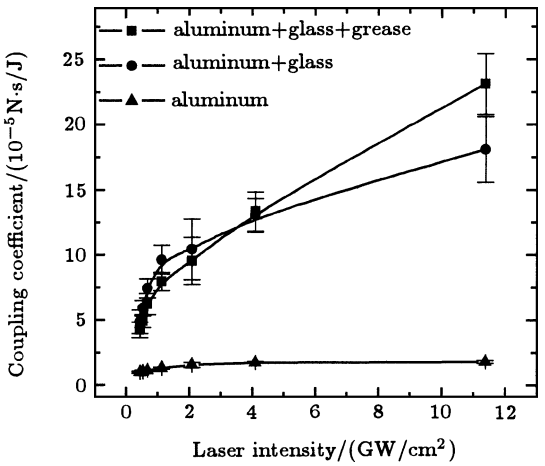


Fig.2. Dependence of the coupling coefficient on the laser intensity for the direct ablation, confined ablation and confined ablation with vacuum grease on the target–layer interface.

Furthermore, with the increase of the laser energy, the confined ablation can also greatly enhance the target momentum, as shown in Fig.3.

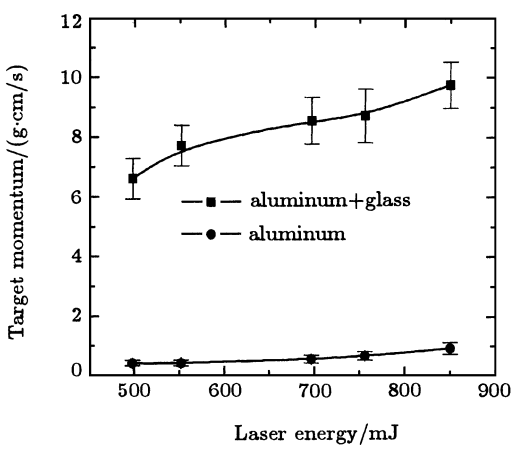


Fig.3. Dependence of the target momentum on the laser energy for the direct ablation and confined ablation. In the confined ablation, the glass layer is 2 mm thick.

For a laser intensity lower than the ionization threshold of the target, most of the laser energy is transferred to heat low-density air and only a small fraction of energy is used to drive the target. For a high laser intensity, a plasma is generated and an intensive detonation wave can be induced. Target momentum transfer is completed mainly through the detonation wave.[6] Compared with the detonation wave, the contribution of the plasma to the target momentum transfer is small. However, it can promote the formation of the detonation wave at the initial stage.[7] In the confined ablation, the plasma expansion is confined by the glass layer. The time for the plasma to interact with target is on the order of nanoseconds,[8,9] but the movement time of the target is on the order of milliseconds. When the target is obviously separated from the glass layer, the plasma has already been recombined and the interaction process completed. It means that the interaction is carried out in a very small space so that the plasma density and plasma temperature are enhanced. Through an inverse bremsstrahlung absorption mechanism, more laser energy is absorbed and converted into plasma kinetic energy. Furthermore, since the glass layer is fixed, the momentum is not conservative in the plasma expansion. The plasma expansion is confined in one direction instead of two opposite directions. From this point, the coupling coefficient can be doubled at least compared with the direct ablation. Moreover, the expansion of the heated air on the interface also adds more momentum to target. These combined factors finally result in a high coupling coefficient in the confined ablation.

When the glass–target interface is filled with the vacuum grease, the mean density of the absorbing medium in the interface increases. This corresponds to a high inverse bremsstrahlung absorption and a high coupling coefficient. On the other hand, due to the adherence of the grease, target movement is partly resisted. The enhanced coupling coefficient is only observed at high laser intensities.

For other target material, such as graphite, its coupling coefficient has the characteristics similar to those for an aluminium target, as shown in Fig.4. In fact, besides the characteristics of the plasma, the coupling coefficient is related to many factors of target material, such as vaporization temperature, melting temperature and thermal conductivity.[10] For the aluminium target, a part of laser energy is lost through the thermal conductivity during the interaction. So the coupling coefficient of aluminium is lower than that of the graphite.

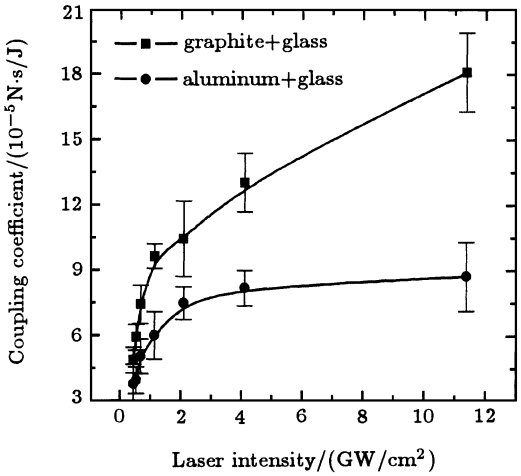


Fig.4. Dependence of the coupling coefficient on the laser intensity for the ablation graphite and aluminium targets each covered with a 2 mm glass layer.

In order to further understand the effect of the glass layer on the laser plasma expansion, the dependence of the coupling coefficient on the gap width between the target surface and the glass layer is investigated. It is shown in Fig.5 that as the gap width increases, the coupling coefficient decreases. Fitting the experimental results, we can obtain

$$C_{\mathrm{m}} = 20.29\exp(-d/0.53), \qquad (1)$$

where C_{m} is the coupling coefficient, and d is the gap width between the target surface and the cover layer. It can be seen that the coupling coefficient exponentially decreases. For a gap width of about 0.5 mm, the coupling coefficient is 15.53×10^{-5}N·s/J. For a 2.0-mm gap width, the coupling coefficient dramatically reduces to 1.65×10^{-5}N·s/J. For an even wider gap, the coupling coefficient is roughly equal to that of direct ablation.

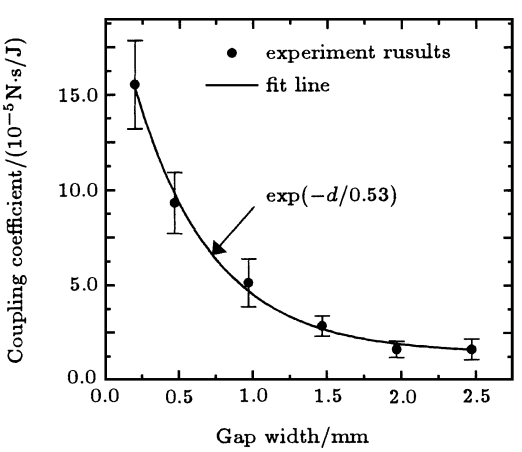


Fig.5. Dependence of the coupling coefficient on the gap width between the target surface and the glass layer. The black dots are for experiment results and the solid line is the fitting line.

Because the maximum plasma expansion is in the normal direction of the target surface,[11] we believe that the interaction space size between the glass layer and target surface determines the coupling coefficient. When the glass layer is very close to the target, the interaction space is so small that the laser pulses can be fully absorbed by the plasma, producing a higher coupling coefficient. A wider gap width offers a larger space for the laser pulses to interact with plasma. The average plasma density and plasma temperature decrease accordingly, leading to a lower coupling coefficient. When the space size is much larger than the plasma plume, the glass layer has no effect on the plasma expansion. The coupling coefficient is equal to that of direct ablation. On the other hand, it is found in our previous experiment that the glass layer can prolong the time of interaction between plasma with target.[12]

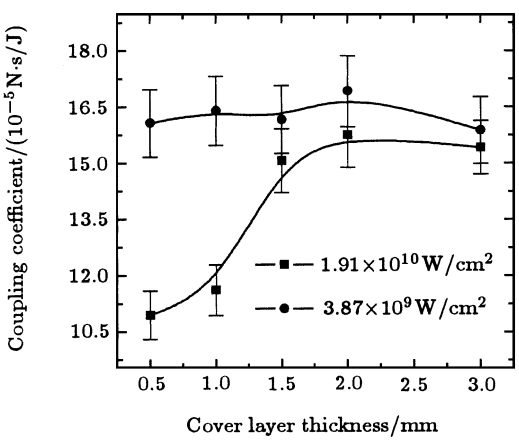


Fig.6. Effect of the glass layer thickness on the coupling coefficient at different laser intensities. The gap width between the glass layer and the target surface is about 0.5 mm.

Besides the laser intensity, laser energy and interaction space size, the coupling coefficient is also related to the cover layer thickness. If the cover layer is too thin, it is easily broken into pieces before the end of the laser pulses. The laser plasma cannot be effectively confined. If the cover layer is too thick, it can absorb and scatter a part of laser energy. The efficiency of laser energy is reduced. So it is necessary to investigate the effect of the cover layer thickness on the coupling coefficient. Figure 6 shows the dependence of the coupling coefficient on the glass layer thickness at laser intensities of 1.91×10^{10} W/cm^2 and 3.87×10^9 W/cm^2. The glass layers each are 0.5 mm, 1 mm, 1.5 mm, 2 mm and 3 mm thick. At a low laser

intensity of 3.87×10^9 W/cm^2, some damage happens at a rear of glass surface. But the glass layers with all the thicknesses above can effectively confine the plasma expansion and the coupling coefficients are little changed. With the irradiation of 1.91×10^{10} W/cm^2, a glass layer with a thickness of 0.5 mm is too thin and easily broken into pieces, and the coupling coefficient decreases to 10.9×10^{-5}N·s/J. If the glass layer is too thick, say about 3 mm, some damage takes place inside the glass layer and the coupling coefficient tends to decrease. At such a laser intensity, the optimal thickness is about 2 mm. In order to obtain a high coupling coefficient, besides the thickness, other characteristics of the cover layer such as high damage threshold, high transmissivity and rigidity should be also considered.

4. Conclusion

By using a glass layer to cover the target surface, the coupling coefficient is significantly enhanced. Compared with direct ablation, the coupling coefficient can be enhanced by an order of magnitude, reaching 18.09×10^{-5}N·s/J, in the confined ablation. The gap width between the glass layer and target surface plays an important role. As the gap width increases, the coupling coefficient exponentially decreases. Furthermore, it is found that the coupling coefficient is also related to the thickness of the cover layer. The optimal thickness is determined by the laser intensity and the characteristics of the cover layer.

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