Static compression experiments for advanced coupling techniques of laser-driven dynamic compression and precompression target

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Abstract. Coupling laser-shock and static-compression techniques allows to generate material conditions unreachable by either single-shock or static technique alone. Static compression experiments on water were performed using a precompression cell for laser-driven shock experiments. The pressure on static compression in this work was reproducively 1.3 – 2.3 times higher than in previous works and theoretical predictions. We have also performed static compression experiments using a new anvil material (Gd\textsubscript{3}Ga\textsubscript{5}O\textsubscript{12}) to apply the cell to reflected shock compression. By coupling laser-driven reflected shock compression with precompression technique, it is possible to generate higher pressure and lower temperature range.
1. Introduction
The major components of giant planets such as Neptune and Uranus are believed to be water, ammonia, and methane, and those are expected to be dense fluid at pressures ranging between 10 GPa and 600 GPa and temperatures between 2500 and 7000 K [1, 2]. The magnetic fields of such planets are produced by a dynamo sustained by convection of an electrically conducting fluid [3]. Planetary magnetic field can be attributed to reveal evolutionary histories and structures of planets [4].

Recently, laser-driven shock compression techniques coupled with the static precompression have given a great possibility to approach the internal conditions of the giant planets, which are unreachable by either static or single-shock technique alone [5-8]. It is important for this method to generate high static pressure using the precompression cell with thin and large unsupported diamond.

Combining reflected shock compression and static precompression allows to generate extreme conditions different from even the coupling technique of static and single-shock compression. The reflected shock compression is able to amplify pressure from the single-shock compression. By coupling the shock reflection with the precompression technique, it is possible to cover a broad range of $P-V-T$ space.

Static compression experiments on water were performed to increase the static precompression pressure. For laser-driven reflected shock experiments, we have also performed static compression experiments using a new anvil material (Gd$_3$Ga$_5$O$_{12}$: GGG ).

2. Static compression experiments on water
A schematic cross section of a wide-opening precompression-cell configuration for laser-driven dynamic compression experiments is shown in figure 1. Dynamic compression produces high pressures and temperatures during the time that the compression wave ( including shock wave ) is passing through the sample. Since the time scale of laser-shock compression is short, the diamond of the shock drive side should be sufficiently thin ( a few 100 $\mu$m ) in order to transmit a high pressure wave in the sample.

The area of the unsupported diamond should be also large enough so that the shock wave can propagate to the sample before side rarefaction wave erode too much the shock planarity. In this work, the thin front diamond thickness was varied between 100 and 200 $\mu$m, and the thick rear diamond thickness was between 200 and 1000 $\mu$m. We used a phosphor bronze gasket of 140 - 220 $\mu$m thickness. Tungsten carbide ( WC ) or stainless steel ( SUS ) was used as the support of diamond plates. The support in the laser incident side has an opening tapered with 40 degrees for the laser incident entrance angle and that in the other side has an opening tapered with 35 degrees for the diode laser.

![Figure 1. Configuration of a precompression cell for laser-driven dynamic compression experiments. The diamond plates are supported by tapered tungsten carbide ( WC ) or stainless steel ( SUS ). A few grains of ruby are placed in the sample chamber for pressure measurements via ruby fluorescence method.](image-url)
diagnostics. The unsupported diamond area diameter was 800 μm in both sides.

Static precompression pressure was measured via ruby-fluorescence method [10]. A few small ruby balls were placed in the sample chamber. The determination accuracy of the static pressure is ± 0.11 GPa.

Maximum pressure load, \( w \), is represented as the relation below,

\[
w = \frac{k_1 S_m t^2}{r^2},
\]

where \( S_m \) is the maximum stress achieved in the diamond which corresponds to the tensile strength of diamond, \( r \) is the unsupported radius, \( t \) is the thickness, and \( k_1 \) is a constant equal to 0.833 [11]. In our case, \( r = 400 \mu m, t = 100, 150, \) or \( 200 \mu m \). We used 2.8 GPa as the value of the \( S_m \) [12]. A typical previous work was performed with a 100, 150, 200, or 500 μm thick diamond in the rear side by Lee et al. [9]. In their case, \( r = 200 \) or 300 μm, and \( t = 100, 150, \) or 200 μm.

Experimental pressures data \( (P_{Exp}) \) divided by the predicted maximum pressure load \( w \) in equation (1) are shown in figure 2 as a function of the radius of thin diamond windows. Present and the previous experimental results are indicated by open and closed symbols, respectively. The open and closed circles, squares, and triangles show the thin diamond thicknesses of 200, 150, and 100 μm, respectively. The previous works are in agreement with the predicted pressure loads. In contrast, all our results are reproducibly 1.3 – 2.3 times pressure higher than the predicted pressure loads. This indicates that our precompression cell arrangement with large radius and thin diamonds is fairly suitable for the laser-driven dynamic compression experiments.

3. Static compression experiments using \( \text{Gd}_3\text{Ga}_5\text{O}_{12} \)

The reflected shock pressure can be high by using an incompressible material, i.e. high shock impedance ( \( \rho U_s \) ) material, as a shock anvil. GGG is one of potential anvil materials for shock reflection to achieve higher pressure because GGG is more incompressible than sapphire and diamond at high pressure [13].

![Figure 2](image-url)
We have performed static compression experiments using GGG in the rear side of the cell. The GGG anvils were oriented with their flat surfaces parallel to (111) and (100). The thicknesses of GGG along [111] and [100] axes were 2 and 0.5 mm, respectively. The mixture of 4 : 1 methanol - ethanol was used as sample. The determination accuracy of the static pressure is $\pm 0.03$ GPa. Other experimental conditions are same as described above.

GGG along [111] axis was broken reproducitively before reaching measurable pressure. In contrast, GGG [100] reached a static pressure of 0.14 GPa. These may indicate that GGG anvil cell is difficult to accept static pressure to a few GPa. Therefore, putting a GGG plate on the thick diamond may allow to generate both high static pressure and high reflected shock pressure.

4. Summary
We performed static compression experiments on water using the precompression cell. All our results are reproducitively 1.3 – 2.3 times pressure higher than the corresponding predicted pressure loads.

Static compression experiments have been performed using GGG. GGG along [111] axis was broken before reaching measurable pressure, and GGG along [100] reached a static pressure of 0.14 GPa. Taking into account these results, a possible target design to satisfy both high precompression pressure and high reflected-shock pressure is to put a GGG plate on the thick diamond.

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