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激光驱动 Al 飞片及利用飞片增加材料压力的实验研究

EXPERIMENTAL STUDY ON Al FLYER DRIVEN BY LASER AND INCREASING MATERIAL PRESSURE WITH FLYER

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摘　要

利用激光驱动特制的斜腔靶研究了飞片飞越不同距离后的动力学特性、飞片到达稳态时的飞行距离及飞行速度；利用飞片技术在材料中实现大幅增压。

关键词：冲击波　飞片　斜腔靶　增压

Experimental Study on Al Flyer Driven by Laser and Increasing Material Pressure with Flyer

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ABSTRACT

The first experimental investigation about the shock wave character produced and impacted by flyer have been reported, which is driven by laser and has flied a different distances shaping a special inclined cavity target with continuous variant cavity length. And the experiment about effect of increasing pressure with flyer is demonstrated and also realizes a great pressure growth more than six times.

Key words: Shock wave, Flyer, Inclined cavity target, Increasing pressure

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In the experimental study of laser equation of state[1~7], flyer technique is an effective way to increasing material pressure[8~10]. However, in order to produce a planar and stable shock wave in target material which impacted flyer, the state characters of flyer while it strike a target must be equipped with a definite demands. The velocity, density etc. of flyer will affect and decide the specialties of shock wave and its propagation in target. It is obvious the flyer's characters depend on flyer material and its thickness, driving laser and flying distance etc. Using the special inclined cavity target in our experiment, the shock luminescent signal from the rear surface of target after impacted by the flyer which flies a different distance, have been observed and recorded with streak camera, thereon the flying distance which the flyer reaches a steady state and its velocity at that time can be deduced and estimated.

The Fig. 1 shows the configuration of inclined cavity target.

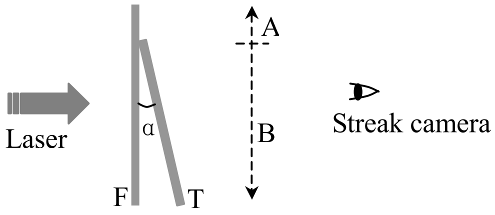
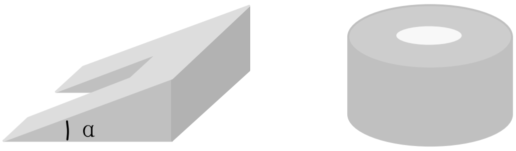


Fig. 1 Figured diagram of inclined cavity target

F and T are Al flyer and Al target respectively, their thickness are the same of 10 μm, the surface roughness of the foils is better than 50 nm and the thickness uniformity of each one is better than 1.5%. A and B are corresponding to the two regions of only flyer and flyer with target respectively, α is about 11.095°, the inclined cavity body between two foils of F and T is manufactured by a slope substance of quartz crystal as showing in Fig. 2 (a).



(a) (b)

Fig. 2 Slope substance

(a) and straight cavity substance; (b) made by quartz crystal.

The experiment was carried out on “Shenguang-Ⅱ” laser facility of NLHPLP. One beam of the driving laser, with 1.053 μm wavelength, about 1 ns near trapezium pulse width, was used in our experiment. By use of the uniformization system combined with the lens-array and principle focal lens[11], the uniform irradiation in the range of about 800 μm on target surface has been realized, and the uniformity is better than 5%. The experimental setup is shown in Fig. 3.

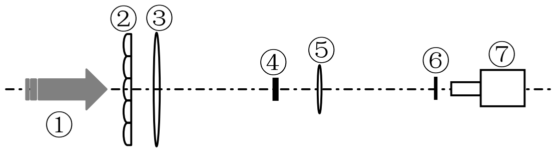


Fig. 3 Experimental setup

①driving laser; ②lens-array; ③focal lens; ④target;

⑤imaging magnifying optical system; ⑥optical attenuating plate; ⑦streak camera

The driving laser with uniform distribution irradiates directly on the flyer F, but covers a part of both space regions A and B (see Fig. 1). A shock wave will come into being in the flyer and quickly uninstall while it reaches the back-surface of flyer, then the material of flyer is going to fly forward with the velocity about near twice times of particle velocity behind shock wave[12]. The energy of driving laser will be absorbed continuously by the flyer and transformed the kinetic energy of the flyer; this process can greatly improve the availability of driving laser. It’s no other than why the flyer can increase the pressure of target material. Also a shock wave will be generated and propagates forward in the target T after struck by the flyer. Because the material of target behind shock wave be heated and its temperature can be raised up to about 10 thousands of degrees, a very strong shock luminescent signal of visible light will be radiated just at the time the shock wave arrives at the back-surface of target. After magnified 17 times by imaging magnifying optical system with space resolution of about 2 μm, it is recorded by streak camera with time resolution of 11.396 ps, given by practical calibration with a laser of ps pulse output, and shows in Fig. 4. In which the power density on the flyer is about 0.8×10^{14} W/cm^2.

In Fig. 4, it’s very clear the shock luminescence of the regions A and B are from back-surfaces of flyer F directly, and target T after impacted flyer, respectively. If the shock luminant leading edge from the region A is assumed to be the zero time

(t=0), the relative time t of shock luminescence from the different place of region B can be measured, and obviously, it has a coincidence relation with the cavity length L which flyer has flied. Fig. 5 shows the result obtained and calculated from Fig. 4.

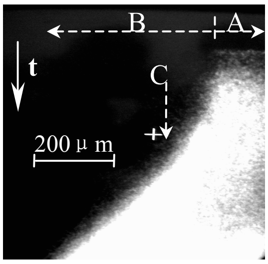


Fig. 4 Photo of shock luminescence from back-surface of inclined cavity target, the vertical from up to down is the direction of time scan, the horizontal is the direction with space resolution and spatial regions A and B are correspondence with that of Fig. 1

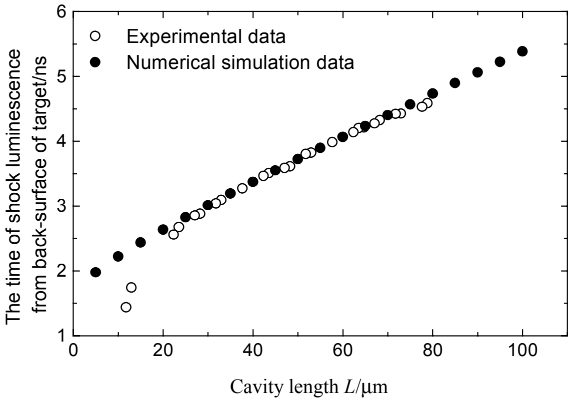


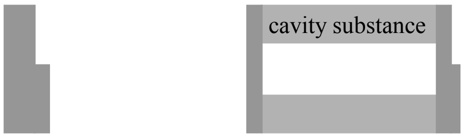
Fig. 5 The results from experiment and numerical simulation with inclined cavity target

It is thus evident that the relative time t keeps on a better linear relationship with the cavity length L after longer than about 30 μm (at the place C in Fig. 4), the correlation coefficient R of linear fitting is about 0.997. Of course, the relative time t include two periods of time, one is the transit time t_1 the flyer flies a certain cavity length, another is t_2 the shock wave propagates through the target T. Because the thickness of the target T is more thinner, t_2 is greatly shorter than t_1 in the linear region in which the cavity length has reached a fairish long volume, in fact in the condition with power density of about 10^{14} W/cm^2, experiment and theoretic estimation represent that the magnitudes of t_2 and t are about 100 ps and several ns respectively. Thus the influence upon t, brought by the change of t_2, can be ignored approximately, or we say the transit time t_2, which shock wave propagates through the 10 μm Al target T, almost keep constant in the linear region, it means the flyer has a flying process with a steady state in this region. It is generally agreed that the character of shock propagation in the target T depends on the release velocity of flyer's kinetic energy, what is called a flying process with a steady state, we can consider such that the flyer takes on a stable velocity to release its kinetic energy in this process, while it impacts the target. Also taking into account that the time during flyer impacting target is very small than t, and the flyer can be supposed a equidensity body during this time, thus an equivalent uniform flying velocity of the flyer can be estimated in the linear region, and is about 30.3 km/s obtained from the experimental data (marked with hollow circle) of Fig. 5.

It is necessary to point out the starting cavity length (for example about 30 μm in this experiment) in which flyer tends to become and reach a steady state, almost depends on the driving laser except the change of flyer parameter. But there is a pity in this experiment, we have not observed the shock luminescence phenomena which the condition with the cavity length longer than about 80 μm, it is mostly caused by the streak camera without enough time scanning length and some problems from optic synchronizer.

The result (marked with solid circle) from numerical calculation with JB-2 code is shown in Fig. 5, and well agreed with the experimental data. The theoretic calculating course is step by step, beginning from the absorption of the driving laser; and it includes the flyer's flying process with density distribution, its characters at the time while striking target, the generation and propagation of shock wave in the target, and the final shock break-out at the back-surface of target. The JB-2 is a one-dimensional and three-temperature hydrodynamic code coupling with super-thermal electron transportation and self-consistent electric field, the considered main physical processes in the code contain inverse Bremsstrahlung and anomalous laser absorption, Coulomb interaction of electron-ion, free-free and free-bond processes of electron-photon, average atomic model and local thermodynamic equilibrium (LTE) in ionization process, free-free, free-bond and bond-bond processes for photon's opacity, coulomb collision between super-thermal electron and thermal ion for scattering mean-free-path, theoretic equation of state given by Thomas-Fermi model and experimental data from high explosive loading facility in respective range of ultrahigh and low pressure, etc.

Further, the experiment to measure the effect of increasing pressure with flyer is also demonstrated. It is verified by use of two kinds of targets shown in Fig. 6.



(a) (b)

Fig. 6 Single step targets without (a) and with (b) flyer, combined of Al foundation base and Al step

In target (a), The thickness of foundation base is about 20 μm , and the step has two kinds of thicknesses with about 10 μm and 5 μm respectively; in target (b), the thicknesses of flyer and foundation base are the same of ～10 μm, the step thickness is about 5 μm, and 100 μm cavity length shaped with a straight cavity substance made by quartz crystal as Fig. 2 (b) shows. Choosing such target’s parameters is to keep the shock stability in the step, what is confirmed in reference [3] for the single step target without flyer, and deduced with theoretic simulation of JB-2 code for the single step target with flyer, the calculating result is shown in Fig. 7, it represents the steady range of shock pressure.

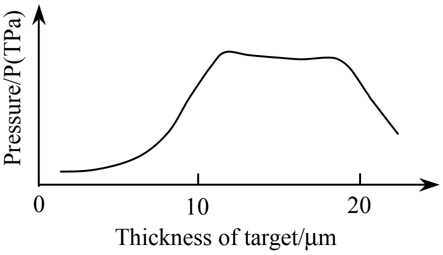
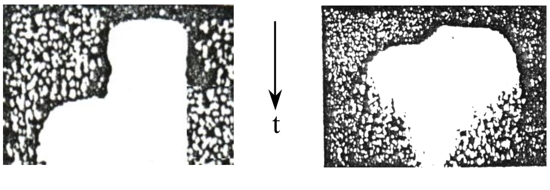


Fig. 7 The relative shock pressure in the target impacted flyer with 100 μm cavity length versus the different thickness of target



(a) (b)

Fig. 8 Shock luminescence from back-surface of target without (a) and with (b) flyer

With the same experimental setup of Fig. 3, the shock luminescence signals from back surface of two kinds of targets have been recorded, and Fig. 8 shows the two representative photos of them.

Use of the prior measured step thickness d and the experimental measured transit time t in the step, the shock velocity D and pressure p can be calculated with the shock wave relational expressions of $D=C_0+\lambda_u$ and $p=\rho_0 D_u$. In the experiment, the driving laser energy has been changed to investigate the characteristic, which the shock pressure p in Al step varies versus the driving laser power density I on target. The Table 1 lists the results of the measurement and calculation, here ρ_0=2.71 g/cm^3, C_0=5.48 km/s, λ=1.304[13].

Table 1 The results of the measurement and calculation

Target	I, ×10^{14}/W • cm^{-2}	d/μm	t/ns	D/km • s^{-1}	p/TPa
Without flyer	1.28	11.73	0.736	15.94	0.346
	1.58	11.57	0.689	16.79	0.395
	1.73	5.930	0.342	17.34	0.427
	2.42	6.120	0.342	17.89	0.462
With flyer	1.17	4.850	0.207	23.43	0.874
	1.86	5.137	0.130	39.52	2.795
	2.09	4.720	0.115	41.04	3.033
	2.48	5.255	0.127	41.38	3.087

The data from Table 1 is also shown in Fig. 9. It is obviously that the effect of increasing pressure with flyer is very prominent. The maximum pressure in Al step with flyer reaches thirty millions atmospheric pressure in this experiment, and is more than six times of that without flyer in the condition of the same driving laser power density.

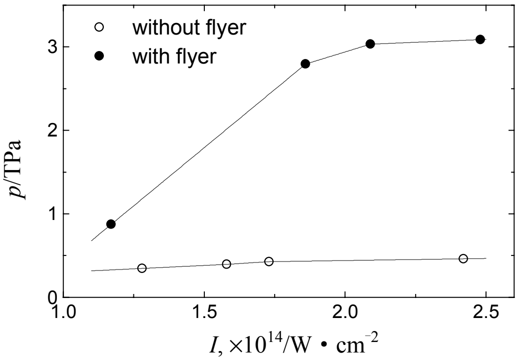


Fig. 9 Shock pressure p versus the power density I of driving laser

In fact, when the high power laser irradiates a solid target, there is a known calibrating dependence between the maximum pressure p in target and the driving laser power density I, it's described as following:

$$p=\alpha I^{\beta} \tag{1}$$

Here α and β are the parameters related with the wavelength of driving laser and target material, etc., and the units of p and I are TPa and 10^{14} W/cm^2 respectively. For the target without flyer, α_0=0.32 and β_0=0.45 are given by fitting with formula (1) and the data from Table 1. For the target with flyer, because the shock pressure in target, produced by flyer struck, also has a process with growth, steady and attenuation (see Fig. 7), which is very similar to the condition with laser direct drive. Thus it can be supposed that the formula (1) still exists in the condition with flyer, and α_{100}=0.73 and β_{100}=1.81 are also obtained in the same way.

The dependence of the pressure p versus the power density I has a great transformation from a slow allometric growth of β<1 to a more rapid allometric growth of β>1, which is corresponding to without and with flyer respectively.

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