Laser-Driven Shock Device for Real-Time Hugoniot Measurement

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Table-top laser-driven shock loading device was developed to make real time measurement of stress and particle velocity histories during shock loading. Use of a shock cell enables us to launch any-type of mini-flyer with the specified speed by controlling the laser power. Since the VISAR system is equipped with the present shock loading device, Hugoniot data can be obtained by the conventional set-up, where the target material is sandwiched by the mini-flyer and the window material. Accuracy in measurement is discussed for copper and PMMA Hugoniots.

[table-top laser shock device, shock cell, mini-flyer, VISAR, real time measurement, Hugoniot]

1. Introduction

Table-top Laser-driven launching system is preferable to investigation of Hugoniot and spallation data from the laser-driven mini-flyer materials and recovered samples [1,2]. One of authors [3] proposed the first system to drive the mini-flyer for time resolved measurement for shock physics and shock chemistry. Authors have been in collaboration for a couple of years to develop a promising table-top shock loading device especially for time resolved evaluation and analysis of various shock treatments of materials [4].

In the present paper, our developed laser-driven shock loading device is introduced for real time measurement of mini-flyer velocity history and shock Hugoniot by using the VISAR system [5]. First, Cu-foil with various thickness is employed as a mini-flyer material to experimentally demonstrate that our developed table-top laser shock loading device with the VISAR system should work well. Next, PMMA (Poly-Methyl-Meta-Acrylate) is used as a window material to make time resolved measurement of Hugoniot both for Cu-flyer and PMMA window. Through comparison between the measured and reference Hugoniot curves, the points to be revised in the present system are discussed for further advancement in the table-top laser-driven shock loading technology.

2. Laser-Driven Shock Loading Device

Nd:YAG laser with the maximum energy of 0.7 J was used as the power source for shock loading. Figure 1 schematically depicts our developed table-top laser shock loading device with the VISAR system. Optical lens system was optimized to make laser power spatial distribution as flat as possible. The generated ray diameter was once expanded three times larger for ray transmission, and gradually focused onto the surface of a mini-flyer generator, or, a shock cell. As explained later, a mini-flyer generator, a spacer between the generator and the target material, and the target material system with/without a window material are all installed into a shock cell. Then, once each

experimental set-up was constructed in this shock cell, any experimental procedures can be performed by using the same optical arrangement both for laser focusing and measurement by the VISAR.

This shock cell was fixed in the vacuum vessel to eliminate the air or other gases for preventing the disturbance of mini-flyer flight. The final focusing lens system can be controlled by two dimensional goniometer to select the focusing spot onto the specified mini-flyer which had been glued on the surface of the substrate. The mini-flyer can be recovered in the inside of the shock cell. As shown in Fig. 1, the VISAR system was triggered by the external signal for onset of laser pulse generation. Through post-processing the measured signal histories, the particle velocity history can be reconstructed. Since the shock cell is isolated both from the laser power generator and the VISAR system, various sensors can be also mounted into the shock cell and utilized together with the VISAR. In particular, use of PVDF gage together with the VISAR [6] might be attractive to deduce the Hugoniot relationship between the particle velocity and the pressure.

Fig. 1. Schematic view of our developed shock loading device.

Figure 2 depicts a mini-flyer generator (a part of a shock cell) made of the sapphire substrate with amorphous carbon and aluminium thin coatings. A mini-flyer material was glued on this Al coating. The laser pulse is first absorbed in this amorphous carbon layer of the multi-layered coating. Due to abrupt heating, a part of aluminium coating is forced to be converted into a plasma. The volumetric change of aluminium coating material in its conversion into plasmas becomes an energy source to accelerate the flyer to its specified velocity within three or four pulse widths of the laser. Both flyer velocity and shock duration time can be controlled by tuning the laser power and varying the thickness of flyer.

In the present study, the thickness of the amorphous carbon and the aluminum coating was controlled to be 0.5 μm and 3.5 μm , respectively. Both two layers were ion-plated on the sapphire substrate with the thickness of 2 mm. Deviation from this standard configuration of the shock cell sometimes leads to deterioration of energy conversion efficiency from the input laser power to the kinetic energy of a flyer.

Fig. 2. A shock cell configuration in the present system.

3. Measurement of Cu Flyer Velocity

VISAR was utilized to make time-resolved measurement of flyer velocity in the function of laser input power. In the present system, copper flyer with the thickness from 5 μm to 100 μm can be launched with the velocity range up to 1 km/s. Even in the time-resolved measurement, the mini-flyer can be often recovered by using the PMMA window material. In every case when the VISAR was not used, both these mini-flyers and targets were all recovered with success. This is one of the most attractive features to the present system for doing the shock treatment of materials.

Figure 3 shows a typical time history of copper mini-flyer movement from 100-200 ns before launching to stationary flying with a constant velocity. Besides the time-resolved measurement of flyer terminate velocity, VISAR can trace the acceleration process in the shock cell with time resolution of ns. The undershooting to negative velocity and its subsequent vibration behavior is just corresponding to the launching condition of a mini-flyer from the surface of aluminium coating.

Fig. 3. Typical mini-flyer velocity history measured by using the VISAR system.

4. Hugoniot Measurement by Copper and PMMA Window

One of authors [3] reported that laser-driven shock loading device should be effective to make time-resolved measurement of Hugoniot. In this study, PMMA window was utilized along with the VISAR for measurement of Cu Hugoniot for standard verification. The experimental set up was shown in Fig. 4 together with a typically measured flyer velocity history. When a flyer shoots on the window material, the flyer velocity abruptly changes to an interfacial velocity between two materials. The measured drop of velocity is corresponding to the mismatch in Hugoniot between two materials for the prescribed flyer velocity. Then, real-time measurement of this speed drop for each flyer velocity can provide the Hugoniot of either material when the other material Hugoniot was known. In general, since the Hugoniot of window material can be cited from literature, the Hugoniot data of unknown flyer material can be directly obtained by this measurement.

Fig. 4. Typically measured mini-flyer velocity history when window material was used.

Figures 5 and 6 show the comparison of the measured Hugoniot relationship between the velocity and the shock pressure with the reference data from literature [7]. The copper Hugoniot was obtained in Fig. 5 by using the Hugoniot curve of

PMMA both for the measured data and the theoretical calculation. The PMMA Hugoniot can be compared in Fig. 6 by commonly using the reference copper Hugoniot. The measured Hugoniot was comparable to the reference data with a noticeable deviation. To be noted, any pair of the flyer and the window materials can be available to directly obtain the Hugoniot data even in the low pressure regime up to 1-2 GPa.

Fig. 5. Comparison of copper Hugoniot between the measured results and the reference data.

Fig. 6. Comparison of PMMA Hugoniot between the measured results and the reference data.

5. Discussion

The maximum flyer velocity is mainly limited by the YAG-laser generator. In the present experimental apparatus, the maximum copper flyer velocity (V_f) is limited by $V_f = 0.8$ km/s. Only by increasing the laser capacity up to 2-3 J, the present system can reach the flyer velocity up to 2 to 2.5 km/s without any change of the optical lens and mirror system at present. One of the most important item to evaluate the performance of the shock loading devices is an energy conversion efficiency (E_{con}) from the laser generating power to the kinetic energy of a flyer. When a laser pulse with the energy of 465 mJ is imposed to a shock cell, $V_f = 550$ m/s for the copper flyer with the thickness of 10 μ m and the diameter of 2 mm. In this case, E_{con} becomes about 9 %. This value is just corresponding to a roughly-estimated figure where 1) 90 % of the laser power is thermally

absorbed into the amorphous carbon, 2) 30 % of this thermal energy is converted to the mechanical energy to propel both the solid part of aluminium and the rest materials, and 3) half of this mechanical energy is used for acceleration of the flyer velocity.

Since the accuracy of the particle velocity measured by the VISAR is strongly dependent on the change of reflected ray strength from the free surface of the material, noticeable decrease of ray strength during the flight leads to error in measurement, resulting in the deviation of Hugoniot data. In order to be free from this inconvenience, the flyer must be shot without any inhomogenous separation from the substrate.

6. Conclusion

Table-top laser-driven shock loading device was developed to be working together with the VISAR system not only for time-resolved Hugoniot measurement but also for investigation of shock-induced transition and reaction. Most of all the experimental set-up configurations listed in the literature [7] can be installed in the shock cell. Hence, various types of experimental procedure can be available in the present shock loading device. Among them, multi-sensored measurement with use of the VISAR is attractive to obtain the history of various physical quantities, to investigate the change of Hugoniot data with increasing the shock pressure or stress, and to make time-resolved diagnosis of the shock treatment.

Acknowledgments

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