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Influence of air pressure on mechanical effect of laser plasma shock wave*

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The influence of air pressure on mechanical effect of laser plasma shock wave in a vacuum chamber produced by a Nd:YAG laser has been studied. The laser pulses with pulse width of 10ns and pulse energy of about 320mJ at 1.06μm wavelength is focused on the aluminium target mounted on a ballistic pendulum, and the air pressure in the chamber changes from 2.8×10^3 to 1.01×10^5Pa. The experimental results show that the impulse coupling coefficient changes as the air pressure and the distance of the target from focus change. The mechanical effects of the plasma shock wave on the target are analysed at different distances from focus and the air pressure.

Keywords: mechanical effect, plasma shock wave, impulse coupling coefficient, air pressure
PACC: 5240H, 5250J

1. Introduction

When a high-power laser pulse irradiates on a target, the target is subjected to an impulse due to the reaction of plasma shock wave produced by the laser pulse. The laser energy is transferred to the target during this process. Laser impulse coupling coefficient ($C_{\rm m}$) is defined as the momentum of the target transferred from unit laser energy, which is an important quantity to show the mechanical effect of laser plasma shock wave. Experiments show that $C_{\rm m}$ is closely related to the parameters of the laser, the properties of the target and the environment condition. David and Scott's results[1] showed that there is always a suitable laser intensity which can make $C_{\rm m}$ reach its maximum for any material, and $C_{\rm m}$ decreases if laser intensity increases continually. Phipps *et al* reported that $C_{\rm m}$ can be estimated approximately by the mode of recoil of laser plasma shock wave, and he determined the dependence of $C_{\rm m}$ on the pulse intensity (I) wavelength (λ), wave width (τ) and other parameters.[2] Afterwards, the model of momentum coupling coefficient was put forward in the fully ionized plasma regime based on experimental data.[3] The experiments performed by Gray and Zheng group respectively showed that $C_{\rm m}$ differs under different target surface conditions, and it increases when the surface of a metal target is coated. They reported also that $C_{\rm m}$ will increase by as much as an order of magnitude by using a multi-layered material system instead of a single-layer material.[4−6] Pakhomov *et al* measured the special impulse of the interaction between laser and target by using three different methods: direct force measurement, a time-of-flight energy analyser, an intensified charge-coupled device (ICCD) imager. In their experiments special impulses on different targets C, Al, Fe, Zn, Cu, Sn, Pb, Si, Ti, Au were measured: the $C_{\rm m}$ of Pb target reaches the maximum (8×10^{-5} N/W), and the $C_{\rm m}$ of Au target is the minimum (1.83×10^{-5} N/W), and the maximum special impulse (20000 s) is obtained on the Al, C target. The conclusion is that the special impulse decreases with the increase of molecular mass, and the impulse force increases with the increase of molecular mass.[7−11] The influence of environment variables on $C_{\rm m}$ has not received attention until recent years. In 2002, Xu *et al* measured the relation between $C_{\rm m}$ and air pressure when laser was applied on LY12 aluminium target and K9 optical glass target with a sensitive ballistic pendulum and discovered that $C_{\rm m}$ increases when the air pressure increases.[12] In 2004, Pakhomov *et al* concluded that $C_{\rm m}$ increases with air pressure and the mass remove ratio decreases when the air pressure increases.[13] In 2005, Zheng *et al* obtained a relation between $C_{\rm m}$ and air pressure in air-breathing mode,

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and they found that there is a peak value of $C_{\rm m}$ when the air pressure is about 34.6×10^3Pa.[14] All the above researchers obtained the different results of effects of air pressure on $C_{\rm m}$ under different experimental conditions. However, up to now there has been still no consistent explanations about the effect of air pressure on $C_{\rm m}$. In this paper we investigate the influences of the air pressure and the distance of target from focus on $C_{\rm m}$, the mechanical effects of plasma shock wave on the target at different distances from focus and the air pressure.

2. Experimental setup and method

2.1. Experimental setup

A schematic diagram of experimental setup is shown in Fig.1.

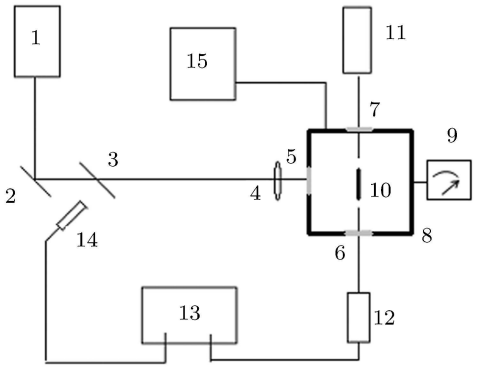


Fig.1. Experimental setup.

A Nd:YAG laser with 10ns pulse width at 1.06μm wavelength and 320mJ pulse energy is used. Laser pulse passes through a reflection mirror 2, a spectroscope 3, a lens with 147mm focus length 4, the glass window 5 of a vacuum chamber 8, and reaches the aluminium target 10. The air pressure in the vacuum chamber is indicated by a barometer 9. Different air pressure can be achieved with a vacuum pump 15. A photo-electricity apparatus measures the speed of target caused by laser action. The schematic diagram of speed measurement is also shown in Fig.1. A He:Ne laser 11 passes through a glass window 7 and reaches the target. When the target leaves the equilibrium place, the intensity of He:Ne laser which enters into a photo-electricity sensor 12 reaches the maximum. When the target returns to the equilibrium position, the intensity of He:Ne laser which enters into the photo-electricity sensor becomes the minimum. The signal of the photo-electricity sensor is recorded by an oscilloscope 13. The time interval when the target passes through the slot of the photo-electricity sensor can be measured by analysing the voltage signal on the oscilloscope.

2.2. Calculation of $C_{\rm m}$

In Fig.2, when the target goes through the slot, the time interval Δt is measured by the photo-electrical sensor. The angular displacement is $\Delta\theta = W/l$, the angular velocity is $\varpi = \Delta\theta/\Delta t$, then the momentum of target is $P = L/l = J\varpi/l$ and $C_{\rm m} = P/E = J\Delta\theta/(E\Delta t l^2)$, where J is the moment of inertia of the target. In this experiment, $W = 0.7$ mm, $l = 47.0$ cm, $R = 1.50$ cm, $J = mR^2/4 + m(l-R)^2$, where R is the radius of the target.

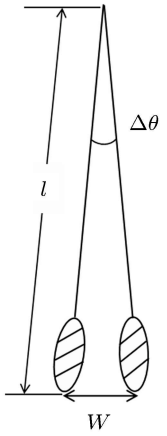


Fig.2. Relationships among pendulum angle, pendulum thread length and slot width.

3. Results and discussion

According to Fig.3, Z is defined as the distance of the target from the focus, d is the diameter of laser beam on the target, and I is the power intensity. When Z is positive, it means that the target locates after the focus of lens. When Z is negative, it means that the target is in front of the focus of the lens. When Z is zero, the target is just at the focus of the lens. Four groups of data have been measured in the experiment and are listed in Table 1.

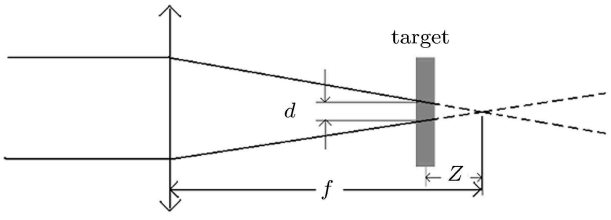


Fig.3. Definition of Z and d.

Table 1. The laser beam diameter on the target and the laser intensity versus Z.

	$Z=-20$ mm	$Z=-8$ mm	$Z=0$ mm	$Z=8$ mm
d/mm	0.89	0.55	0.3	0.53
$I/(\mathrm{W/cm^2})$	5.15×10^9	1.35×10^{10}	4.53×10^{10}	breakdown before the target

3.1. The target at the focus ($Z=0$ mm)

At the focus point, according to Fig.4, C_m increases quickly as air pressure increases when the air pressure is low. C_m reaches the maximum at about 4×10^3Pa, and then it decreases slowly.

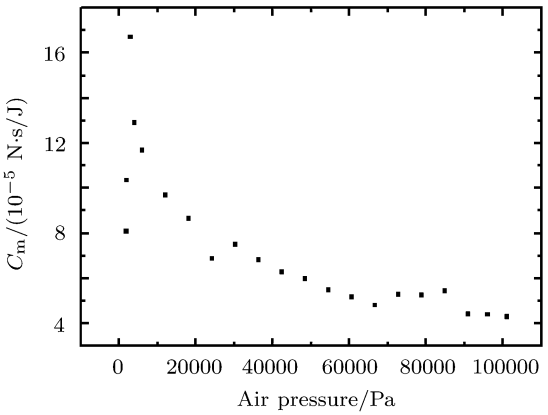


Fig.4. The relationship between C_m and air pressure at $Z=0$.

At $Z=0$ mm, the laser intensity is maximum, impulse coupling is mainly induced by the recoil of material remove induced by laser irradiation and the recoil of laser-supported detonation (LSD) wave induced by laser plasma on the surface of the target. LSD wave plays a main role gradually with the increase of air pressure from zero. When laser intensity is I_0, according to Pirri's theory,[15] the velocity of LSD wave is $D=[2(\gamma^2-1)I_0/\rho_0]^{1/3}$, and the density, pressure and particle velocity of the plasma after LSD wave can be derived.

$$\begin{aligned}\rho_\mathrm{J}&=(\gamma+1)\rho_0/\gamma,\\ P_\mathrm{J}&=\rho_0D^2/(\gamma+1)\\ &=4^{1/3}(\gamma-1)^{2/3}(\gamma+1)^{-1/3}\rho_0^{1/3}I_0^{2/3},\\ u_\mathrm{J}&=D/(\gamma+1)\\ &=[2(\gamma^2-1)]^{1/3}(\gamma+1)^{-1}\rho_0^{-1/3}I_0^{1/3}.\end{aligned}\tag{1}$$

Here we obtain the pressure on the target surface using plasma media as

$$P_\mathrm{T}=[(\gamma+1)/2\gamma]^{2\gamma/(\gamma-1)}P_\mathrm{J}.\tag{2}$$

From Eqs.(1) and (2), when laser intensity is I_0 and isentropic exponent γ is given, the pressure on the target surface increases with the surrounding air density, and C_m also increases with it.

When the surrounding air pressure increases from 4×10^3Pa continually, C_m decreases. Two factors play the main role during the process. One factor is the two-dimensional rarefaction wave. Phipps *et al* put forward the size about one-dimensional laser spot model as follows:[2]

$$D_\mathrm{s}\propto A^{7/16}\lambda^{7/4}\tau^{7/8}I_0^{3/4},\tag{3}$$

where D_s is the laser spot diameter, A is the molecular mass of the target, I_0 is the intensity of the incident laser, λ is wavelength, and τ is pulse width.

$$D_\mathrm{s}>2C_\mathrm{a}\tau,\tag{4}$$

where C_a is the sound speed.

Elliot and Stanley's research showed that the velocity of LSD wave increases with the decrease of laser spot.[16] In Table 1, at $Z=0$ mm, the power intensity is the maximum and the spot area is the minimum. But the diameter of the spot area that can meet the requirement of one-dimensional model should be the biggest according to Eqs.(3) and (4). This means that the effect of the two-dimensional rarefaction wave is the biggest at $Z=0$ mm in this experiment. The effect caused by the rarefaction wave increases with the increase of air pressure. This leads to the decrease of LSD wave and also makes C_m increase. The other factor is the plasma shielding effect. The breakdown thresholddecreases and the plasma intensity increases with the increase of air pressure from Young's study,[17] and the shielding effect increases with the increase of the plasma intensity from Liu's study.[18] Therefore, when the air pressure increases, the shielding effect increases, the laser energy that reaches the target decreases, and C_m decreases.

3.2. Distance of target from focus $Z\neq0$

3.2.1. $Z=-20$ mm

It can be seen from Fig.5 that C_m increases with the air pressure when $Z=-20$ mm.

When the distance of target from focus is negative, the laser action on the target is mainly ablation. In the process of ablation, the conservation of energy can be expressed as:

$$E = E_{\mathrm{AB}} + Q^* M, \tag{5}$$

where E is laser energy, E_{AB} is the energy consumed in breakdown of air, Q^* is the energy needed to ablate a unit mass of the target, M is the mass removed by ablation. It has been proven that mass removal ratio decreases with the increase of air pressure.[11] The energy needed to remove a unit mass of the target decreases and the energy needed to break down air to produce LSD wave increases. From Eq.(1), the recoil on the target impinged by LSD wave increases accordingly. So C_{m} increases with the air pressure.

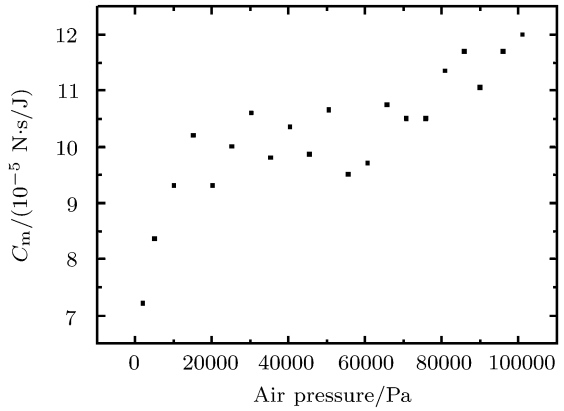


Fig.5. Relationship between C_{m} and air pressure for target at $Z = -20$ mm.

3.2.2. $Z = -8$ mm

Generally, the relationship between C_{m} and air pressure at $Z = -8$ mm is similar to that at $Z = -20$ mm as can be seen from Fig.6, but C_{m} decreases slowly when air pressure is over 6×10^4 Pa.

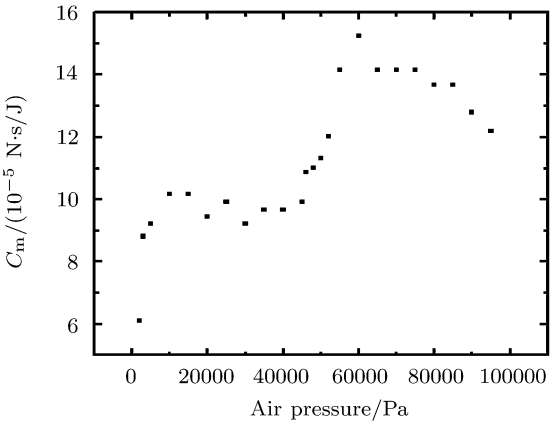


Fig.6. Relationship between C_{m} and air pressure at $Z = -8$ mm.

It can be seen from Table 1 that the action from rarefaction wave and plasma shielding at $Z = -8$ mm is weaker than that at $Z = 0$ and stronger than that at $Z = -20$ mm. However, the actions from rarefaction wave and plasma shielding all increase at higher air pressure. This makes C_{m} decrease.

3.2.3. $Z = 8$ mm

According to Fig.7 the relationship between C_{m} and air pressure at $Z = 8$ mm is similar to that at $Z = 0$, but the interaction mechanism is different. When air pressure is low, the impulse coupling comes mainly from the recoil of mass removal on target surface. There are three kinds of forces acting upon the target when air pressure increases slowly:

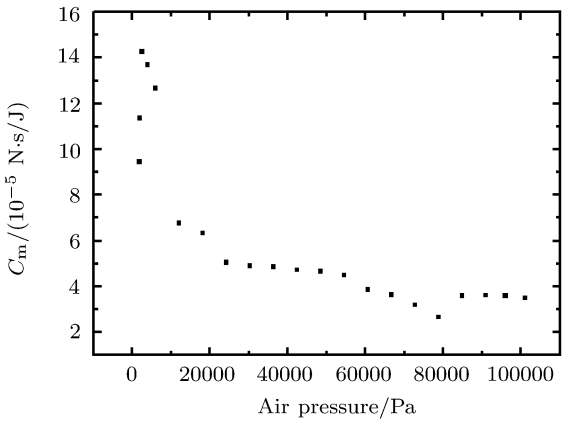


Fig.7. Relationship between C_{m} and air pressure at $Z = 8$ mm.

1) The reaction of LSD wave induced by the break down of air at the focus, 2) the reaction of LSD wave at the surface of target induced by the laser energy, which is transferred to the target before or during the process of the breakdown of the air, 3) the recoil of mass removal. Different effects dominate in different phase though the whole process is complicated. Mass removal dominates at lower air pressure, so C_{m} is small. With the increase of air pressure, the air density increases. The interaction of LSD waves plays a key role, which exists at the focus and the surface of the target. Because both of them increase with the air pressure, C_{m} increases rapidly with air pressure. This process continues before the plasma shielding dominates, which appears when the plasma density induced by breakdown is high enough. The plasma shielding weakens the LSD wave or extinguishes it. So with the continual increase of air pressure, both the rarefaction

and the plasma shielding effects increase too. For this reason, $C_{\rm m}$ decreases with the increase of air pressure.

4. Conclusion

It has been proven in this paper that the mechanical effect of plasma shock wave on the target material is affected by the surrounding air pressure and the distance of target from focus. The pressure exerted by the shock wave on the target increases with the increase of air pressure and the surrounding air density. This naturally leads to the increase of $C_{\rm m}$ with the air pressure. However, at different distances of target from focus, the influence of air pressure on the mechanical effect of plasma shock wave is different. The plasma shielding effect and the rarefaction wave effect are different at different distance of target from focus. The interaction mechanism of laser with target is quite different when the distance from focus is positive or negative. It is concluded that:

1) At $Z = 0$ mm, $C_{\rm m}$ increases rapidly with the increase of air pressure, when the air pressure is low; it reaches the maximum at 4×10^3Pa, and then decreases slowly.

2) At $Z = -20$ mm, $C_{\rm m}$ increases with the increase of air pressure.

3) At $Z = -8$ mm, $C_{\rm m}$ increases with the increase of air pressure at first, reaches the maximum at 6.5×10^4 Pa, and then decreases.

4) At $Z = 8$ mm the relation between $C_{\rm m}$ and air pressure is similar to that at $Z = 0$, but the peak value is lower.

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