Laser and Particle Beams (2001), *19*, 623–630. Printed in the USA.

DOI: 10.1017.S0263034601194097

Flyer acceleration experiments using a KrF laser system with a long pulse duration and pressure and thickness of isobaric zone induced in impacted materials

T. KADONO,[1] M. YOSHIDA,[1] N.K. MITANI,[1] T. MATSUMURA,[1] E. TAKAHASHI,[2] I. MATSUSHIMA,[2] Y. OWADANO,[2] Y. SASATANI,[3,4] K. FUJITA,[3,4] N. OZAKI,[3,4] K. TAKAMATSU,[3,4] M. NAKANO,[3,4] K.A. TANAKA,[3,4] H. TAKENAKA,[5] H. ITO,[5] AND K. KONDO[6]

[1]National Institute of Materials and Chemical Research, 1-1 Higashi, Tsukuba, Ibaraki 305-8565, Japan
[2]Electrotechnical Laboratory, 1-1-4 Umezono, Tsukuba, Ibaraki 305-8568, Japan
[3]Institute of Laser Engineering, Osaka University, 2-6 Yamada-Oka, Suita, Osaka 565-0871, Japan
[4]Faculty of Engineering, Osaka University, 2-6 Yamada-Oka, Suita, Osaka 565-0871, Japan
[5]NTT Advanced Technology Corporation, 3-9-11 Midori, Musashino, Tokyo 180-8585, Japan
[6]Materials and Structures Laboratory, Tokyo Institute of Technology, 4259 Nagatsuta, Midori, Yokohama, Kanagawa 226-8503, Japan

(RECEIVED 7 March 2001; ACCEPTED 4 June 2001)

Abstract

Flyer acceleration experiments are carried out using a KrF laser system with a pulse duration of 10–15 ns and an intensity of $\sim 1.0 \times 10^{13}$ W/cm^2. Three-layered targets (aluminum–polyimide–tantalum) are used. First, an average velocity of laser-driven tantalum flyers with a thickness of 4 and 8 μm is estimated. Then, in a collision of a flyer with a copper layer attached to a diamond plate, we measure a transit time of a shock wave in the diamond. The impact velocity is estimated based on the transit time and a numerical simulation. This numerical simulation also shows that the initial peak pressure caused by the impact of a 4-μm-thick flyer is kept at 11 Mbar for 12–13 μm in thickness. Finally, whether this thickness is enough for EOS measurements is discussed.

Keywords: Flyer acceleration; KrF laser; Long pulse duration; Pressure and thickness of isobaric zone

1. INTRODUCTION

Recent development of high-power laser facilities leads us to investigate the properties of materials at very high pressures above 10 Mbar. Equation of state (EOS) data at high pressures ($\sim$10 Mbar) have been derived for some materials either by direct irradiation (Ng *et al.*, 1985; Koenig *et al.*, 1995; Fu *et al.*, 1995; Benuzzi *et al.*, 1996; Da Silva *et al.*, 1997; Wakabayashi *et al.*, 2000) or by indirect ways such as intense thermal soft X rays (Benuzzi *et al.*, 1996; Evans *et al.*, 1996; Cauble *et al.*, 1998).

Also, it has been indicated that a technique of laser-driven colliding flyers can generate very high pressures (e.g., Cauble *et al.*, 1993), but there are few studies of EOS measurements using laser-driven flyers. The main reason is that it is difficult to sustain high peak pressures for a large thickness, that is, a rarefaction wave generated at a free surface (rear surface) of thin flyers catches up the shock wave very soon. Thus it is necessary to accelerate a thick flyer efficiently to high velocities.

Recently, we have shown that three-layered targets (TLT), which consist of aluminum (Al), polyimide (PI), and tantalum (Ta) layers, and a laser system with a short wavelength and a long pulse duration are useful for accelerating a flyer efficiently (Tanaka *et al.*, 2000; Kadono *et al.*, 2000a; Ozaki *et al.*, 2001). In this paper, using a low intensity laser system of $\sim 10^{13}$ W/cm^2, we accelerate a thick flyer to a high velocity of over 10 km/s, where it is expected that a shock pressure is more than 10 Mbar and that the thickness of an isobaric zone is enough to carry out EOS measurements. First the average velocities of flyers with 4 and 8 μm thick are estimated. Then, in a collision of a 4-μm-thick flyer with a copper (Cu) layer attached to a diamond plate, we measure a transit time of a shock wave in the diamond. The impact velocity is estimated based on the transit time and a numer-

Address correspondence and reprint requests to: Toshihiko Kadono, Earthquake Research Institute, University of Tokyo, 1-1-1 Yayoi, Bunkyo, Tokyo 113-0032, Japan. E-mail: kadono@eri.u-tokyo.ac.jp

ical simulation. This numerical simulation also indicates that the initial peak pressure caused by the impact of a 4-μm-thick flyer is kept at 11 Mbar for 12–13 μm in thickness. Finally, whether this thickness is enough for EOS measurements is discussed.

2. EXPERIMENT

We used a high-power KrF laser system, Super-ASHURA, at the Electrotechnical Laboratory (Owadano *et al.*, 1989, 1993) and carried out flyer acceleration experiments by laser irradiation. The wavelength of the laser beam was ~249 nm and the beam energy was set to be 60–80 J per one beam. The laser intensity was $\sim 1.0 \times 10^{13}$ W/cm^2.

Figure 1a shows a typical temporal pulse shape, which was measured using a biplanar photo tube. The pulse duration was 10–15 ns at full width at half maximum (FWHM). When a laser intensity has a temporally short duration or rises rapidly to its maximum, there will be a strong shock generated in the target and the entropy may increase extremely to the extent that the flyer will be vaporized. Hence, in order to reduce the entropy and temperature increase in the flyer, a long pulse beam with gradually increasing intensity is expected to be suitable.

Figure 1b shows a typical spatial beam pattern (the intensity distribution). This was taken from a fluorescence image which was generated when the KrF laser beam irradiated a glass plate. The focal spot diameter of the beam is ~300 μm at FWHM.

One laser beam perpendicularly irradiated a target surface and ablated the Al and PI layers of TLT and the rear layer (Ta) is accelerated as a flyer. The thicknesses of the Ta layer were 4 and 8 μm. By the numerical simulation of flyer acceleration described in Kadono *et al.* (2000a), the thickness of the PI layer was determined to maximize the velocity of flyers and was set to be 90 μm. The thickness of the Al layer was 2 μm. The thickness of each layer was measured by a contact surface profiler and the accuracy was ± 0.0025 μm. The description of the TLT is found in Tanaka *et al.* (2000) and Kadono *et al.* (2000a) in detail.

The observation system used in our experiments is shown in Figure 2. A probe laser beam produced by Verdi (Coherent) whose maximum intensity was 5 W operating at 532 nm was linearly focused by a cylindrical lens with a focal length *f* of 15 mm and passed through an image fiber with a diameter of 1.2 mm and a length of 3 m, which was a fiber-optic bundle, into a vacuum chamber (Fig. 2a). In the chamber, the laser beam passed through two lenses with a different focal length L1 ($f = 12$ mm) and L2 ($f = 15$ mm) to a target rear surface (Fig. 2b). The length of the beam focused on the surface was about 400 μm. The light reflecting from the target surface was collected by L2, then reflected by a half mirror, and was collimated by L3 ($f = 12$ mm). One end of another image fiber with the same effective diameter and length was mounted in the focus of L3 and the image was transferred to the outside of the chamber. The light radiating from the other end of the image fiber is finally imaged on the

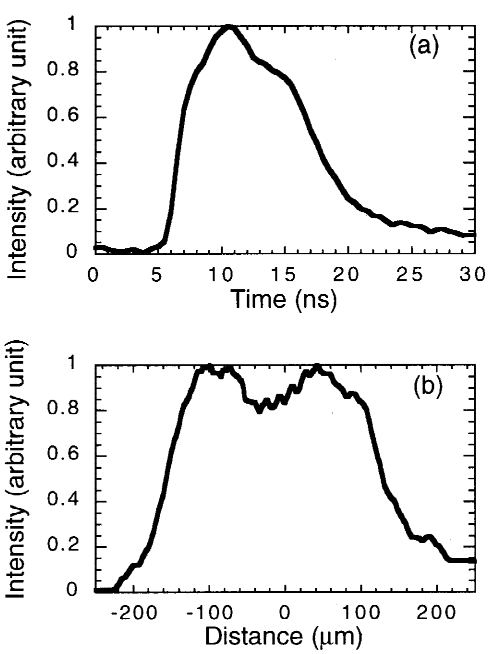

Fig. 1. (a) Typical temporal beam profile and (b) spatial beam pattern in the experiments. The pulse duration is 10–15 ns at FWHM. The focal spot diameter of beam is ~300 μm at FWHM.

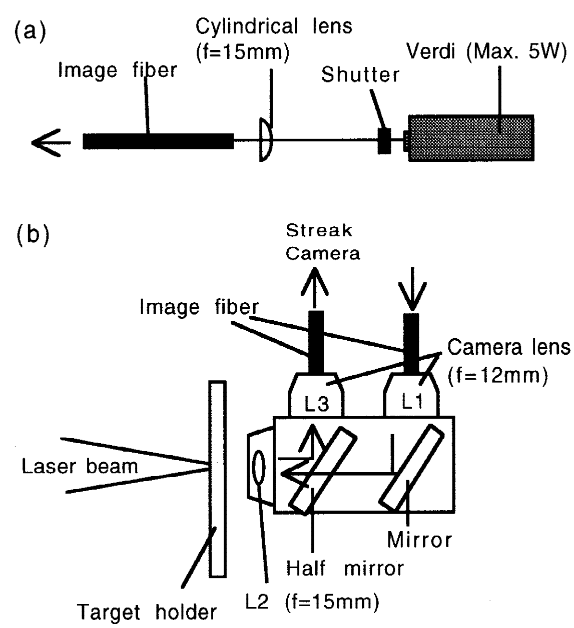

Fig. 2. Schematic experimental setup. (a) A probe laser beam is linearly focused by a cylindrical lens and passes through an image fiber into a vacuum chamber. (b) In the vacuum chamber, the probe laser beam passes through two lenses, L1 and L2, to a target surface. The light reflecting from the target surface is collected by L2, then reflects by a half mirror, and is collimated by L3. One end of another image fiber is mounted in the focus of L3 and the image is transferred to the outside of the chamber. The light radiating from the other end of the image fiber is finally imaged on the entrance slit of a streak camera.

https://doi.org/10.1017/S0263034601194097 Published online by Cambridge University Press

entrance slit of a streak camera C5680 (Hamamatsu Photonics). It should be noted that we used an interferometer which was put just before the streak camera to set a line imaging ORVIS, which is recently applied in laser experiments (Kadono *et al.*, 2000b); hence the reflected probe light showed a fringe pattern.

All experiments were performed under an ambient pressure less than 0.1 Torr.

3. AVERAGE FLYER VELOCITY

3.1. Target setup

An accelerated flyer collided with a transparent quartz plate, which was put at a separation distance of 100 μm and a plastic tape with a thickness of 50 μm was set as a step on half of the quartz plate (Fig. 3a). The separation distance and the thickness of the tape were measured using a contact height gauge and the accuracy was ± 3 μm. The time of flyer start can be determined by observing the time when the intensity of the reflected probe light begins to change. Also the arrival time of the flyer at the quartz plate or the step surface is known by observing a luminous visible light generated by the collision of the flyer. Thus the time of flight can be obtained and an average velocity is estimated.

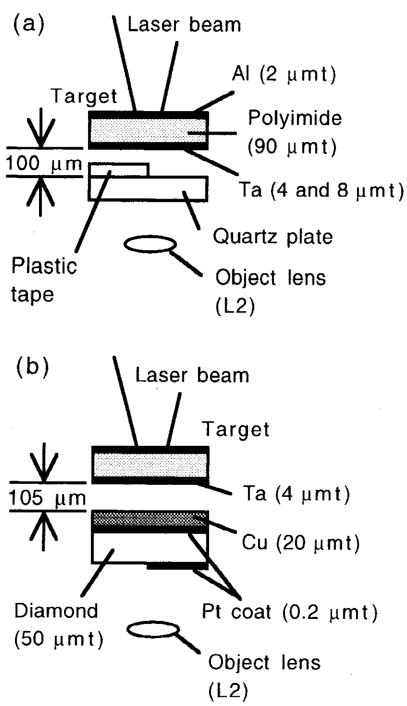

Fig. 3. Target setup. The laser irradiates the three-layered targets (Al-PI-Ta) and ablates the Al and PI layers. (a) The rear layer (Ta) is accelerated as a flyer and collides with a transparent quartz plate, which is put at a separation distance of 100 μm, and a plastic tape with a thickness of 50 μm is set as a step on half of the quartz plate. (b) The Ta flyer collides with a Cu layer with a thickness of 20 μm attaching to a diamond plate with 50 μm. Between the Cu layer and the diamond, a thin Pt layer of 0.2 μm is coated. On the rear surface of the diamond plate, a Pt layer of 0.2 μm is also coated on the half part of the surface.

3.2. Results and discussion

Figure 4 shows a streak camera image in the case of the collision of a Ta flyer with a thickness of 8 μm with the quartz plate. The input laser energy was 66.4 J. Time proceeds from top to bottom. The time and space scales are indicated in the figure. Unfortunately, the ORVIS did not effectively work in the experiments described here, because the reflectivity of flyer surfaces significantly decreased and the fringes disappear for the duration of the flight.

When flyers vaporize, they are converted into a rapidly expanding vapor cloud and the density profile deforms rapidly during flight (Schmalz & Meyer-ter-Vehn, 1985). Therefore, if the flyers vaporize, the features of the impact flash are expected to be quite different from those in the cases of condensed state flyers as seen in the previous studies (e.g., Kadono *et al.*, 2000a). For example, the duration of the impact flash at the quartz plate is expected to become much longer. Figure 4 shows that the features of the impact flash look similar to those seen in the previous studies: The impact flash is lasting less than 10 ns. Hence, we believe that the Ta flyers are in a condensed state. However, as described in Tanaka *et al.* (2000), the Ta flyers could be in a liquid state. Since we had not measured the Ta layer temperature in this experiment, it is difficult to discuss further details of the Ta phase state. The detailed study of the Ta state should be measured thoroughly in the near future.

In Figure 4, at first the fringes are parallel to the time axis. When the shock wave arrives at the rear surface of the TLT, the intensity of the reflected probe light decreases. We can therefore know the time of shock-wave arrivals at the rear surface of targets, which corresponds to the time when the flyers start.

From Figure 4 the flyer planarity can be observed. Though it seems that the planarity is better than that in the previous

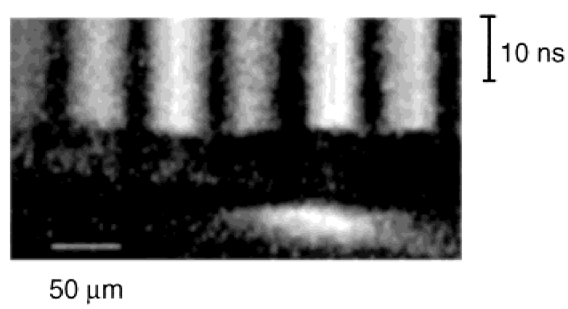

Fig. 4. A streak camera image in the case of the collision of a Ta flyer with a thickness of 8 μm with the quartz plate. Input laser energy is 66.4 J. Time proceeds from top to bottom. The time and space scales are indicated. When the shock wave arrives at the rear surface of the target, the intensity of the reflected probe light decreases. The impact flash at the surface of the quartz plate is observed on the right-hand side. On the left-hand side, a plastic tape is set as a step, but the impact flash is very weak.

https://doi.org/10.1017/S0263034601194097 Published online by Cambridge University Press

study using a KrF laser system, in which the flyers have a conical shape (Kadono *et al.*, 2000a), this is not enough for accurate EOS measurements. We should further improve the spatial beam pattern.

As described before, a plastic tape was set as a step, which was on the left-hand side of the quartz plate in this case. However, the impact flash was very weak at the top of the step. Consequently, the impact flash can be seen only on the right.

Figure 5 shows the time of flight of Ta flyers in two cases of (a) 4 μm and (b) 8 μm in thickness. The horizontal axis is the distance from the original position of the flyers. The times of flyer start and arrival are determined from the temporal intensity profiles along the positions of the fringes, where the spatial intensity distribution is averaged over the width of each fringe.

We can derive an average velocity between the initial position of the flyers and the quartz plate surface, which is defined as the separation distance (100 μm) divided by the time of flight. We obtain 12.41 $\pm$ 1.11 km/s (74.8 J) and 13.24 $\pm$ 1.00 km/s (66.4 J) for 4-μm-thick flyers and 9.24 $\pm$ 0.73 km/s (70.2 J) and 7.93 $\pm$ 0.54 km/s (66.4 J) for 8-μm-thick flyers. The 4-μm-thick Ta flyers are accelerated to velocities of over 10 km/s.

We have performed a simulation of laser ablation and flyer acceleration (Tanaka *et al.*, 2000; Kadono *et al.*, 2000a; Ozaki *et al.*, 2001). Here, we also carry out a simulation using the same code and compare the numerical results with the experimental ones. In this code, we quote EOS data from the SESAME library (1990) for Al and Marsh (1980) and Kinslow (1970) for Ta. Since there are no data for PI in the SESAME library, we substitute a mixed material of two plastics, teflon and parylene-*d*, for which there are EOS data in the SESAME library. The mixture ratio is determined to satisfy the condition that the bulk density, the averaged atomic number, and the averaged atomic mass of the mixed material are equal to those of PI. The value of a parameter relating to the laser–vapor interaction is set to be the same as that in Kadono *et al.* (2000a), and temporal beam shape used in the calculation is a natural cubic spline function which fits the beam shape shown in Figure 1a.

In Figure 5, we plot the curves obtained by the numerical simulations with some laser input energies. We can see that the experimental data exist around the curve with 80 J and that the difference between the experimental data and the numerical ones is not large. The numerical simulations almost reproduce the experimental results.

It can be seen that the curve with 20 J for 4-μm-thick flyers is near to that with 20 J for 1-μm-thick flyers in the previous case (Kadono *et al.*, 2000a). This is because, in our case, the pulse duration and the spot diameter are slightly shorter and, as a result, the acceleration is rapid.

We can obtain the velocity profiles by the simulations. Figure 6 shows them as a function of distance (solid curves). The oscillation of velocity can be seen, which is thought to be caused by the wave reverberation between the flyer and the laser beam absorption point. The mechanism of the oscillation is described by Tanaka *et al.* (2000) in detail. This figure shows that 4- and 8-μm-thick flyers are accelerated to a final velocity of 16 and 11 km/s at a distance of 100 μm with an input laser energy of 80 J, respectively. These final velocities with 80 J are about twice of those with 20 J: When the input energy is four times, the final velocity is about twice. Also, this figure indicates that when a

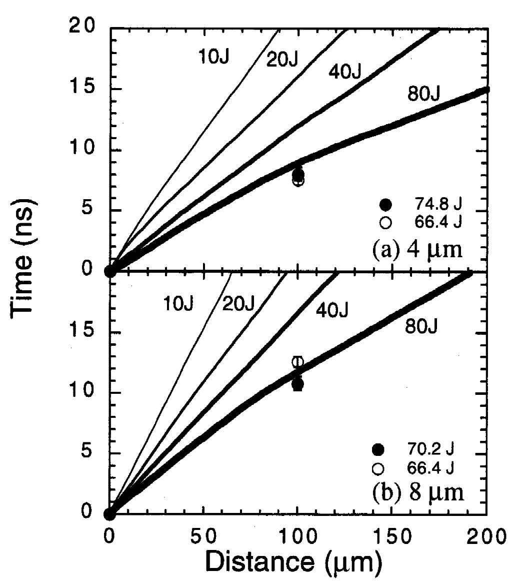

Fig. 5. The time of flight of flyers in two cases at (a) 4 μm and (b) 8 μm thick as a function of the distance from the rear surface of targets. The time 0 is corresponding to the time of flyer starts. The solid curves show the acceleration profiles obtained by the numerical simulations in various laser energies, 10, 20, 40, and 80 J.

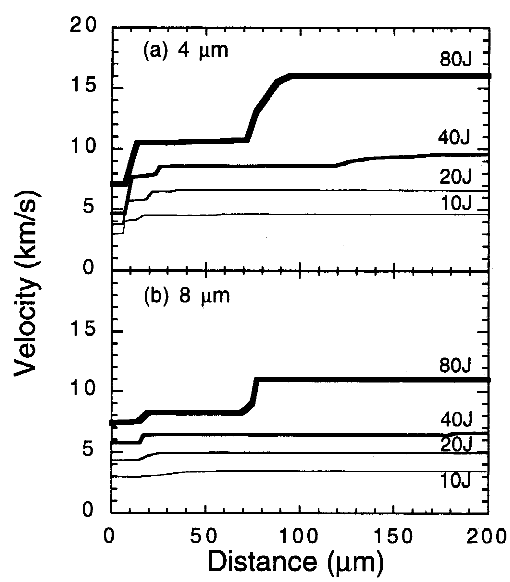

Fig. 6. The velocity profiles in two cases at (a) 4 μm and (b) 8 μm thick obtained by numerical simulations in various laser energies, 10, 20, 40, and 80 J.

https://doi.org/10.1017/S0263034601194097 Published online by Cambridge University Press

thickness is half with the same energy, the final velocity is $\sim\sqrt{2}$ times.

It should be noted that the line-ORVIS should be improved in order to discuss these velocity profiles obtained by the simulation. The intensity of reflected probe light in the optical system was slightly low. Hence it should become high enough to observe the acceleration profiles of flyers.

3.3. Comparison with the previous results

A similar flyer acceleration experiment with TLT has been carried out using a glass laser system with a similar intensity of $\sim 1.6 \times 10^{13}$ W/cm^2, a laser energy of 20 J, a wavelength of 1053 nm, and a pulse duration of 1 ns (Tanaka *et al.*, 2000). The Ta flyers with a thickness of 4 or 8 μm were accelerated to 2–4 km/s, which is rather lower than our results, though the laser intensity is comparable. Also, another flyer acceleration experiment with TLT has been carried out using a glass laser system with a higher intensity of 7×10^{13} W/cm^2, a laser energy of 300×2 J, a wavelength of 527 nm, and a pulse duration of 2 ns. The velocity of Ta flyers with 5 μm achieves 12–13 km/s (Fujimoto *et al.*, 1999). In spite of the lower intensity, we observe similar flyer velocities. Thus, it is confirmed that the laser system with the short laser wavelength and the long pulse duration are useful for accelerating a flyer efficiently. Very high absorption rates at short laser wavelengths and long pulse duration (Garban-Labaune *et al.*, 1982; Trainor *et al.*, 1983; Cottet *et al.*, 1984; Fabbro *et al.*, 1984, 1985, 1986; Faral *et al.*, 1990) are expected to result in a higher velocity of flyers using the relatively lower intensity laser system.

4. ISOBARIC ZONE CAUSED BY FLYER IMPACT

4.1. Target setup

A Ta flyer collided with a Cu layer attached to a diamond plate (Fig. 3b). By the collision of the Ta flyer with the Cu layer, shock waves are generated and propagate into the Ta flyer and the Cu layer. When the shock wave in the Ta flyer arrives at the free surface (the rear of the Ta flyer) a rarefaction wave is generated. The rarefaction wave catches up the shock front in the Cu layer and the pressure at the shock front begins to decrease. The shock front passes through the interface between the Cu layer and the diamond and finally arrives at the rear surface of the diamond plate. Between the Cu layer and the diamond plate a thin platinum (Pt) layer was coated. Also a thin Pt layer was coated on half of the other side surface of the diamond plate. When a shock wave arrives at the interface between the Cu layer and the diamond plate, we observe the change of the intensity of the probe light reflecting from the Pt layer at the interface (on the left in Fig. 3b). Then, when it arrives at the free surface of the diamond plate, the intensity of the probe light reflecting from the Pt layer on the free surface (on the right in Fig. 3b) also changes. Thus we can know the time it takes for shock waves to pass through the diamond plate. From this transit time, we estimate the impact velocity and the pressure of an isobaric zone using another one-dimensional numerical code. This is a hydrodynamic Eulerian code developed for hypervelocity impacts and shock wave attenuation (Mitani, 2001), in which the Hugoniot EOS, density, and the Grüneisen parameter for Ta and Cu are quoted from Marsh (1980) and Kinslow (1970), and for diamond these are from Pavlovskii (1971).

The thickness of the Ta flyer was 4 μm, and the initial separation distance between the Ta flyer and the Cu layer was 105 μm. The Cu and diamond thicknesses were determined to be adequate for our observation system: If they are too thin, the accuracy becomes not good. Using the numerical code, the thicknesses were set to be 20 μm for the Cu layer and 50 μm for the diamond plate. The thickness of the Pt layers was 0.2 μm.

The Pt and Cu layers were deposited onto the diamond plate using an RF magnetron sputtering deposition system at NTT Advanced Technology Corporation. The thicknesses of the Cu and Pt layers were measured using the contact surface profiler and the accuracy was ± 0.0025 μm. Also the thickness of the diamond plate was measured using a laser surface profiler and the accuracy was ± 0.5 μm.

4.2. Shock-wave transit time in diamond

Figure 7a shows a streak image in the case of a flyer impact on the Cu layer attached to the diamond plate. The input laser energy was 61.0 J. The Pt layer is coated on the right-hand side and the boundary is indicated with a bold arrow. It can be seen that the intensity of the reflected probe light on the left-hand side decreases first and then that on the right-hand side does. Figure 7b shows the temporal intensity profiles of the nearest fringes to the boundary (indicated by the narrow arrows), where the spatial intensity distributions are averaged over the width of each fringe. The intensity of the reflected light on the left starts decreasing 2.53 ± 0.10 ns before that on the right does. Thus we obtain 2.53 ns as the transit time of the shock wave in the diamond plate.

4.3. Impact velocity, shock pressure, and thickness of the isobaric zone

Here we estimate the impact velocity of Ta flyers and the pressure and thickness of an isobaric zone by the numerical simulation. In Figure 8, the calculated initial peak pressure and transit time of shock waves in the diamond plate are shown as a function of impact velocity. The simulations are performed at several different velocities with an interval of 1 km/s. The result in Figure 7 that the transit time in the diamond plate is 2.53 ns corresponds to an impact velocity of $\sim$14 km/s and an initial peak pressure of $\sim$11 Mbar. This is consistent with the numerical results in Figure 6a. Thus

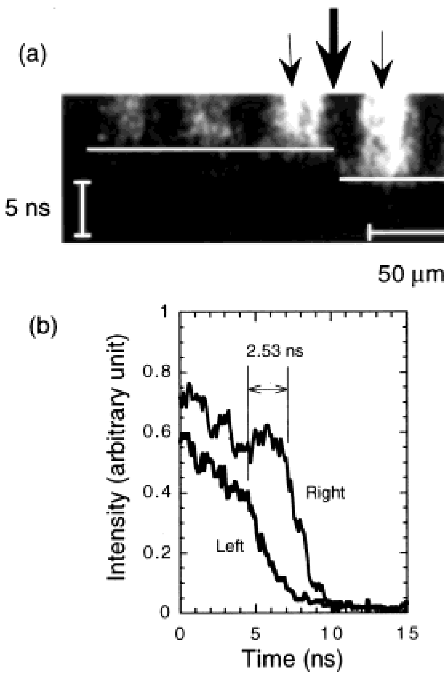

Fig. 7. (a) A streak image obtained in the experiment of the flyer impact on a Cu layer attached to a diamond plate. The right-hand side of the free surface of the diamond plate is coated. It can be seen that the intensity of the reflected probe light on the left-hand side decreases first and then the intensity on the right-hand side does. (b) The temporal intensity profiles of the reflected probe light. The intensity of the reflected light on the left starts decreasing 2.53 ns before that on the right does.

we obtain another indication that a 4-μm-thick flyer is accelerated over 10 km/s.

Figure 9 shows the calculated pressure at shock front against the distance from the impact point (the surface of the Cu layer) obtained using the numerical code for shock-wave attenuation. The impact velocity is set to be 14 km/s. The distances from 0 to 20 μm and from 20 to 70 μm correspond

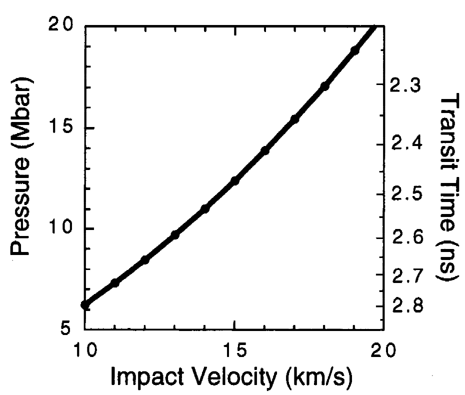

Fig. 8. In the collision of the Ta flyer of 4 μm with the 20-μm-thick Cu layer attached to the 50-μm-thick diamond plate, the initial peak pressure and the transit time of the shock wave in the diamond are shown as a function of impact velocity. The simulations are performed at different velocities with an interval of 1 km/s.

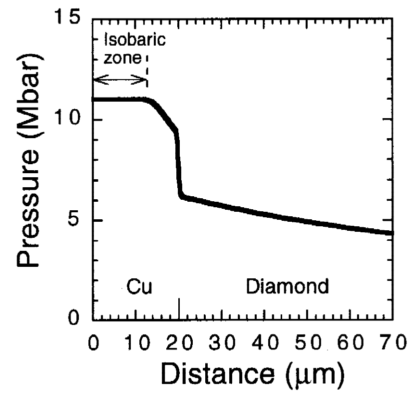

Fig. 9. The pressure at the shock front against the distance from the impact point obtained by a numerical simulation. The impact velocity is set to be 14 km/s. It can be seen that the thickness of the isobaric zone is 12–13 μm, where the initial peak pressure is kept constant at 11 Mbar.

to the Cu layer and the diamond, respectively. It can be seen that the thickness of the isobaric zone is 12–13 μm, where the initial peak pressure is kept constant at 11 Mbar.

Thus it is expected that the present flyer technique produces an isobaric zone with a pressure of 11 Mbar and a thickness of 12–13 μm in the case of a collision of a laser-driven flyer with a thickness of 4 μm at 14 km/s.

4.4. Possibility of EOS measurements

In general, in EOS measurements using the impedance matching method the shock-wave velocities in the steps of a standard and unknown material are often measured. The shock-wave velocity and the pressure should be constant in the steps. In the previous laser experiments in which EOS at ~10 Mbar was investigated by the impedance matching method, the step thicknesses are set to be about 10 μm (Fu *et al.*, 1995; Koenig *et al.*, 1995; Benuzzi *et al.*, 1996; Evans *et al.*, 1996; Wakabayashi *et al.*, 2000). Hence, as one of the necessary conditions for EOS measurements at ~10 Mbar in laser experiments, we should satisfy the condition that the initial peak pressure is kept constant for a thickness of at least 10 μm. In Figure 9, the peak pressure is kept at 11 Mbar for the thickness of 12–13 μm. This suggests that EOS measurements at high pressures of ~10 Mbar using laser-driven flyers are possible.

5. SUMMARY

The flyer acceleration experiments with TLT are carried out using a KrF laser system with a long pulse duration of 10–15 ns and an intensity of $\sim 1.0 \times 10^{13}$ W/cm^2. The velocity of flyers is estimated by two methods and the pressure and the thickness of the isobaric zone caused by the impact of a flyer are calculated.

First, the average velocity of laser-driven flyers is estimated. The Ta flyers 4 and 8 μm thick are accelerated to velocities of ~12 km/s and ~8 km/s. Then, in a collision of

https://doi.org/10.1017/S0263034601194097 Published online by Cambridge University Press

a 4-μm-thick Ta flyer with a Cu layer, we measure a transit time of a shock wave in the diamond plate attached to the Cu layer. From this transit time and a numerical simulation for shock-wave attenuation, we estimate that the impact velocity is ~14 km/s. This simulation also indicates that the initial peak pressure caused by the impact of the flyer is kept at 11 Mbar for 12–13 μm in thickness. The thickness over 10 μm of the isobaric zone with ~10 Mbar is comparable to the thickness of the steps in the previous EOS measurements at ~10 Mbar by the impedance matching method.

Thus it can be said that the present laser-driven flyer technique might be applied to EOS experiments. However, before EOS measurements, we should develop some points. First the line-ORVIS should be improved, as commented. Second the time resolution should become good enough to directly observe the shock-wave velocity in the Cu layer using wedge or step targets. Third, since as shown in Figure 4, the flyer planarity is not enough for EOS measurements, the spatial intensity distribution of the laser beams should be flatter. We are developing a PZP (phase zone plate) to flatten the spatial intensity pattern (Matsushima *et al*., 2001).

As a future plan, we would like to investigate EOS of metals at 10 Mbar pressures. Shock-compressed metals remain in the solid state up to pressures of typically 1–2 Mbar while, at shock pressures of ~10 Mbar, they are a partially ionized fluid on a continuous transition from condensed matter in the liquid state to dense plasma. The theoretical description of partially ionized fluids is complex and hence the extensive experimental investigation of the properties of matters at pressures of ~10 Mbar is needed to confirm or improve theoretical predictions. At present most laser systems which have driven over 10 Mbar shocks have a very high intensity ($\gtrsim 10^{14}$ W/cm^2) and often a very high power ($\gtrsim$TW). However, the flyer technique has a possibility of providing 10 Mbar pressures using a system with several tens of joules and $\sim 10^{13}$ W/cm^2 such as in our cases, and, therefore, extensive experiments using low intensity and low power laser systems become possible. Thus EOS of metals at the 10 Mbar region would be accurately investigated.

ACKNOWLEDGMENTS

The authors would like to thank N. Kozu, K. Wakabayashi, T. Tada, S. Sugita, S. Usuba, and H. Kinoshita for cooperating on the experiments and for useful comments. We are also grateful to two anonymous reviewers for helpful comments. This work has been supported by the CREST (Core Research for Evolutional Science and Technology) program of the Japan Science and Technology Corporation (JST).

REFERENCES

Benuzzi, A., Löwer, T., Koenig, M., Faral, B., Batani, D., Beretta, D., Danson, C. & Pepler, D. (1996). Indirect and direct laser driven shock waves and applications to copper equation of state measurements in the 10–40 Mbar pressure range. *Phys. Rev. E* **54**, 2162–2165.

Cauble, R., Perry, T.S., Bach, D.R., Budil, K.S., Hammel, B.A., Collins, G.W., Gold, D.M., Dunn, J., Celliers, P., Da Silva, L.B., Foord, M.E., Wallace, R.J., Stewart, R.S. & Woolsey, N.C. (1998). Absolute equation-of-state data in the 10–40 Mbar (1–4 TPa) regime. *Phys. Rev. Lett.* **80**, 1248–1251.

Cauble, R., Phillion, D.W., Hoover, T.J., Holmes, N.C., Kilkenny, J.D. & Lee, R.W. (1993). Demonstration of 0.75 Gbar planar shocks in X-ray driven colliding foils. *Phys. Rev. Lett.* **70**, 2102–2105.

Cottet, F., Romain, J.P., Fabbro, R. & Faral, B. (1984). Ultrahigh-pressure laser-driven shock-wave experiments at 0.26 μm wavelength. *Phys. Rev. Lett.* **52**, 1884–1886.

Da Silva, L.B., Celliers, P., Collins, G.W., Budil, K.S., Holmes, N.C., Barbee, T.W., Jr., Hammel, B.A., Kilkenny, J.D., Wallace, R.J., Ross, M., Cauble, R., Ng, A. & Chiu, G. (1997). Absolute equation-of-state measurements on shocked liquid deuterium up to 200 GPa (2 Mbar). *Phys. Rev. Lett.* **78**, 483–486.

Evans, A.M., Freeman, N.J., Graham, P., Horsfield, C.J., Rothman, S.D., Thomas, B.R. & Tyrrell, A.J. (1996). Hugoniot EOS measurements at Mbar pressures. *Laser Part. Beams* **14**, 113–123.

Fabbro, R., Faral, B., Cottet, F. & Romain, J.P. (1984). Experimental study of laser acceleration of planar targets at the wavelength 0.26 μm. *J. Appl. Phys.* **56**, 3204–3208.

Fabbro, R., Faral, B., Virmont, J., Cottet, F., Romain, J.P. & Pepin, H. (1985). Experimental study of ablation pressures and target velocities obtained in 0.26 μm wavelength laser experiments in planar geometry. *Phys. Fluids* **28**, 3414–3423.

Fabbro, R., Faral, B., Virmont, J., Pepin, H., Cottet, F. & Romain, J.P. (1986). Experimental evidence of the generation of multi-hundred megabar pressures in 0.26 μm wavelength laser experiments. *Laser Part. Beams* **4**, 413–419.

Faral, B., Fabbro, R., Virmont, J., Cottet, F., Romain, J.P. & Pepin, H. (1990). Importance of two-dimensional effects for the generation of ultra high pressures obtained in laser colliding foil experiments. *Phys. Fluids* B**2**, 371–377.

Fu, S., Gu, Y., Wu, J. & Wang, S. (1995). Laser-driven shock stability in Al and shock compressibilities of Fe up to 0.8 TPa and SiO_2 up to 0.4 TPa. *Phys. Plasmas* **2**, 3461–3465.

Fujimoto, Y., Yoshida, M., Wakabayashi, K., Kondo, K., Kozu, N., Sasatani, Y., Tanaka, K.A. & Takenaka, H. (1999). Flyer acceleration by laser irradiation. *Proc. Symp. on Shock Wave, Japan '99*, pp. 617–620 (in Japanese).

Garban-Labaune, C., Fabre, E., Max, C.E., Fabbro, R., Amiranoff, F., Virmont, J., Weinfeld, M. & Michard, A. (1982). Effect of laser wavelength and pulse duration on laser-light absorption and back reflection. *Phys. Rev. Lett.* **48**, 1018–1021.

Kadono, T., Yoshida, M., Kozu, N. & Kondo, K. (2000b). Investigation of the Hugoniot equation of state in laser-driven shock experiments by a line-imaging optically recording velocity interferometer system. *Rev. Sci. Instr.* **71**, 4674–4676.

Kadono, T., Yoshida, M., Takahashi, E., Matsushima, I., Owadano, Y., Ozaki, N., Fujita, K., Nakano, M., Tanaka, K.A., Takenaka, H. & Kondo, K. (2000a). Flyer acceleration by a high-power KrF laser with a long pulse duration. *J. Appl. Phys.* **88**, 2943–2947.

Kinslow, R. ed. (1970). *High-Velocity Impact Phenomena*. New York: Academic.

Koenig, M., Faral, B., Boudenne, J.M., Batani, D., Benuzzi, A., Bossi, S., Rémond, C., Perrine, J.P., Temporal, M. & Atzeni, A. (1995). Relative consistency of equations of state by laser driven shock waves. *Phys. Rev. Lett.* **74**, 2260–2263.

Marsh, S.P. ed. (1980). *LASL Shock Hugoniot Data*. Berkeley: University of California Press.

Matsushima, I., Takahashi, E., Owadano, Y., Kadono, T., Yoshida, M., and AEOS project members (2001). Target acceleration by high power KrF laser ASHURA. *Proc. 8th NIRIM Int. Symp. on Advanced Materials (ISAM 2001)*, pp. 63–64.

Mitani, N.K. (2001). Numerical simulations of shock attenuation in solids induced by hypervelocity impacts. *J. Geophys. Res.* (in press).

Ng, A., Parfeniuk, D. & Da Silva, L. (1985). Hugoniot measurements for laser-generated shock waves in aluminum. *Phys. Rev. Lett.* **54**, 2604–2607.

Owadano, Y., Okuda, I., Matsumoto, Y., Matsushima, I., Koyama, K., Tomie, T. & Yano, M. (1993). Performance of the ASHURA KrF laser and its upgrading plan. *Laser Part. Beams* **11**, 347–351.

Owadano, Y., Okuda, I., Matsumoto, Y., Tanimoto, M., Tomie, T., Koyama, K. & Yano, M. (1989). Development of a high-power KrF laser system, ASHURA. *Laser Part. Beams* **7**, 383–392.

Ozaki, N., Sasatani, Y., Kishida, K., Nakano, M., Miyanaga, N., Nagai, K., Nishihara, K., Norimatsu, T., Tanaka, K.A., Fujimoto, Y., Wakabayashi, K., Hattori, S., Tange, T., Kondo, K., Yoshida, M., Kozu, N., Ishiguchi, M. & Takenaka, H. (2001). Planar shock wave generated by uniform irradiation from two overlapped partially coherent laser beams. *J. Appl. Phys.* **89**, 2571–2575.

Pavlovskii, M.N. (1971). Shock compression of diamond. *Sov. Phys. Solid State* **13**, 741–742.

Schmalz, R.F. & Meyer-ter-Vehn, J. (1985). Equation-of-state effects on laser-accelerated foils. *Phys. Fluids* **28**, 932–940.

SESAME: The Los Alamos National Laboratory Equation of State Database (1990). Report No. LA-UR-92-3407, Los Alamos, NM: Los Alamos National Laboratory.

Tanaka, K.A., Hara, M., Ozaki, N., Sasatani, Y., Anisimov, S.I., Kondo, K., Nakano, M., Nishihara, K., Takenaka, H., Yoshida, M. & Mima, K. (2000). Multi-layered flyer accelerated by laser induced shock waves. *Phys. Plasmas* **7**, 676–680.

Trainor, R.J., Holmes, N.C., Anderson, R.A., Campbell, E.M., Mead, W.C., Olness, R.J., Turner, R.E. & Ze, F. (1983). Shock wave pressure enhancement using short wavelength (0.35 μm) laser irradiation. *Appl. Phys. Lett.* **43**, 542–544.

Wakabayashi, K., Hattori, S., Tange, T., Fujimoto, Y., Yoshida, M., Kozu, N., Tanaka, K.A., Ozaki, N., Sasatani, Y., Takenaka, H., Nakamura, K.G. & Kondo, K. (2000). Laser-induced shock compression of tantalum to 1.7 TPa. *Jpn. J. Appl. Phys.* **39**, 1815–1816.