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Investigation of crater creation efficiency by means of single and double targets in the PALS experiment

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Abstract. The paper concerns investigation of the efficiency of crater creation process for different types of targets made of Al: single massive target and double targets consisting of foil or disk placed before the massive target at chosen distance (300 μm and 500 μm). Targets were irradiated by the PALS facility laser beam: $E_L = 100 \div 500$ J at the first harmonic ($\lambda = 1.315$ μm), the focal spot diameter of 250 μm, and pulse duration of 400 ps. Velocities of accelerated foil or disk and electron density distribution of plasma streams were determined by means of three-frame interferometry. Shapes and volumes of craters were obtained by employing crater replica technology and microscopy measurement. This investigation has confirmed that the most effective method of crater creation is the direct laser-target interaction. However, contrary to our expectation, it turned out that the disk acceleration method is somewhat less effective in comparison with that using the foil acceleration (the craters created are deeper but narrower).

1. Introduction

The laser-planar target experiments play a fundamental role in the study of laser-produced plasma physics and in the problems related to inertial confinement fusion (ICF). They represent a starting point for numerous physical phenomena analysis and provide information necessary for research work in the domain of complex configurations such as implosion experiments with spherical targets on which the idea of laser fusion is based. The experiments utilizing ablatively accelerated planar targets can model large pellet shells in their early implosion phase. Instead of imploding a pellet, a disk target can be accelerated and treated as a section of a sphere (until convergence effects dominate). The craters created by an accelerated macroparticle can provide some very useful data for better comprehension of many features of interest. Studies of the shapes and volumes of craters produced in experiments with fixed laser pulse parameters, target material etc., which are complemented by suitable theoretical models, can lead to some scaling laws. Such laws provide information about the transfer efficiency of absorbed laser energy into a shock wave propagating in massive target directly or indirectly (by an impact of accelerated macroparticle with solid material), laser radiation absorption efficiency, thermal conductivity and so on.

2. Experimental conditions and results

The experiment was carried out with the use of the PALS laser facility [1]. The plasma was generated by the first harmonic of the iodine laser beam (λ=1.315 μm) with energy of 100-500 J, a focal spot diameter of

250 μm, and a pulse duration of 400 ps. To study the plasma expansion and macroparticle acceleration, a 3-frame interferometric system with automatic image processing was employed. In this experiment several types of targets were used: a single massive planar Al target and double targets consisting of 11 μm thick Al foil or disk (with a diameter of 300 μm) placed in front of the massive target at a distance of either 300 or 500 μm. Disks were held by a thin mylar foil 2.5 μm thick. Double targets with a gap of 500 μm were used to determine the accelerated macroparticle velocity. Shapes and volumes of the craters obtained at using the 300-μm gap were determined by employing crater replica technology and microscopy measurement. The average macroparticles velocities are summarized in Table 1.

Table 1: The set of average macroparticles' velocities.

Laser energy	Foil fragment velocity	Disk velocity
120 J	$3.4 \cdot 10^6$ cm/s	$4.0 \cdot 10^6$ cm/s
240 J	$4.8 \cdot 10^6$ cm/s	$5.4 \cdot 10^6$ cm/s

Unfortunately, for the laser energies above 250 J the velocity measurement was impossible due to a disturbance of the observation area by a strong X-ray radiation. The interferometric measurement of the electron density distributions for exemplary results allowed us to assume that the conditions of the laser energy absorption and of the target heating are roughly the same for all the target types. The diagrams of the crater volumes as a function of the laser energy are presented in Fig. 1. These diagrams show some tendencies in the crater volume changes with the increasing laser energy. In the cases of a single massive target and a foil-massive target combination, the crater volume grows linearly with energy. In the case of disks, the crater volume increase is stopped for laser energies above 250 J.

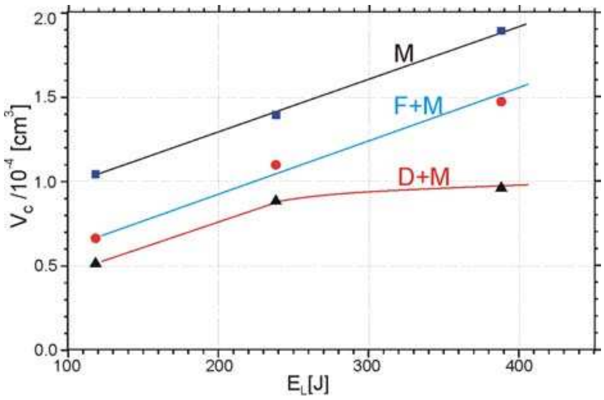

Fig. 1: Diagrams of the crater volumes as a function of the laser energy for different types of the targets, where: M - single target, F+M - double target with foil, and D+M - double target with disk.

3. Theoretical analysis of experimental results

At the direct method the crater volume depends on the efficiency of the laser energy transformation into a shock wave propagating in the unevaporated part of the solid target. This is characterized by the efficiency of laser-driven loading (η) defined as the ratio of the shock wave energy to the laser energy. The efficiency of laser-driven loading is the product of the laser absorption efficiency ($K_{ab} = E_{ab}/E_L$, where E_{ab} is the absorbed laser energy) and the ablation loading efficiency σ ($\eta = K_{ab}\sigma$). This last efficiency is given by the ratio of the shock wave energy E_s to the absorbed laser energy. In the case of the double targets, the collision of the macroparticle with the massive part of such target constitutes an additional process of energy transformation. The crater volume also depends on the energy transfer efficiency during the impact of a macroparticle with a massive target. In order to evaluate the above transformation efficiencies the theoretical models of expanding plasma streams and the shock wave formed by the ablation pressure were used [2, 3]. Results of our calculation for a single massive target are presented in Table 2.

Table 2: The set of experimental data and theoretical calculation of parameters of the expanding plasma and shock waves in solid targets.

Laser energy E_L (J)	120	240	390
Experimental crater volume			
Crater volume V_c (10^{-4}cm^3)	1.05	1.40	1.90
Calculated parameters of the expanding plasma torch			
Plasma scale length ξ (μm)	230	281	338
Plasma pressure P (Mbar)	1.70	1.65	1.60
Calculated parameters of the shock wave in solid targets			
Ablation loading efficiency σ	0.0078	0.0067	0.0060
Laser absorption efficiency K_{ab}	0.6000	0.4600	0.4300
Efficiency of laser-driven loading $\eta = \sigma K_{ab}$ (%)	0.4700	0.3000	0.2600
Shock wave energy E_s (J)	0.5600	0.7200	1.0500
Pressure behind the wave front P_0 (Mbar)	4.5000	4.3000	4.1000
Shock wave velocity D_0 (10^6 cm/s)	1.7200	1.6800	1.6400
Reach of the shock wave during the laser action H_0 (μm)	6.9000	6.700	6.5000

These results allow us to draw some important conclusions: Firstly, we should stress that the radius of the expanding plasma torch exceeds the laser beam radius significantly for all the laser energies used. The torch radius increases with the laser energy due to an increase of the expansion velocity with laser intensity. As the laser beam radius was kept constant, the role of the deviation of plasma expansion from the planar shape increases with laser energy. This is the exact reason, why the ablation loading efficiency drops from 0.78 % at the laser energy of 120 J to the value 0.6 % at the laser energy of 390 J. The laser absorption also decreases from 60 % at the laser energy of 120 J to the value 43 % for laser energy of 390 J. However, the dependence of the laser-driven loading efficiency $\eta = \sigma K_{ab}$ from laser energy to the shock wave energy is weaker than inversely proportional. Consequently, the shock wave energy rises from 0.56 J at laser energy of 120 J to 1.05 J for 390 J. The plasma plume pressure at the ablation surface is approximately 1.6 Mbar and the shock wave pressure is equal to 4 Mbar. It is practically independent of the laser energy due to compensation of the plasma temperature rise by the plasma density drop, caused by a rise of importance of the two-dimensional plasma expansion. Thus, the initial velocity of the shock wave and the depth of the shock wave penetration during the laser pulse action (constant in our experiment) were practically conserved at an increase of the laser energy and amounted to $1.7 \cdot 10^6$ cm/s and 6.6 μm, respectively. Several important conclusions may be derived from the analysis of the laser beam-double target interaction on the basis of the presented experiment. Because the shock wave penetration depth during the laser pulse is less than the foil thickness (equal to 11 μm), the results of the laser pulse action on the foil and on the massive target are similar at the moment of the laser pulse end. In particular, the same energies are transferred from the laser beam to these two types of targets. Consequently, the weakness of indirect laser action on the massive target in the double target compared to the direct laser action is caused only by the process of the energy transfer from the macroparticle to the massive target. Thus, the dependence of the crater volume on the laser energy in the double target should additionally include the energy transformation efficiency β, describing a macroparticle impact on the wall: $V_c = \quad K_{ab}E_L$. The efficiency $\beta = E_w/E_m$, where E_w is the energy of the shock wave in the massive target and E_m is the energy of the incident foil fragment. Therefore, the efficiency β may be found experimentally from the ratio of the crater volume for the double target (V_{double}) to the volume of the directly irradiated massive target (V_{single}):

$\beta = V_{double}/V_{single}$. The value $\beta = 0.7$ is derived from the experimental data presented in Fig. 1. The efficiency of energy transformation during inelastic collision of the accelerated macroparticle with the wall depends on the ratio of the macroparticle density ρ_p to the wall density ρ_w, and also on the adiabatic exponents of both materials. An accurate solution for the efficiency of the energy transfer from the accelerated macroparticle to the massive wall was found in paper [4]. According to this solution, the efficiency $\beta = 0.58$ for the same flyer and wall densities ($\rho_p = \rho_w$) and for the adiabatic exponent for Al ($\gamma_s = 5/2$). This, relatively small, distinction between theoretical estimation and experimental result is acceptable.

The above results allow us to assume that the efficiency β for the disk is approximately the same as for the foil, where $\beta = 0.7$. On the basis of the experimental data (Fig. 1), the efficiencies of the laser-driven loading for the double target with disk are found: $\eta = 0.38$ %, 0.24 % and 0.16 % for the laser energies of 120 J, 240 J and 390 J, respectively. The drop of η in this case as compared to the values of η for the foil is, in our opinion, caused by the decrease of σ. Because of the limited disk area, the ablation pressure initiates a shock wave propagating in the outer part of the target in the direction of the disk axis and thus the energy transfer into the longitudinal target motion is less effective. The decreased crater radius and the flatter crater shape, especially apparent for the highest laser energy, when the plasma stream size in comparison with the disk radius reaches its maximum, may serve as an indirect experimental indication for the above explanation.

4. Conclusions

The results concerning the velocities of the accelerated disks are not unusual, as these velocities were indeed higher than those for the extracted foil fragments. However, the craters obtained by means of the former method are not only considerably smaller but also their volume growth is suppressed at a certain threshold. Moreover, above the threshold energy, irregular crater shapes become rather typical. The smaller volume of the crater in the case of a double target with disk, when compared to that with foil, can be explained by lower efficiency of the laser absorption in the solid part of the disk. This decrease of the ablation loading efficiency becomes more pronounced with the increasing laser energy and it results from a two-dimensional expansion of the plasma stream. As a result, the radius of the action area of the evaporated material pressure exceeds the disk radius. Thus, for any fixed disk radius a degree of this excess grows up simultaneously with the laser energy.

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