Particle Acceleration via Laser Ablation

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Abstract

Recently, the biolistic process is emerging as an effective needle-free drug delivery technique to transfer adequate concentrations of pharmacologic agents to soft living tissues with minimum side effects. We have started developing an effective method for delivering drug coated particles using laser ablation. A thin metal foil with deposited micro-particles on one side is irradiated with laser beam on the opposite side so that a shock wave is generated. This shock wave travels through the foil and is reflected, which causes and instantaneous deformation of the foil. Due to such a sudden deformation, the micro-particles are ejected at a very high speed. Here we present the experimental results of direct and confined laser ablation, which correspond to the initial stage of the whole experiment.

Laser Ablation

The name 'laser ablation' is generically used to describe the laser-material interaction, which involves coupling of optical energy into a solid, resulting in vaporization; ejection of atoms, ions, molecular species and fragments; shock waves; plasma initiation and expansion; and a hybrid of these and other processes. Laser irradiance and the thermo-optical properties of the material are critical parameters that influence these processes [1].

Before proceeding to particle acceleration, we first executed experiments on direct laser ablation in order to generate shock waves, measure their velocities at different conditions, so that the most efficient condition can be chosen for the confined ablation particle acceleration. Then, we carried on with particle acceleration experiments, on both direct and confined ablation, from which we were able to get qualitative comparisons.

Direct laser ablation

In direct laser ablation, as seen in Fig. 1, a target material is directly irradiated with laser beam, which evaporates part of the material and generates plasma. As the plasma expansion is supersonic, a shock wave is also generated. The experimental setup is shown in Fig. 1.

An Nd:Yag laser with a wavelength of 532nm and pulse duration of 10ns was used for the experiment. The energy was set to 200mJ/pulse and the target materials were 1mm thick copper, aluminum and brass. Velocities of the shock waves were measured from the shadowgraphic images and were compared with Sedov's blast wave theory [2]. As can be seen in Fig. 2, they are in good agreement, so this theory was used to analyze the amount of energy transmitted to the shock wave.

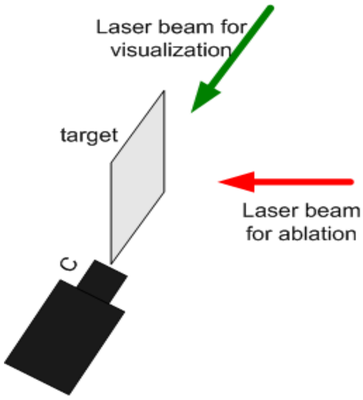

Fig. 1. Schematic of the direct laser ablation experiment

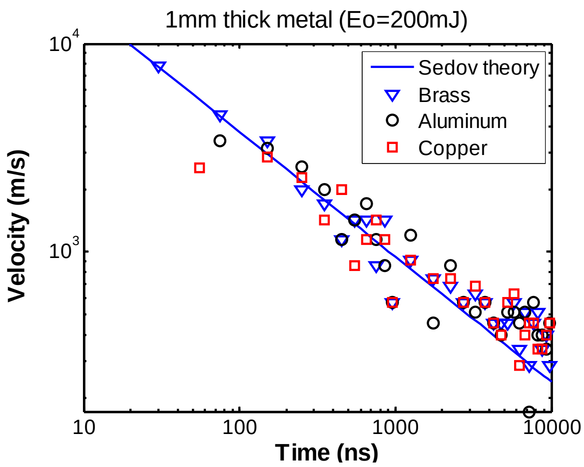

Fig. 2. Propagation velocity of the shock wave at different times.

Because Sedov's theory describes the propagation of shock waves after a strong explosion, the atmospheric pressure p_1 which is right behind the shock wave pressure p_2 can be neglected. Therefore the shock wave problem can be expressed in terms of air density ρ_1, shock wave energy E_0, specific heat ratio γ, and time t. Defining r_2 as the shock wave radius, we can get the following equation.

$$r_2 = \left(\frac{E_0}{\rho_1}\right)^{1/(2+\nu)} t^{2/(2+\nu)} \lambda_0 \qquad (1)$$

where ν represents the dimensionality of the propagation (ν=1 for planar, ν=2 for cylindrical, and ν=3 for spherical propagation), and λ_0 is a non-dimensional coefficient. In the above equation, $E_0=\alpha E$, E being the laser energy. Rearranging Eq. (1) in order to obtain the value of E_0 we get

$$E_0 = \frac{r_2^{(2+\nu)} \rho_1}{t^2} \qquad (2)$$

This way, we were able to calculate the energy transferred to the shock wave, by substituting the measured propagation distance into r_2. Table 1 shows the different values of α of each metal that were averaged except during the pulse duration.

	Aluminum	Brass	Copper
α	0.5534	0.4877	0.4655
T_m	~ 650 °C	~ 915 °C	~ 1083 °C
T_b	~ 2200 °C	~ 2300 °C	~ 2310 °C

Table 1. Calculated values of α of each metal.

Among the three metals that were used as the target material, aluminum was found out to be the one that transfers the most energy into the shock wave. This is presumed to be because of its low meting/boiling point. Assuming that metals are irradiated with the same energy, when the melting/boiling point is low the amount of metal vapor produced will increase so the ambient air around will be pushed more strongly. From this we can deduce that the most efficient metal for accelerating particles will be aluminum.

Confined laser ablation

Compared to direct ablation, confined ablation is a very efficient way of enhancing the momentum transfer to the target. When the target is irradiated, it absorbs energy and generates plasma with supersonic expansion. If the target is covered with a transparent material, the generated plasma can be confined, and therefore the momentum transfer and coupling coefficient can be greatly enhanced. Some of the factors that contribute to this enhancement are as follow. The interaction takes in a very small place, so the plasma density and temperature are enhanced. The plasma is confined in one direction instead of two opposite directions. From this point, the coupling coefficient can be doubled at least compared to the direct ablation. Moreover, the expansion of the heated air on the interface also adds more momentum to the target. These combined factors finally result in a high coupling coefficient. Zheng Zhi-Yuan et al [3] showed in their experiments of direct and confined laser ablation, using aluminum as the target, that the momentum transfer was around ten times bigger in confined ablation, compared to direct ablation. Based on this, we designed a holder as seen in Fig. 3 to accelerate particles with confined ablation.

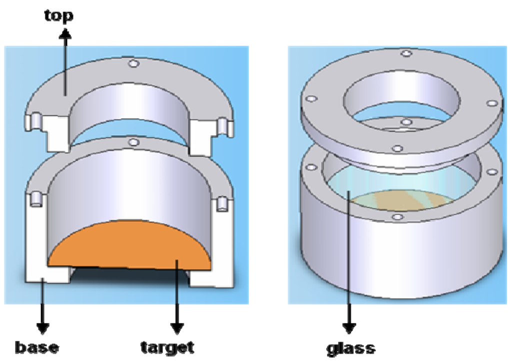

Fig. 3. Design of the holder for confined ablation.

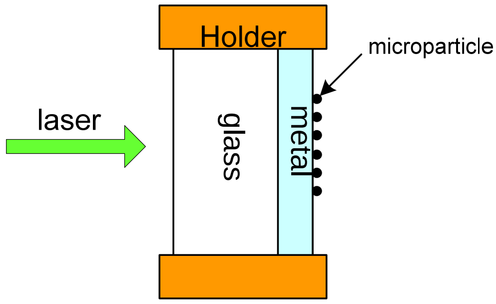

Fig. 4. Particle acceleration through confined ablation.

Particle acceleration

Figure 4 shows the schematic of particle acceleration through confined ablation [4]. A thin layer of micro particles is deposited on one of the surfaces of the metal foil and the rear side is irradiated with the laser beam, which passes through a transparent material, in this case glass. The deposited laser energy causes vaporization of a small portion of the foil. This ionized vapor expands, generating a shock wave, which travels through the metal target. When the shock wave reaches the end of the foil surface, it gets reflected as an expansion wave due to its acoustic impedance mismatch between the air and the metal foil. The backward propagation of the expansion wave causes the metal foil to deform suddenly, and this instantaneous deformation makes the deposited layer of particles get ejected at a very high speed. The BK7 glass overlay helps confining the laser ablation, making the shock wave stronger [5].

We executed experiments using 0.05mm thick copper as the target material, 3mm thick BK7 glass for confinement, laser energy of about 11mJ/pulse, and fluorescent polymer microspheres with density of 1.05g/㎤ as the particle to be ejected.

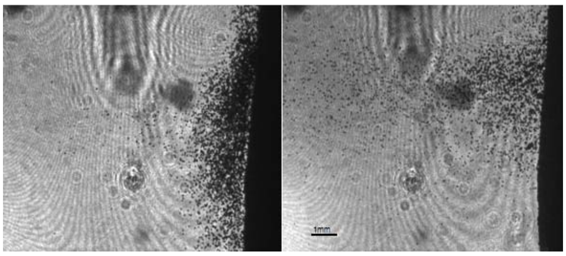

Fig. 5. Accelerated particles through confined ablation at (a) t=0.5ms and (b) t=1ms.

Figure 5 shows some images of the accelerated particles. Through the experiments, we could verify that the particles were ejected from the foil at very high velocity in the range of milliseconds, and very soon after the ejection they are greatly decelerated. Since the camera used was not a high speed camera, each frame represents an individual experiment. Also, because the particles were not equally distributed over the surface, exact quantification based on these images were not made.

Instead, we estimated the surface velocity of the foil from the first principles using continuum mechanics, based on plastic deformation in the foil due to shock wave loading.

As the shock wave propagation through the metal foil is a longitudinal compressive wave, its velocity inside a thin metal foil, C_l can be given by

$$C_l = \sqrt{\frac{E_m(1-\nu_m)}{\rho_m(1+\nu_m)(1-2\nu_m)}} \tag{3}$$

where E_m is the Young's modulus, ρ_m is the density and υ_m is the Poisson's ratio of the metal.
Assuming that the shock wave increases the metal foil's pressure (P), the displacement (S) can be expressed as

$$S = \frac{2PC_l\tau}{E_m} \tag{4}$$

where τ is the time needed for the wave to travel once through the foil. As the displacement of the foil is the plastic deformation in the foil due to shock wave loading, and can be physically measured, the pressure (P) induced in the foil can be estimated.

Knowing the values of P and C_l, the velocity of the foil can be calculated by differentiating Eq. 4.

$$V = \frac{PC_l}{E_m} \tag{5}$$

In this case the value of V works out to be 4973m/s. Since the thickness of the foil is very small, the surface of the metal target on which the particles are deposited is expected to accelerate to this velocity and so are the particles. Hence, the particles will have an initial velocity of around 4900m/s. The deformed metal foil after shock wave loading is shown in Fig. 6.

Once we get the initial velocity of the particles from Eq. 5, the velocity of the particles near the target can be deduced from the equations of motion.

The equation of motion of the particle can be written as

$$-D + w = m\frac{dV}{dt} \tag{6}$$

where D is the drag force, w is the weight, m is the mass and dV/dt is the deceleration of the particle. The final velocity of the particle can be computed using the following expression

$$V_p = \left[V_\infty^2 - \left(2\frac{dV}{dt}Sd\right)\right]^{1/2} \tag{7}$$

where Sd represents the distance of the particle from the metal foil. In this case, for a target stand-off distance of 10mm, V_p works out to be about 3040m/s.

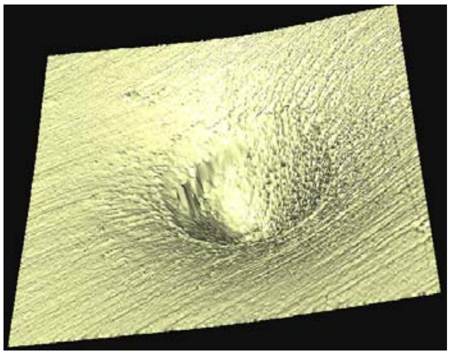

Fig. 6. Magnified image of the metal foil deformed due to shock wave loading, using 3D surface profiler

To qualitatively verify that the confined ablation was a more effective way for particle acceleration than direct ablation we accelerated particles using direct ablation as well.

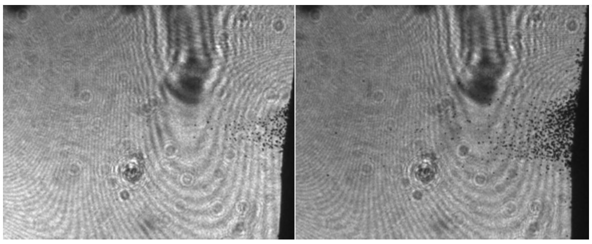

Fig. 7. Accelerated particles through direct ablation at (a) t=0.5ms and (b) t=1ms.

As seen in Fig. 7, the particles do get accelerated but compared to Fig. 5 the velocity is much lower, and of course, the deformation of the foil was very weak. Experiments executed with aluminum as the metal target with different types of particles are also in progress, and will be discussed on the next phase of the research.

Conclusion

So far, we have concentrated on developing a laser ablation based particle acceleration device. We started the first phase of the process by setting up the experiments for direct laser ablation in order to generate shock waves. We measured the velocities of the shock waves and compared them with Sedov's blast wave theory, which allowed us to estimate the energy transferred to the shock waves. From this we were able to verify some important conditions regarding efficiency. Then, we carried on experiments on accelerating the particles via confined and direct laser ablation. Through these experiments we verified that with confined ablation, the particles were ejected from the foil at hypersonic speeds even with low laser energy. The next phase of this research will include penetration of particles into soft targets, quantification on spread diameter and penetration depth, as well as optimization of the experimental conditions to maximize the velocity of the particles and their penetration depth. At the same time, miniaturization of the device with the help of endoscopes and optical fibers, and finding other applications of accelerating micro particles will be in important features to be studied.

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