Development of laser-driven shock compression system with a line-imaging ORVIS to determine the Hugoniot equation-of-state

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Abstract. A laser-driven shock compression system using a table-top type pulsed laser was developed in order to investigate the Hugoniot equation-of-state (EOS) of laser-shocked materials. A line-imaging optically recording velocity interferometer system (ORVIS) was implemented for measurements of both shock wave velocity ($U_s$) and particle velocity ($u_p$). The measurement of Hugoniot equation-of-state of nitromethane was performed by using the developed experimental system. The obtained experimental results showed a good agreement with the previous data. It was indicated that the developed experimental system and the analytical method implemented in this study were worked well and useful to investigate the Hugoniot equation-of-state of transparent materials such as nitromethane.

1. Introduction

Equation-of-state (EOS) of materials at high pressure is very important not only for material science but also for astrophysics and/or geophysics, because it provides fundamental information on thermophysical and mechanical properties of materials under extreme high pressure conditions. Shock compression is a useful technique for inducing high pressures in materials, and high pressures have been achieved traditionally with strong shock waves generated by explosives or impact guns. Equation-of-state of shocked-materials, which was called as Hugoniot, has been investigated by using these shock compression techniques.

Laser-driven shock compression technique has been recognized as a powerful tool for investigation of Hugoniot EOS, because this technique makes it possible to generate ultra high pressure up to several terapascals in a laboratory. Actually, Hugoniot EOS under terapascal pressure region has been measured by using a high energy and high power laser[1]. However, measurement technique of Hugoniot with a table-top type laser in common use in a laboratory was not established enough.
In this paper, we described preliminary development of a shock compression system using a table-top type pulsed laser and implementation of a line-imaging optically recording velocity interferometer system (ORVIS)[2-3] to determine the Hugoniot equation-of-state of laser-shocked materials. With use of a line-imaging ORVIS, the spatial velocity distribution of moving object can be measured. This velocity measurement technique, using an appropriate target assembly as described below, enables us to measure both shock wave and particle velocity simultaneously without a standard material. The effectiveness of the developed experimental system was evaluated by demonstration experiments.

2. Development of laser-driven shock compression system

2.1. Laser-driven shock compression system with a line-imaging ORVIS

A schematic drawing of a laser-driven shock compression system developed here was shown in figure 1. A table-top pulsed type Nd:YAG laser (YG2671-10, Continuum, Inc.) was used for shock wave generation. A maximum beam energy and wavelength of the laser pulse are 900 mJ and 1064 nm, respectively. Temporal profile was near Gaussian with about 10 ns duration at full width at half maximum. The laser beam was irradiated through a lens at the surface of the target at a normal incidence. Irradiation energy on the target was changed by using filters with different transmission. The spot diameter on the target was about 1.5-2 mm.

![Figure 1](image1.png)

**Figure 1.** A schematic drawing of a laser-driven shock compression system with a line-imaging ORVIS. F:filter, BS:beam sampler, L1-6:lens, CL:cylindrical lens, M:mirror, RM:removable mirror.

Continuous-wave Nd:YVO₄ laser (Verdi V-5, Coherent Inc.) was used as a probe light for velocity measurement. The output power of the probe light was 5 watt at maximum operating at a wavelength of 532 nm. The probe light was passed through a cylindrical lens CL, a cube-type half beam splitter CBS and a lens L2, then focused linearly on the target surface across the center opposite to the irradiation area of shock generation laser. Spatial size of the probe light on the target surface was about 2 mm in length and less than several tens of micrometer in width. The reflected probe light, which affected Doppler effect due to motion of target surface driven by laser-induced shock wave, was collected by a lens L2, then passing through a cube-type half beam splitter CBS again, and focused on one end of an image-fiber (FIGH-15-600N, Fujikura Inc., length=5 m) by a lens L4[4]. Image circle diameter of the image fiber was 550 µm, and has 15,000 picture elements. The output of probe light from another end of an image-fiber was collected by a lens L5 and introduced into an interferometer (model 605-FCV-SC, ATA Associates Inc.). The probe light after passing through an interferometer was collected by a lens L6, and images on the entrance slit of a streak camera (C5680, Hamamatsu

![Figure 2](image2.png)

**Figure 2.** Target assembly. Nitromethane was filled in the shaded area.
Photonics K.K.). An image of target surface was relayed to the entrance slit of a streak camera through light collection optical elements, an image-fiber and an interferometer. A focus of image and a contrast of interference fringes were adjusted precisely by a charge-coupled device camera, which was placed at spatially equivalent position against the entrance slit of a streak camera. Total magnification of image on the entrance slit of a streak camera was about 6.

2.2. Target assembly
The target assembly as shown in figure 2 has a glass-confinement geometry[5] consisting of a back-up glass substrate (BK7, 5 mm thick), an aluminum foil (25-50 µm thick), a spacer (Teflon or aluminium) and a window substrate (BK7, 5 mm thick). An aluminum foil was glued on a back-up glass substrate by ultraviolet cure adhesive. We chose a nitromethane as a test sample. Since the Hugoniot of nitromethane has been studied well, it was suitable for present demonstration experiments to verify the effectiveness of the developed system. Nitromethane was filled in a space surrounded by an aluminum foil, a spacer and a window substrate. A part of a window substrate in contact with nitromethane was coated with thin aluminum (approximately 100 nm thick, see figure 2). Sample was 141-150 µm thick, which was measured by a surface-profilometer (VF-7510, Keyence Co.).

3. Results and Discussion
Figure 3 shows a typical fringe image obtained by a streak camera. Time increases from left to right, and time window is 200 ns. The field of view is 900 µm. The surface of an aluminum foil was a lower half and the surface of a window with aluminum coating was an upper half. Since nitromethane used as sample was transparent, it was possible to measure the velocity of an aluminum foil surface.

![Figure 3. Typical fringe image obtained by a streak camera.](image)

![Figure 4. Particle velocity history. The black and red line indicates the velocity of an aluminium foil surface and a coated surface, respectively.](image)

As shown in figure 3, the fringes from the surface of aluminum foil were moved at time A. The moment when the fringes start to move corresponds with the time when the shock wave enters from an aluminum foil to nitromethane. After the shock wave propagated inside the nitromethane, the shock wave arrived at the coated surface of the window at time B indicated in figure 3. When the shock wave arrived at the coated surface of window, the fringes changed. Since the fringes at the central part of shocked area of less than 300 µm in diameter start to move almost at the same time, this indicates that the spatial profile of shock wave front was approximately flat. Consequently, we applied image processing techniques based on fast Fourier transform[6] to fringe image and fitted the fringe intensity distribution at the central part of shocked area to a sine function at each time. Then the temporal change of phase and velocity were derived. Obtained velocity history of both an aluminum surface and a coated surface on window were shown in figure 4. Obtained Hugoniot equation-of-state parameter of nitromethane in $U_s$-$up$ and $P$-$up$ relations were shown in figure 5 and 6 as open circles. The $U_s$ was
derived by dividing the thickness of the sample by the shock propagation time. The error of the $U_s$, which was mainly caused by uncertainty of sample thickness and the time-resolution of streak camera, was less than a few percent. The particle velocity increased rapidly up to maximum when the shock wave enters into the nitromethane. Afterwards, particle velocity decreased gradually with time, because pressure generated by pulse-laser irradiation decreases during the shock wave propagates inside the sample. The particle velocity ($u_p$) was obtained by arithmetic average of particle velocity history during the transit time of shock wave in nitromethane. The major error source of $u_p$ was attributed to its unsteadiness. The closed squares in figure 5 and 6 indicate the previous data obtained by another method[7]. The solid lines in these figures were obtained by fitting the data in reference. Our Hugoniot data obtained by laser-driven shock compression technique agreed well with the previous data. The extrapolation of fitting line of our data, which was indicated by dotted line in figure 5, was also consistent better with the longitudinal sound velocity (1.34 km/s). It would be supposed that the developed laser-driven shock compression system and the analytical method implemented in this study were worked well and useful to investigate the Hugoniot equation-of-state.

4. Conclusions
Laser-driven shock compression system with a line-imaging ORVIS was developed in order to investigate the Hugoniot equation-of-state of laser-shocked materials. It was indicated that the developed experimental system and the analytical method implemented in this study were worked well and useful to investigate the Hugoniot equation-of-state through demonstration experiments on nitromethane. In the future work, we are planning to progress two dimensional analytical methods of a line-ORVIS data to study two dimensional effect of shock compressed state.

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References
[1] Benuzzi A et al. 1996 Phys. Rev. E 54 2162
[2] Hemsing W et al. 1992 Shock Compression of Condensed Matter-1991, (New York: Elsevier) pp 767-770
[3] Trott W M and Asay J R 1998 Shock Compression of Condensed Matter-1997, (New York: AIP) pp 837-840
[4] Kadono T, Yoshida M, Kozu N and Kondo K 2000 Rev. Sci. Instrum. 71 4674
[5] Devaux D, Fabbro R, Tollier L and Bartnicki E 1993 J. Appl. Phys. 74 2268
[6] Fisk G A, Mastin G A and Sheffield S A 1986 J. Appl. Phys. 60 2266
[7] Marsh S P 1980 LASL Shock Hugoniot Data, (Berkeley: Univ. of California Press) p 599