INVESTIGATION OF LASER SUPPORTED DETONATION WAVES AND THERMAL COUPLING USING 2.8 μ m HF LASER IRRADIATED METAL TARGETS

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Résumé.— La formation et la propagation de vagues de détonation supportées par laser (LSD) et l'accouplement thermique pour les cibles solides irradiées par laser HF ont été étudiées en tant que fonction d'un matériau de cible, de l'irradiation et de la pression ambiante. La photographie à grande vitesse a été utilisée pour étudier la dynamique de plasma et les seuils auxquels le plasmotron et la production de vagues LSD sont obtenus. Pour les impulsions d'une durée de 300nsec (FWHM) et les points focaux de 1-2mm qui ont été utilisés, le seuil LSD pour les cibles d'aluminium, d'acier inoxydable et de platine mesurait $\sim(2-3) \times 10^8$ W.cm⁻². Au-dessus du seuil LSD, la vitesse d'expansion initiale semblait conforme à la dépendance d'irradiance prédite par la théorie. Des données supplémentaires sur l'action réciproque du platine ont été obtenues en utilisant des thermocouples pour mesurer l'accouplement thermique de la cible en tant que fonction de la taille du point, l'irradiance et la pression ambiante. Un coefficient maximum de 14-18% a été mesuré à un niveau d'irradiance légèrement au-dessous du seuil de l'ignition de la vague LSD.

Abstract.— The formation and propagation of laser supported detonation (LSD) waves and thermal coupling for HF laser irradiated solid targets have been investigated as a function of target material, irradiance and ambient pressure. High speed photography has been employed to study the plasma dynamics and the thresholds for plasmotron and LSD wave production obtained. For the 300nsec duration (FWHM) pulses and 1-2mm diameter focal spots used, the LSD thresholds for aluminium, stainless steel and platinum targets were measured to be $\sim(2-3) \times 10^8$ W.cm⁻². Above the LSD threshold the initial expansion velocity showed good agreement with the $I^{1/3}$ irradiance dependence predicted by theory. Additional data on the interaction for platinum were obtained using thermocouples to measure the thermal coupling to the target as a function of spot size, irradiance and ambient pressure. A maximum thermal coupling coefficient of 14-18% was measured at an irradiance level slightly below the LSD wave ignition threshold.

1. Introduction

There is considerable interest in the interaction of high power, pulsed infrared gas lasers with metallic targets in gaseous backgrounds. Both CO₂ and HF chemical lasers offer high power and energy capabilities, and whilst extensive studies of laser supported detonation waves and thermal coupling have been made at 10.6 μ m⁽¹⁻⁷⁾ there has been little published work on experiments at 2.8 μ m^(8,9). In this paper, we report a study of the ignition and propagation of laser supported detonation (LSD) waves produced from HF laser irradiated metal targets (aluminium, stainless steel and platinum) and present thermal coupling data for platinum as a function of target irradiance, ambient pressure and spot size.

2. Experimental technique

The pulsed HF chemical laser used in this investigation was a pin-bar device⁽¹⁰⁾ and was operated with SF₆ - C₃H₈ gas mixtures at $\sim 40-60$ torr. With a stable resonator operating multi-mode, a laser energy of ~ 8 J was obtained in a ~ 300 nsec. pulse (FWHM). The laser output was focused onto various targets using a plano-convex NaCl lens (20 or 50cm focal length). A direct measurement of the spot size was obtained by attenuating the beam and irradiating various thin metal foils and developed unexposed Polaroid film located at the position of the target. A high speed streak camera was employed to study the plasma dynamics.

The experimental arrangement used to measure the thermal coupling coefficient is shown in Fig.1.

Figure 1 Experimental configuration for thermal coupling studies. J - Joulemeter, PS - pulse shape monitor.

The temperature rise of the target was measured using a single thermocouple of chromel-alumel wire spot welded onto the rear surface of the target. The time integrated thermal coupling coefficient, α , corresponding to a temperature rise T , was defined as $\alpha = \rho d A C T / E$, where ρ is the density of the target material, d the target thickness, C the specific heat capacity, A the target area and E the laser energy incident on the target.

3. Experimental results

(a) Plasma Studies

Figs. 2a-b show typical streak photographs

Figure 2 Streak photographs of plasmas produced from an aluminium target in atmospheric air. Irradiance $\sim 3.5 \times 10^8 \text{ W.cm}^{-2}$; (a) camera aperture $f/22$, 10 db ND filter, (b) same as (a), 12 db ND filter.

obtained, under two conditions of exposure, using a polished aluminium target. It can be seen that following ignition the plasma became rapidly detached from the target in a manner characteristic of LSD wave propagation. The initial expansion velocity was estimated to be $\sim 2 \times 10^6 \text{ cm.sec}^{-1}$, and was found to be in reasonable agreement with that obtained from the LSD wave model⁽¹¹⁾. It should be noted that in contrast to the interaction with pulsed CO_2 laser radiation at similar irradiance⁽¹⁾, there was no subsequent recoupling of the laser radiation to the target. However, when the target irradiance was reduced to $\sim 9.6 \times 10^7 \text{ W.cm}^{-2}$ only a surface plasma, a plasmotron⁽²⁾, extending to the entire duration of the laser pulse could be seen. The threshold for the transition from the plasmotron to the LSD regime was estimated to be $(1.6 - 2.0) \times 10^8 \text{ W.cm}^{-2}$. This can be compared with a LSD threshold of $\sim 2 \times 10^7 \text{ W.cm}^{-2}$ at $10.6 \mu\text{m}$ under comparable conditions. For target induced breakdown a threshold of $\sim 2 \times 10^7 \text{ W.cm}^{-2}$ was obtained, this agreeing reasonably well with the value of $6 \times 10^7 \text{ W.cm}^{-2}$ obtained from the vaporisation - cascade ionisation model⁽¹²⁾.

Figs. 3,4 show streak photographs obtained when polished stainless steel targets were irradiated at a level of $\sim 1 \times 10^8$ and $2.3 \times 10^8 \text{ W.cm}^{-2}$, these representing the approximate thresholds for plasmotron and LSD formation respectively.

Figure 3 Streak photograph of a stainless steel plasmotron in atmospheric air. Irradiance $\sim 1 \times 10^8 \text{ W.cm}^{-2}$; camera aperture $f/22$.

Figure 4 Streak photographs of plasma production from a stainless steel target in atmospheric air. Irradiance $\sim 2.3 \times 10^8 \text{ W.cm}^{-2}$; camera aperture f/22; (a) 6 db and (b) 10 db filters respectively.

Comparison with the aluminium data indicated that while in both cases LSD initiation occurred at similar levels of irradiance, the threshold for plasmotron was somewhat higher for stainless steel. Above the LSD threshold the initial expansion velocity showed an approximate $I^{1/3}$ dependence on irradiance (Fig. 5), there being no significant difference between the data for aluminium and stainless steel.

Figure 5 Initial plasma expansion velocity as a function of target irradiance.

- x - Aluminium (spot area $\sim 0.036 \text{ cm}^2$)
- o - Stainless steel (spot area $\sim 0.036 \text{ cm}^2$)
- - Platinum (spot area $\sim 0.036 \text{ cm}^2$)
- - spot area $\sim 0.008 \text{ cm}^2$

Studies using stainless steel were also performed as a function of air pressure in the range 20-760 torr. This showed that there was some reduction in the plasmotron threshold as the pressure was decreased, while the LSD threshold remained essentially unchanged. Above 100 torr the initial expansion velocity exhibited a $p^{-0.32}$ pressure dependence (Fig. 6), this being in very good agreement with theory⁽¹¹⁾.

Figure 6 Initial expansion velocity as a function of pressure at constant irradiance.

Fig. 7 shows a streak photograph of the plasma produced when an unpolished platinum target was irradiated at $\sim 1.3 \times 10^8 \text{ W.cm}^{-2}$; a LSD wave can be seen, together with a weak plasmotron. From streak photographs obtained under various conditions

Figure 7 Streak photograph of plasma produced from a platinum target in air at atmospheric pressure. Irradiance $\sim 1.3 \times 10^8 \text{ W.cm}^{-2}$. Camera aperture f/22, 25 db ND filter.

ions, the plasmotron threshold was estimated to be $\sim 1.2 \times 10^8 \text{ W.cm}^{-2}$. The initial expansion velocity showed an irradiance dependence similar to that obtained with aluminium and stainless steel (Fig.5).

(b) Thermal coupling

In Fig. 8 the thermal coupling coefficient, α , for platinum is shown as a function of laser fluence (J.cm^{-2}) for three target diameters, the ratio of the focal spot to target diameter in each case being held approximately constant. It was found that the coupling coefficient initially increased as the laser fluence was increased, reaching a peak of $\sim 14 - 18\%$ at or near LSD threshold fluence. Thereafter, the coupling decreased with increasing fluence due to the more rapid movement of the plasma away from the target in a LSD mode. Measurements performed using various focal spot sizes and target diameters indicated no significant dependence of the thermal coupling on these parameters. It is worth noting that coupling measurements at $10.6\mu\text{m}$ have shown that in one case an increase in the spot size

Figure 8 Thermal coupling coefficient as a function of laser fluence.

	Target diameter (mm)	Spot diameter (mm)
■	3.0	1.1
●	4.8	2.1
▲	8.1	3.3

resulted in a marginal enhancement in the peak coupling⁽⁴⁾, whereas in another instance⁽⁶⁾ a slight reduction occurred.

In Fig. 9 the laser irradiance corresponding to peak coupling is shown as a function of the spot size, together with theoretically predicted results (solid curves) for the LSD maintenance threshold⁽¹³⁾. It can be seen that the experimental points are in close proximity of the theoretical curve, this indicating that the optimum irradiance for peak thermal coupling is approximately the minimum irradiance required to maintain a LSD wave. This is in broad agreement with previous results obtained using $1.06\mu\text{m}$ ⁽¹⁴⁾ and $10.6\mu\text{m}$ ⁽⁶⁾ pulsed lasers. A close examination of the streak photographs showed that the fluence corresponding to peak coupling was located in the very narrow regime bounded by the plasmotron and LSD thresholds.

Figure 9 Irradiance at peak thermal coupling as a function of focal spot radius.

In Fig.10 the variation of thermal coupling with fluence (for a 3mm diameter target and $\sim 1\text{mm}$ spot) is shown for pressures of 760 and 100 torr. There was no significant difference between the two cases, the peak coupling being $\sim 15 - 16\%$. The slightly reduced coupling at 100 torr is probably

due to a more rapid decoupling caused by an increased LSD wave velocity (Fig. 6). In Fig. 11 the thermal coupling coefficient is shown as a function of pressure at a fixed laser fluence of $\sim 100 \text{ J.cm}^{-2}$. It can be seen that the coupling coefficient showed little variation in the range 760 - 40 torr, but increased slightly as the pressure was reduced to 10 torr. These results are in general agreement with previous results reported for $1.06^{(14)}$ and $10.6\mu\text{m}^{(4,6)}$ laser radiation.

Figure 10 Thermal coupling coefficient as a function of fluence; 3mm diameter platinum target in air at pressures of 760 and 100 torr.

Figure 11 Variation of thermal coupling coefficient with air pressure. 3mm diameter platinum target and 1.1mm diameter focal spot. Laser fluence $\sim 108 \text{ J.cm}^{-2}$; irradiance $2.4 \times 10^8 \text{ W.cm}^{-2}$.

4. Conclusions

The formation and propagation of laser supported detonation waves produced when the radiation from a pulsed, $\sim 8 \text{ J}$ HF laser was focused onto metal targets, have been investigated as a function of various parameters such as target irradiance and ambient pressure. For 300 nsec (FWHM) duration pulses and 1 - 2 mm diameter spots employed in these experiments LSD thresholds of $\sim (2-3) \times 10^8 \text{ W.cm}^{-2}$ were obtained for aluminium, platinum and stainless steel. When the target was irradiated at or above the LSD threshold irradiance, a rapid decoupling of the laser radiation from the target occurred and in contrast to the case of target interaction using CO_2 laser radiation there was no subsequent recoupling of the laser to the target.

The thermal coupling of $2.8\mu\text{m}$ laser radiation to platinum was investigated as a function of spot size, target irradiance and ambient pressure. The maximum thermal coupling coefficient was measured to be $\sim 14 - 18\%$, and the irradiance at peak coupling found to be approximately the same as, or slightly less than, the LSD formation threshold. It should be noted that the $14 - 18\%$ coupling coefficient obtained in this study is considerably lower than that reported for various metals at $10.6\mu\text{m}^{(4,6)}$. Unfortunately, the lack of $10.6\mu\text{m}$ coupling data for platinum at this stage preclude a direct comparison.

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