Multiple Shock Compression of Diamond Foils with a Shaped Laser Pulse over 1 TPa

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Abstract. Experiments on shock compression of diamond foils with intense laser are reported. In order to explore high-pressure and low-temperature region of the carbon phase-diagram, we irradiate single-crystal (Type-Ib) crystal foils with a shaped (ramp) pulse at the pressure of over 1TPa. We observed time-resolved reflectivity from the rear surface of the diamond during the shock compression with velocity interferometer system for any reflector (VISAR). Simultaneous observation of optical measurements and x-ray diffraction has been tested. Preliminary results on decompression of the diamond crystal due to x-ray heating were observed.

1. Introduction
Diamond is very interesting and important material both for science and industry applications. Diamond is broadly employed as an anvil material (such like as a diamond anvil cell: DAC) for high pressure science experiments because of its hardness. However, there are still unknown issues over the pressure of DAC compression limit (~ 350 GPa). Strong shock wave with intense laser irradiation can reveal the unknown properties in carbon phase diagram [1-5] at ultra-high pressure.
There has been many works on shock-compression of diamond beyond the pressure of 1 TPa [6]. However, most works were done with single shock compression on its principal Hugoniot curve. In this paper, we present recent experimental results on shock compression of diamond foils under ultra-high pressure with intense laser. We irradiated the diamond foils with shaped laser pulse in order to create low isentrope conditions below the Hugoniot temperature.

2. Experiments

2.1. Experimental conditions
Experiments were done on GEKKO-XII/HIPER irradiation facility at Institute of Laser Engineering, Osaka University [7]. The GEKKO-HIPER facility has 12 beams which irradiates planar target from one direction. The main advantage of its irradiation configuration is excellent spatial uniformity of the drive laser. Another advantage is that it is possible to create shaped laser pulses with time delay between the individual beams [8].

We irradiated single crystal diamond foils (Type-Ib) of 50 μm thickness with (100) surface orientation. In order to protect from preheating, gold (Au) coating of 5 μm was applied on the laser-irradiated surface. Typical pulse shape of this experiment is shown in figure 1. The basic design of the experiment is to reach the pressure of over 1TPa at the peak compression. The drive pulse shape was nearly four-stepped pulse to produce multiple shock. The peak laser intensity was \( (1\text{~}2.5) \times 10^{14} \text{ W/cm}^2 \). The total pulse duration and the spot diameter were 6 ns and 300 μm, respectively. Test calculations were done with one-dimensional radiation hydrodynamic code ILESTA-1D [9]. Flow diagram of the compressed diamond is also shown in figure 1. The calculation results suggest that the peak shocked temperature is 2000 – 3000 K at the pressure of over 1TPa whereas the shocked temperature is 20000K for single shock compression. This implies that it is possible to reach post-diamond phase (BC8 structure) with the shaped laser pulse irradiation.

2.2. Optical measurements and x-ray diffraction
Figure 2 shows schematic view of the experimental setup. The main diagnostics for the experiments is based on optical measurements. We employed two VISARs (velocity interferometer system for any reflector [10]) in order to observe the reflectivity and the rear surface velocity after the shock breakout. One of the VISARs was very “insensitive” one mainly for reflectivity observation. The probe light of the VISARs was second harmonics of the YAG laser (\( \lambda \): 532 nm). We also measured the rear surface
temperature with streaked pyrometer with spectrograph [11]. The detection threshold of the pyrometer was 6000K.
In addition to the optical observations, x-ray diffraction measurements [12] were done in the same data shots. We placed an x-ray source target (Cu) for the diffraction measurement. The diffracted x-ray was measured by an imaging plate which covered the rear surface of the target. The incident angle of the quasi-point source x-ray was 40 degrees (Bragg angle). We designed the position of the x-ray source and the imaging place not to disturb the optical path of the VISAR and the self emission measurements.

3. Results and discussions
Raw streaked VISAR images are shown in figure 3 for (a) without aluminium coating at the rear surface and (b) with aluminium coating (~ 0.05 μm) at the rear surface. From figure 3(a) it is shown that strong reflection from the Au surface is seen in early time. The reflection then decreases due to shock transit between the interface of Au and diamond. After that, the weak reflectance still remains from the rear diamond surface because there was no anti-reflection coating at the rear surface. Phase shifts are seen when the first and second shock (~ 0.9 TPa) breaks out the rear diamond surface. After the phase shift, the fringes are gone when the third and fourth shock (~ 2.5 TPa) broke out at the rear surface. The shock breakout timing from the VISAR measurements is in good agreement with calculation with ILESTA-1D simulation.
From figure 3(b), it is seen that clear fringes from the rear Al surface prior to the shock breakout. However, phase shifts and very strong reflectance was observed where the first and second shock (~ 0.9 TPa) breakout at the rear surface. The peak laser energy for figure 3(b) data is smaller (~ 1.5 TPa) than that for figure 3(a) data. The strong reflectance might be due to several reasons (phase change, melting, etc), but still under discussion. The measured temperature with the pyrometer was under the detection threshold (~ 6000 K).
We also measured the crystal structure of the shock compressed diamond. Since there was a lot of x-rays from the laser-irradiated surface, however, we could not obtain simultaneous observation data for high-pressure compression region. Figure 3 shows the diffraction data for a “without drive” shot. Clear “static” diffraction curves of many orientations were observed. Moreover, we also observed some shifted curve in there. This is because some soft x-ray components directly irradiated the rear surface of the diamond foil. The x-ray irradiation heated up the diamond, which lead the expansion

![Figure 3. Raw streaked image from the VISAR for diamond targets (a) without aluminium (Al) coating at the rear surface (b) with Al coating at the rear surface.](image_url)
(decompression) and weak shock compression of the diamond crystal. Figure 3(b) shows the diffracted curve for (400) surface of the diamond, which is parallel to the surface orientation. The decompression ratio was approximately 1%, which shows ~ 4300K from the coefficients of thermal expansion for standard ambient pressure and temperature. Since the coefficients of thermal expansion increases with temperature, the temperature should be below the melting point of the diamond (~ 3500K). The data also implies some stress shifts due to compression by the x-ray driven shock wave. This is very interesting for understanding the elastic-plastic (E-P) transition of the diamond. We are planning to take data at less pressure region for the E-P transition by the laser-driven shock.

4. Conclusion
We have started the experiments on shock compression of single crystal diamond with the shaped pulse laser. We measured reflectivity of the diamond the VISAR. The fundamental hydrodynamics of the shock propagation is in good agreements with the 1-D ILESTA simulation calculation. The strong reflectance implies the phase change, but still needed more data for further understanding. We also started simultaneous measurements of optical diagnostics and x-ray diffraction. Preliminary data suggests that this technique is very powerful tool for understanding the shock-compressed diamond at high-pressure phase with intense laser irradiation.

References
[1] Alder B and Christian R 1961 Phys. Rev. Lett. 7 367
[2] Wang C, Scandolo S, and Car R 2006 Phys. Rev. Lett. 95 185701
[3] Bundy F, Bassett W, Weathers M, Hemley R, Mao H, and Goncharov A 1996 Carbon 34 141
[4] Grumbach M and Martin R 1996 Phys Rev. B 54 15730
[5] Correa A, Bonev S, and Galli G 2007 Proc. Natl. Acad. Sci. 103 1204
[6] Bryggo S, Henry E, Loubeyre P, Eggert J, Koenig M, Loupias B, Benuzzi-Mounaix A, and Gloahec M 2007 Nature Mat. 6 274; Bradley D, Eggert J, Hicks D, Celliers P, Moon S, Cauble R, and Collins G 2004 Phys. Rev. Lett. 93, 195506 and references therein
[7] Miyanaga M et al. 2000 Fusion Energy IFP/14
[8] Shigemori K, Ichinoe D, Irifune T, Otani K, Shiota T, Sakaiya T, and Azechi H 2007 Eur. Phys. J. D 44 301
[9] Takabe H et al. 1988 Phys. Fluids 31 2884
[10] Baker L and Hollenbach R 1972 J. Appl. Phys. 43 4669
[11] Shigemori K, Otani K, Shiota T, Azechi H, and Mima K 2006 Jap. J. Appl. Phys. 45 5A 4224
[12] Kalantar D, Bringa E, Caturla N, Colvin J, Lorenz K, Kumar M, Stolken J, Allen A, Rosolankova K, Wark J, Meyers M, Schneider M, Boehly T 2003 Rev. Sci. Instrum. 74 1929