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Calorimetric study of laser-irradiated thin foil targets

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Abstract. Hydrodynamic efficiency of laser-irradiated thin aluminum and gold-coated aluminum targets was experimentally determined using a specially designed cone calorimeter. Velocity of the accelerated target and ablation pressure were also estimated from the experimental data. The laser irradiance range used in the experiments was between 10^{12} and 10^{13} watts/cm^2. Experiments indicate that the fall in the hydrodynamic efficiency due to gold coating on aluminum target is about 12% at an irradiance of 8×10^{12} W/cm^2.

Keywords. Plasma; laser fusion; ablative acceleration; x-rays; calorimetry.

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1. Introduction

In laser-driven fusion concept, coupling of absorbed laser energy to the uniform inward motion of the spherical fusion pellet is very important. It is because of the fact that the entire energy requirement for the fuel compression and central ignition is derived from the kinetic energy of the imploding shell (Nuckolls *et al* 1972). Therefore, high efficiency implosion of targets is vital for inertial confinement fusion scheme. The interaction of intense laser radiation on the target pellet surface creates a hot and dense plasma which expands radially outward and residual target accelerates and moves inward due to rocket effect (Ripin *et al* 1980). The ratio of kinetic energy associated with the accelerated target shell to the absorbed laser energy is defined as hydrodynamic efficiency. Thus hydrodynamic efficiency indicates the implosion efficiency of the target. However uniform and symmetric target surface ablation has been a problem in efficient fuel compression (Bodner 1981). Spatial uniformity of laser intensity at the target surface is thus very crucial. This is primarily due to the fact that high power laser beams usually have incoherent spatial nonuniformities because of diffraction at apertures, minute dust particles etc. In addition, filamentation of the beam in the coronal region of the plasma can also introduce spatial non-uniformities. In the absence of good beam uniformity one has to resort to modification of the target itself. Recently it has been shown that a coating of high atomic mass (A) material like gold, on a low atomic mass (A) target at the irradiation side can reduce ablation non-uniformity due to non-uniform laser irradiation (Bocher *et al* 1984; Dhareshwar *et al* 1986). However the effect of high A coating on hydrodynamic efficiency has not been studied exclusively till date.

Compression studies of spherical shell pellets are of current interest. However to simplify the diagnostic arrangements, thin planar foil targets are often used. In the planar foil targets, the interaction area can be considered to model a small section of a hollow spherical target. This provides an easy access to the rear side of the target. In our present work we have determined hydrodynamic efficiency of laser-accelerated thin foil target (6 μm Al) and gold coated (0·1 μm) 6 μm Al targets using a simple cone calorimeter. Our efforts are directed towards observing the effect of gold layer on hydrodynamic efficiency and pressure of the accelerated target.

2. Experiment

In the experiments described here a Nd : glass laser capable of delivering 5 J of optical energy in 5 nsec was used. The laser beam was focussed using a lens of aperture 50 mm in diameter and focal length (f) = 30 cm on thin foil target strips (5 mm × 15 mm) held on a specially designed holder and placed inside an evacuated chamber. The holder could be moved vertically without disturbing the focussing condition such that a fresh target surface was exposed to each laser shot. The laser focal diameter (full width at half maximum) was 100 μm which was measured by attenuating the beam and using calibrated infrared photographic films at the focal plane of the beam. The intensity at the target surface was varied by suitably attenuating the laser beam using neutral density filters. A small fraction (8 %) of the incident laser energy was made to reflect from a beam splitter before entering the interaction chamber. The reflected radiation was used to estimate the incident laser energy.

Cone calorimeter is an anodized aluminum hollow cone of 20 mm base diameter and 60 mm height. It was kept at a distance of 15 mm at the rear side of the target with the base facing the target. The outer surface of the cone was thermally connected to a series of chromel-Constantan thermocouples with cold junctions placed in close contact with a massive anodized aluminum ring. This ring also served as a mechanical support to the cone. The thermocouple output was amplified in an amplifier of gain 100 for better sensitivity.

The cone calorimeter was calibrated by dissipating a known amount of energy from a capacitor into a thin resistance wire attached thermally on the inner surface of the cone. The mass of the wire was very small compared to that of cone. The rise of the cone temperature was recorded by the thermocouples attached to the cone. A graph thus drawn between dissipated energy and thermocouple emf provided the calorimeter calibration. The calibration was also crosschecked by putting known laser energy (1·06 μm wavelength) into the cone of the calorimeter. Thus the sensitivity of the cone has been determined as 295 μV/J.

The accuracy of measurements can be effected by the following factors: (a) thermal energy of the accelerated foil; (b) radiation losses from the heated cone; (c) reflection of debris from the cone; (d) sputtering of the cone material by the target debris. Effects due to (a) and (b) can be neglected because the accelerated target cools rather rapidly and at the time of deposition its total thermal energy is negligible (Naik, Private communication). Cone temperature rise was quite small ($< 2°$C) thus radiation losses can be neglected. The geometry of the cone in our experiment (open base to height ratio 1:3) would not allow a significant amount of the reflection of debris or expulsion of sputtered material. Moreover values of hydrodynamic efficiencies obtained in our experiment using aluminum as well as plastic foil targets match reasonably well with those obtained by using charge collector method in our laboratory (Gupta 1984) and elsewhere (Ripin *et al* 1980). However in the present paper we shall discuss results obtained using aluminum and gold-coated aluminum targets only. Debris of the foil ablatively accelerated due to laser irradiation were collected in the cone. Assuming the entire kinetic energy of the foil is converted into cone's thermal energy the kinetic energy of the foil was estimated. Since laser intensity at the target surface did not exceed 10^{13} W/cm^2 in our experiments we have assumed near complete absorption of the laser energy, i.e. $I_{\rm inc} = I_a$ (Ripin *et al* 1980). The schematic of the experimental set-up and cone calorimeter is shown in figures 1(a) and 1(b) respectively. Hydrodynamic efficiency was calculated from the ratio of kinetic energy of the foil to the absorbed laser energy. Ablation pressure was also calculated from the kinetic energy data. The terminal velocity of the detached foil is given by

$$V_{\rm foil} = (2E_{\rm foil}/m)^{1/2},$$

where $E_{\rm foil}$ and m are the kinetic energy and mass of the detached foil respectively. The mass was calculated by taking the area of the detached foil equal to that of laser focal

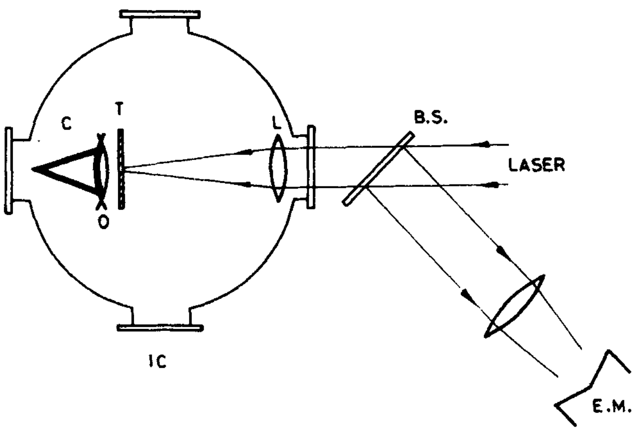

Figure 1. (a) Schematic of experimental set-up. T, target; C, cone calorimeter; O, thermocouple output; IC, interaction chamber BS, beam splitter and EM cone energy meter.

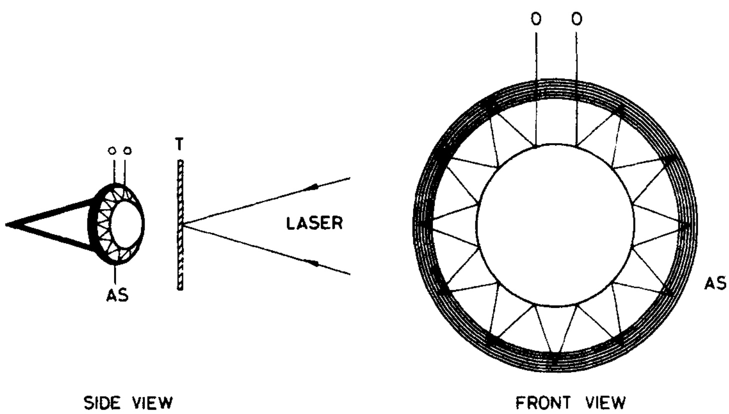

Figure 1. (b) Schematic diagram of cone calorimeter. T, target; O, thermocouple output and AS, aluminum support.

spot (100 μm) and neglecting the mass of the ablated foil in comparison to the detached foil mass as ablation thickness is about 1 μm at the irradiance used in our experiments. A significant lateral transport edge effect does not seem to occur at irradiances and foil thickness used in our experiments (Meyer and Thiell 1984; Ripin *et al* 1980). Ablation thickness was obtained earlier using burn-through measurements of aluminum-layered targets (Gupta *et al* 1983). These ablation measurements are also in good agreement with those reported by other authors (Goldsack *et al* 1982). Ablation pressure was then calculated using the formula (Ripin *et al* 1980).

$$P_a = \rho t v_{\text{foil}}/\tau_L$$

where ρ and t are density and thickness of the foil material. τ_L is the acceleration time (laser pulse duration was taken as the acceleration time in our experiments).

3. Results and discussion

Hydrodynamic efficiency and ablation pressure of 6 μm thick aluminum and gold (0·1 μm) coated 6 μm thick aluminum targets for various values of laser irradiance is shown in figures 2 and 3 respectively. It can be seen that hydrodynamic efficiency for gold-coated aluminum foil is slightly lower than that of pure aluminum at higher irradiance. It is interesting to note that the ablation pressure (P_a) for pure aluminum target scales as $I_a^{0.75}$ (where I_a is absorbed irradiance) which is very close to the theoretically predicted scaling of I^α where α varies between 0·66 and 0·78 (Grun *et al* 1983). Our results for pure aluminum targets are in good agreement with some of the published work on ablation pressure variation as a function of absorbed intensity from

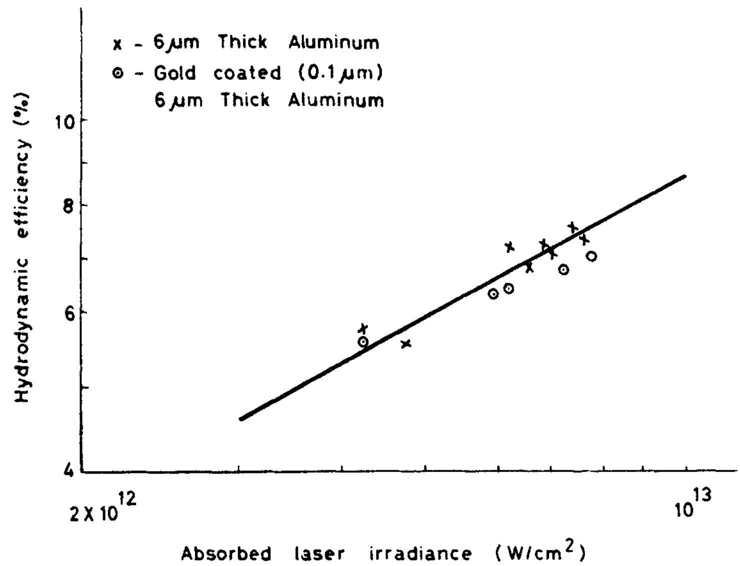

Figure 2. Variation of hydrodynamic efficiency of pure 6 μm thick aluminum and gold-coated (0·1 μm) 6 μm thick aluminum with absorbed laser irradiance.

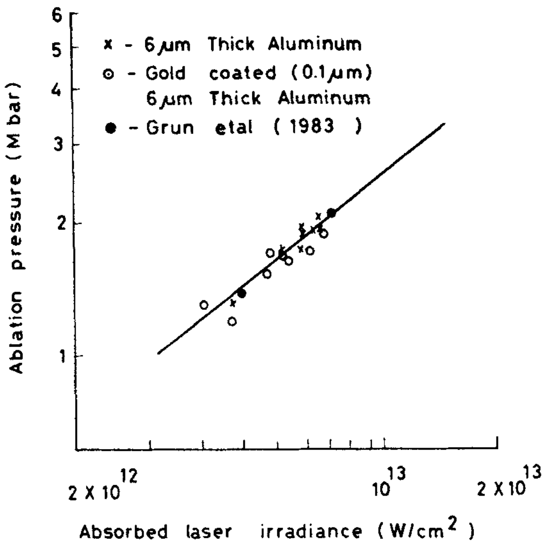

Figure 3. Variation of ablation pressure for pure 6 μm thick aluminum and gold-coated (0·1 μm) 6 μm thick aluminum target with absorbed laser irradiance.

other laboratories. In figure 3 some experimental points have been included from Naval Research Lab (USA) (Grun *et al* 1983).

The observed lowering (10–12 %) of hydrodynamic efficiency can be explained on the basis of different areal mass of the targets. For gold-coated aluminum targets areal mass is approximately 10 % higher than that of pure aluminum. However the role of x-rays emitted from gold plasma cannot be disregarded. Approximately 30 % x-ray conversion from targets having atomic mass above 70 have been reported at laser irradiance of 10^{13} W/cm^2 (Violet *et al* 1975). For gold targets too a similar high conversion efficiency has been observed (Heinle and Rosen 1980) for long laser pulses at 10^{13} W/cm^2. These x-rays are produced in the neighbourhood of critical density of the expanding plasma. For the outer vicinity these radiations are a loss but they are energy carriers for mass ablation in the inner vicinity. The x-radiation mean-free path can be less than the plasma scale length and the heat flux due to radiation can be compared to the electron thermal flux (Nishimura *et al* 1983; Nishihara and Yuchi 1983). Although loss of radiation to the outer vicinity can cause a reduction in the absorbed irradiance, its reabsorption at the ablation surface should improve the hydrodynamic efficiency. Reabsorption of x-rays emitted during interaction has also been observed while looking for improved spatial uniformity of ablation (Bocher *et al* 1984; Dhareshwar *et al* 1986). In fact a near black body Planckian radiation spectrum corresponding to 70 eV temperature has been observed in experiments with gold targets irradiated at 10^{13} W/cm^2 using 1·06 μm wavelength laser (Nishimura *et al* 1983), suggesting a small radiation mean-free path. This would mean that an additional thermal radiation supported ablation is possibly present in our experiments. Thus x-ray reabsorption appears to compensate for a drastic fall in the hydrodynamic efficiency. Considering the efficacy of gold layer for producing spatially uniform ablation, a slight lowering of hydrodynamic efficiency is probably acceptable.

4. Conclusion

Using a simple cone calorimeter we have measured hydrodynamic efficiency and ablation pressure for ablatively accelerated pure aluminum and gold-coated aluminum foil targets. For gold-coated targets hydrodynamic efficiency is slightly lower than for pure aluminum targets. Ablation pressure scaling matches reasonably well with those determined using more elaborate methods. Reabsorption of x-rays emitted from gold plasma in the ablation zone appears to prevent a significant fall in the hydrodynamic efficiency. Our results indicate that a gold layer which has shown its efficacy for producing uniform ablation can be used on imploding shell targets without a significant loss of hydrodynamic efficiency.

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