Experimental observation of radiation heat waves*

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Abstract Radiation heat waves play an important role in high-temperature hydro-dynamic phenomena which is very important for laser fusion. Therefore, the propagation of a radiation heat wave through a thin foil of solid aluminium is observed. The wave is driven by the intense soft-X-ray radiation in acylindrical cavity heated by the intense laser pulse. Experiments are carried out with two beams of $\lambda = 1.05\mu m$ light from the Shenguang Nd-glass laser facility. The pulse energy is about 600 J and the pulse duration 0.8 ns. Evidence of radiation heat wave is obtained by observing the delayed signal of intense thermal emission from the outside of the foil. The delay is 850 ps for $1.5\mu m$ thick foil and the mass ablation rate is about 4.8×10^5 g/(cm^2·s) under the X-ray flux of about 1×10^{13} W/cm^2. Also, the radiation-driven shock waves of (2±1)TPa are observed from different shots in the experiments.

Keywords Radiation heat wave, Shock wave, Time and spectrum resolved soft-X-ray diagnostics, Laser plasma

1 Introduction

The investigation on radiation heat waves that play a key role in high-temperature hydrodynamic phenomena[1] is important for indirect-driven laser fusion and for obtaining the information on opacity of a radiation-heated material. Marshak[2] was apparently the first to notice that under the condition of complete local thermodynamic equilibrium between radiation and matter the diffusion of intense thermal radiation into an optically thick wall leads to the formation of a radiation heat wave. Its investigation in the laboratory became possible with realization of modern pulsed power sources, in particular laser, allowing the generation of intense thermal radiation.[3-5] In this paper, the observation of radiation heat waves driven by intense laser-generated soft X-rays is performed.

2 Experiments and results

As shown schematically in Fig. 1(a), the X-ray impinging on the front of a sample foil drives a heat wave. Because of the strong increase in radiation heat conductivity with temperature the heat wave has a sharp front followed by a temperature plateau. Evidence of the propagating heat wave can be obtained by observing the X-ray emission from the rear of the foil and its delay time Δt as shown in Fig. 1 (b).

The Planckian radiation generated in a laser-heated gold cylindrical cavity was approximately used as driving radiation. It should be noted that the closed geometry of the cavity provides uniform and intense irradiation under the condition close to thermodynamic equilibrium, which is not easily achieved by other configurations. Based on a lot of experiments about intense laser-cylindrical cavity interaction we designed and performed the special experiments to observe radiation heat waves in time and spectrum resolution.

The experiments of cavity targets were carried out with two beams of $\lambda = 1.05\mu m$ light from Shenguang Nd-glass Laser Facility. The operated laser energy was about 600 J and the pulse duration 0.8 ns. Two beams of intense laser were injected onto a cylindrical gold cavity having one or two diagnostic holes on its wall. One carries a thin aluminium foil (1.5 or 3-μm thick) for observing the radiation heat wave. On its opposite the other carries a stepped aluminium foil (10 μm step) for surely observing the shock wave in the case of the targets with two diagnostic holes. The aluminium foils

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mounted on the wall of the cylindrical cavity were ablated by the soft X-ray radiation produced by laser in the cavity.

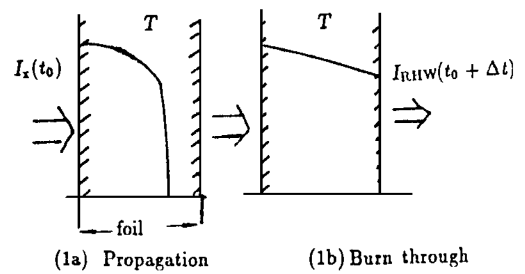

Fig. 1 Propagation of X-ray-driven radiation heat wavein a thin foil

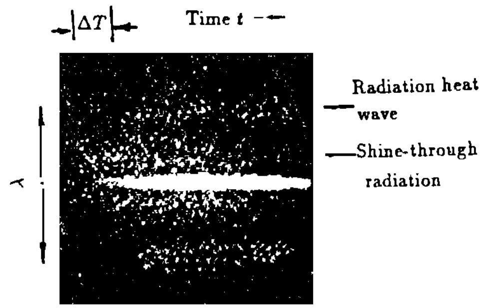

Fig. 2 Typical image of radiation from thin aluminium foil

The radiation from the hole was measured by means of a soft X-ray streak camera combined with a soft X-ray transmission grating with 853 L/mm. The spectral resolution is about 0.4 nm. The time resolution of the X-ray streak camera is 34 ps. Simultaneously, a sub-keV X-ray spectrometer (seven channels of filter X-ray diodes) was also used to detect the radiation. The filters used in the spectrometer were boron, carbon, titanium, chromium, nickel, zinc and aluminium, respectively. In addition, a laser-timing signal was fed to the spectrometer. In order to surely detect the radiation only from the thin aluminum foil a shield was placed between the X-ray streak camera and the target.

The luminous signals of the shock wave from the aluminium stepped foils were imaged on the slit of an optical streak camera with spatial resolution and with the time resolution of 10 ps. (see Fig.2). The spectrum of the radiation heat wave was observed near 4.8 nm under the condition that 1.5 μm thick aluminium foil was mounted on the diagnostic hole of a cylindrical cavity and two laser beams were of pulse energy 560 J and 554 J and pulse duration 920 ps and 880 ps, respectively. The delay between the radiation heat wave and the shine-through radiation is 850 ps. It corresponds to the burn through time for a 1.5 μm thick aluminium foil.

Also, the evidence of the radiation heat wave was provided by the results from the sub-keV X-ray spectrometer. Comparing the wave forms measured by the sub-keV X-ray spectrometer on the targets of the diagnostic holes

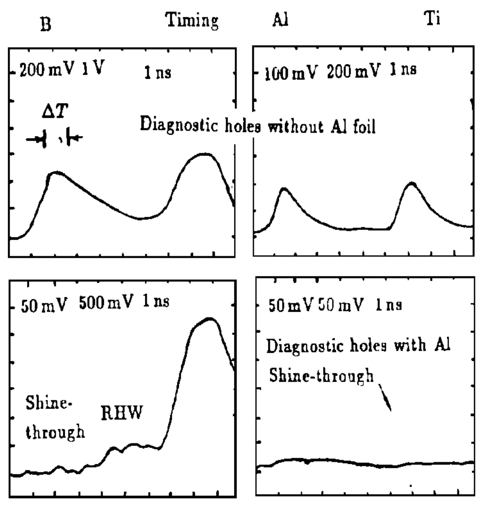

Fig. 3 Oscilloscope traces obtained from the sub-keV X-ray spectrometer

with and without aluminium foil, we found that a delayed emission from outside aluminium appeared in boron and carbon channels and only attenuated shine-through signal appeared in other channels. For example, the typical wave forms for B-, Al- and Ti- channels are shown in Fig.3. The spectral responses of B- and C- channels are about 170 eV and 250 eV, respectively, and other channels respond to the high photon energy. The delay time and the spectral

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range of the radiation heat wave were measured with two different methods and well agreed with each other. It is proved that we have observed radiation heat wave indeed.

According to the thickness of the aluminium foil and the burn through time measured by X-ray streak camera we infer the mass-ablation rate to be about 4.8×10^5 g/(cm^2·s). Based on a lot of experiments performed in the similar conditions, the average X-ray flux on the wall of cavity was about $S_X\approx1\times10^{13}$W/cm^2. Our experimental datum in comparison with other authors' experimental data and Nakai's[6] theoretical results are shown in Fig. 4.

It can be seen from Fig. 5 that the luminous shocks for the thick and thin stepped foils appear at different times, respectively. The laser signal is also shown in Fig. 5 for reference. According to the thickness of the foil and the delay between two luminous signals the shock speed can be obtained. Furthermore, based on the Hugoniot relation, the shock pressure is inferred to be (2 ± 1) TPa from different shots in our experiments.

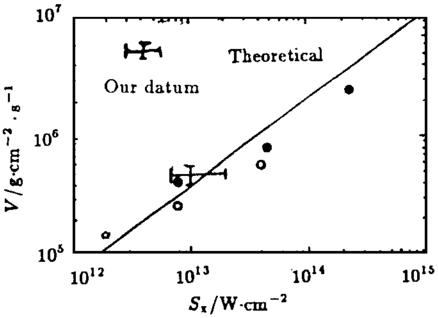

Fig. 4 Relation between mass-ablation rate and the flux of X-rays for irradiating aluminium

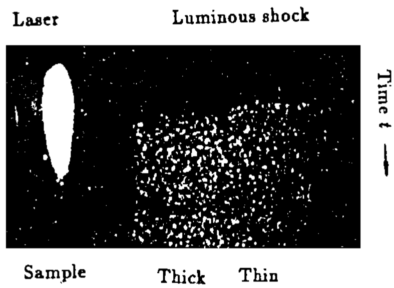

Fig. 5 Luminous shock at the stepped Al foil

3 Summary

We have observed the radiation heat wave from a thin aluminum foil heated by the intense thermal radiation in cylindrical cavity produced by intense laser pulse. It opens up the possibilities for the investigation on high-temperature hydrodynamic phenomena in the laboratory, which is of interest for obtaining a basic insight into the state of matter at high density and high temperature and has potential applications in inertial confinement fusion.

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