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Shock Response of Diamond Crystals

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Shock Response of Diamond Crystals

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ABSTRACT

Sandia is investigating the shock response of single-crystal diamond up to several Mbar pressure in a collaborative effort with the Institute for Shock Physics (ISP) at Washington State University (WSU). This is project intended to determine (i) the usefulness of diamond as a window material for high pressure velocity interferometry measurements, (ii) the maximum stress level at which diamond remains transparent in the visible region, (iii) if a two-wave structure can be detected and analyzed, and if so, (iv) the Hugoniot elastic limit (HEL) for the [110] orientation of diamond. To this end experiments have been designed and performed, scoping the shock response in diamond in the 2-3 Mbar pressure range using conventional velocity interferometry techniques (conventional VISAR diagnostic). In order to perform more detailed and highly resolved measurements, an improved line-imaging VISAR has been developed and experiments using this technique have been designed. Prior to performing these more detailed experiments, additional scoping experiments are being performed using conventional techniques at WSU to refine the experimental design.

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Shock wave experiments are the typical method used to investigate the high-pressure equation of state (EOS) of materials. One of the principal diagnostics used in shock wave experiments is the velocity interferometer (VISAR) [1]. The diagnostic measures the Doppler shift of an accelerating surface and determines the velocity history of the surface to a high degree of accuracy. Often the measurement surface is the interface between the specimen being investigated and a transparent "window" material. The window material is useful for maintaining pressure within the specimen of interest while the VISAR measurement is being made, for minimizing the wave interactions that occur due to the presence of the surface, and for providing a means for measuring deceleration of a specimen surface where the specimen has lost material strength or undergone melt.

Currently a small number of materials have been adequately characterized for use as VISAR window materials. These materials include lithium fluoride (LiF) [2], sapphire [3,4], fused silica [3,4], PMMA [3], and z-cut quartz [5]. These window materials span a narrow range of shock impedances and usable pressures. Sapphire provides the highest shock impedance, but is limited to pressures below approximately 200 kbar [3,4]. LiF can be used to pressures approaching 2 Mbar, however it exhibits a relatively low shock impedance [2]. There is a need to identify an additional window material that exhibits a high shock impedance and can be used to pressures in the several hundred kbar to few Mbar pressure range. Diamond is such a candidate material.

The purpose of this study was to investigate the shock response of single-crystal diamond up to several Mbar pressure. In particular this project intended to determine (i) the usefulness of diamond as a window material for high pressure VISAR measurements, (ii) the maximum stress level at which the diamond remains transparent in the visible region under shock compression, (iii), if a two-wave structure can be detected and analyzed, and if so, (iv) the Hugoniot elastic limit (HEL) for the [110] orientation of diamond.

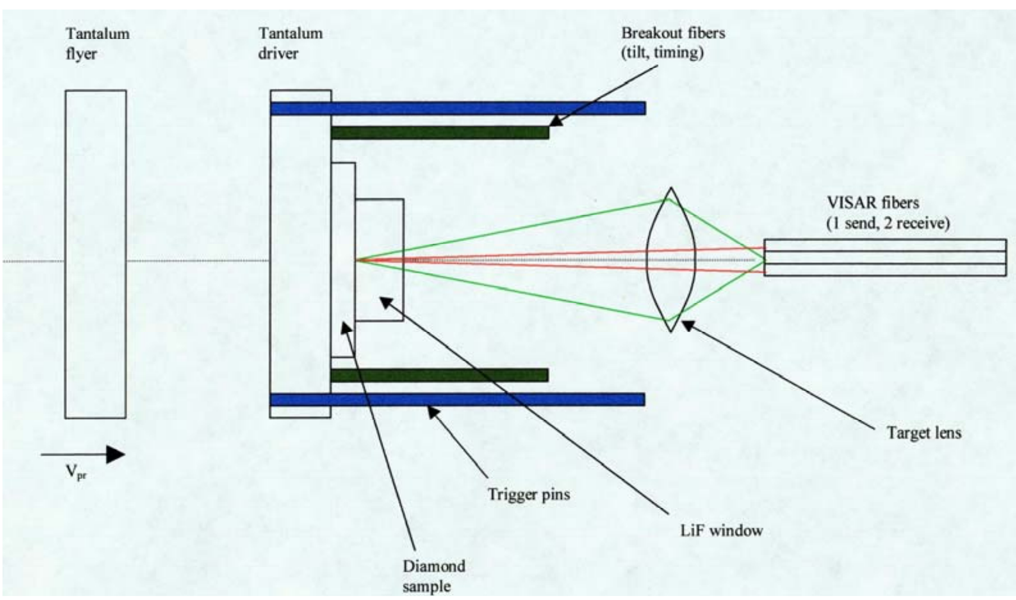

Fig. 1: Schematic of experimental design. A tantalum or platinum projectile impacts a tantalum or platinum driver plate, upon which is mounted a diamond sample and LiF window. Break out fibers are utilized to obtain timing data. The configuration shown measures particle velocity at the diamond/LiF interface.

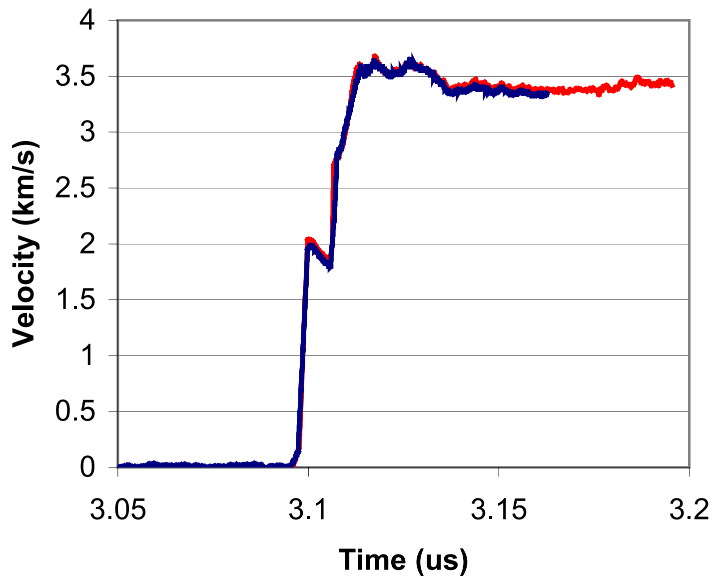

Fig. 2: Wave-profile data for diamond experiment to ~2 Mbar. The two traces correspond to two different sensitivity VISAR measurements. The kink at ~2 km/s corresponds to the HEL.

Due to the considerable expense of large single-crystal diamond specimens, little work has been done investigating the shock response of diamond. Only one study appears in the literature in which an inclined mirror technique was used to analyze the shock response of diamond shock-compressed along an orientation intermediate between the [111] and [110] crystallographic axes [6]. It was reported in this study that diamond shocked along this intermediate axis undergoes an HEL at approximately 630 kbar. However, data is ambiguous and it has been questioned as to the validity of this interpretation of the results [7].

In order to address this issue in more detail, collaborative efforts with WSU personnel yielded an experimental design that would produce instantaneous elastic stresses up to ~2-3 Mbar in diamond crystals (see figure 1). This design utilized a tantalum/tantalum projectile/driver configuration. The principal measurement apparatus was the VISAR diagnostic in place at the SNL gas gun facility. The basic questions to be addressed in these experiments were (i) can a two-wave structure be detected and analyzed, and if so, (ii) what is the HEL of diamond shocked along the crystal [110] orientation.

Two experiments were performed at the SNL gas gun facility with projectile velocities of 4.6 and 5.2 km/s, respectively. The results of these experiments are shown in figures 2 and 3. A two-wave structure was clearly seen in both of these experiments. The diamond/LiF interface is observed to undergo a rapid acceleration to a velocity of ~2 km/s, followed by a relatively slow deceleration. Subsequently, the interface is again rapidly accelerated to peak velocities of approximately 3.6 and 4.2 km/s respectively. This two-wave structure is indicative of the onset of elastic-plastic deformation, or the HEL. The first wave corresponds to an elastic wave with a peak amplitude of approximately 900-1000 kbar. This wave is followed by a second, slower plastic wave with amplitude of approximately 2 and 2.5 Mbar, respectively.

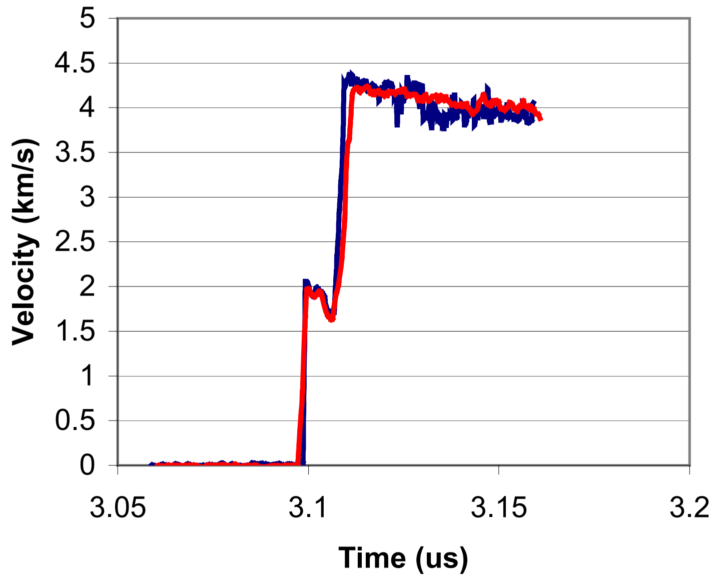

Fig. 3: Wave-profile data for diamond experiment to ~2.5 Mbar. The two traces correspond to two different sensitivity VISAR measurements. The kink at ~2 km/s corresponds to the HEL.

These experiments represent the first, definitive identification of the HEL in single crystal diamond samples. However, because of the extremely high wave speeds in diamond, the diamond samples used in these experiments were necessarily very thin and the time duration of the experiments were likewise quite short. The SNL owned VISAR diagnostics utilize amplified photo-multiplier tubes (PMTs) to record the optical signals, which have ~1-2 ns time resolution. This relatively slow time resolution was found to be inadequate to fully resolve the features of the wave profile. Therefore it was not possible to determine accurately the HEL of diamond. In order to perform more detailed and highly resolved measurements, an improvement had to be made in the VISAR diagnostic.

Two approaches were pursued. One approach was to improve the time resolution of the conventional VISAR diagnostic. WSU personnel made modifications to their VISAR diagnostic that enabled them to utilize much faster time response photodiodes, with ~100 ps temporal resolution, to record the optical signals from the VISAR diagnostic. This change increased the time resolution by nearly an order of magnitude. The second approach to improving the VISAR diagnostic was to fabricate a line-imaging VISAR diagnostic [8] at the SNL gas gun facility. This diagnostic utilizes a streak camera as the detector, and thus has extremely fast time resolution.

The line-imaging VISAR had not yet been completed at the time this report was written, thus it was decided to pursue an experimental campaign utilizing the fast photodiode VISAR at WSU and their powder gun facility. Since the WSU powder gun is limited in projectile velocity, platinum/platinum projectile/driver configurations, capable of producing peak pressures slightly over 1 Mbar in the diamond, were designed and fabricated. Experiments were to be performed in pairs having similar projectile velocities but subtle target differences that would yield both wave speed and particle velocity, elastic-plastic behavior, and measure the diamond transparency up to the maximum stress. The difference in the target for each shot in a pair is the placement of the VISAR reflector. For one target of each pair, the particle velocity measurement was to be made at the diamond/LiF window interface, to yield information about the two-wave structure and the HEL. In the second configuration, the reflecting surface is at the platinum/diamond interface. VISAR measurement from this surface would yield information about the transparency of the shocked diamond, and the wave speed. Ancillary measurements using trigger pins and/or shock break out fibers would be made for both configurations. Furthermore, within the uncertainty induced by repeatability of projectile velocity in these shot pairs, an approximately VISAR window calibration factor [2-5] for diamond could be obtained under this scheme, yielding information about the refractive index under shock compression.

An experimental campaign utilizing this configuration was to begin in Q4 of FY 01. Unfortunately, a projectile failure occurred during the first experiment, which resulted in separation of the platinum impactor from the projectile. This set back prevented any further experimentation to occur during FY 01. These experiments, as well as future experiments at the SNL gas gun facility utilizing a line-imaging VISAR, will be performed as soon as possible.

In conclusion, collaborative experiments with personnel at WSU to investigate the shock response of single-crystal diamond have begun. Initial experiments performed at the SNL gas gun facility have shown for the first time a two-wave structure upon shock compression, indicative of the HEL. These results imply that the HEL of diamond shocked along the [110] orientation is between 900-1000 kbar. Based upon these findings, it is believed that diamond could be used as a high impedance VISAR window to pressures approaching 1 Mbar. Further, more detailed experiments will be performed at both the WSU powder gun facility and the SNL gas gun facility to refine the HEL measurements, to obtain information concerning the wave speed and particle velocity, elastic-plastic behavior, the maximum stress at which diamond remains transparent under shock compression, and the refractive index under shock compression.

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