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Basic Material Properties Using Laser-Driven Shocks

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Shock waves can be induced in samples by illumination with an intense laser; pressure is generated as the target absorbs energy, and atoms are ablated from the surface to form a plasma plume. Our team is investigating the response of materials to dynamic loading using the Trident laser with *in situ* optical and x-ray diagnostics complemented by post-shot microstructural analysis.

Accurate models of the response of materials to dynamic loading are important for simulations of the performance and safety of weapons and for the design of the fuel capsule in inertial confinement fusion (ICF). These models are devised and calibrated using experiments in which samples are subjected to high pressures, usually from shock waves induced by the detonation of high explosives or the impact of flyers.[1] New classes of models are being developed that use more detailed underlying physics, such as dislocation dynamics, rather than ad hoc empirical relations to describe the response. Laser-driven materials experiments offer promising possibilities to contribute to model development, including convenient new diagnostics such as transient x-ray diffraction (TXD) to measure the response of materials at the microstructural level.

Laser-Induced Shock Experiments

Shock waves—whether induced by laser ablation or more traditional methods—can be regarded as a region of high pressure that moves through a body of material. By measuring the response as material is subjected to dynamic loading and unloading, we can understand its behavior in terms of a pressure-volume-temperature relation [often called the equation of state (EOS)], phase diagram, phase-change kinetics (including chemical reactions), plasticity, and fracture. The simplest measurement is the speed of the shock wave, from its transit time through the sample. The velocity imparted to the material by the shock is inferred from the velocity history at the surface of the sample; features in the velocity history also provide information about plasticity and phase changes.[1] We have developed and applied other diagnostics on laser experiments. TXD—applied to single crystals and polycrystalline ensembles—provides detailed information on the shock response of material at the level of the atomic lattice, including plasticity and phase changes.[2,3] Ellipsometry measures the polarization-dependent reflectivity of a surface and can be a sensitive test for phase transitions. We have recorded surface velocity and displacement in one and two spatial dimensions—with time resolution as well—to investigate the effect of a material's microstructure on shock propagation.[4,5]

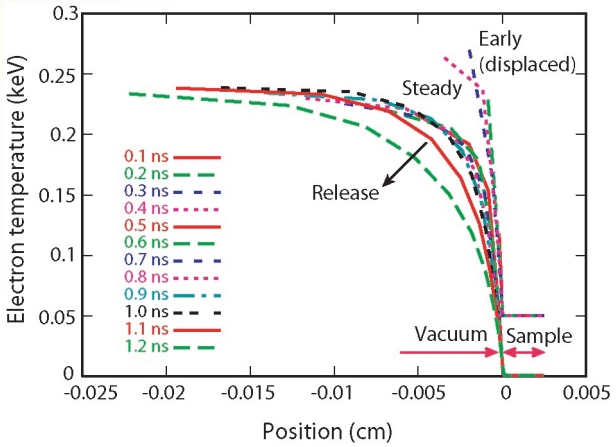

Figure 1. Profiles of electron temperature at different times during the interaction of a laser pulse 1 ns long and 1 PW/m² with an iron target 25 μm thick (right).

Laser-induced shock experiments have some disadvantages compared with traditional shock techniques. Principally, it is more difficult to ensure that the shock has a constant pressure. (Conversely, it can be easier to induce other loading histories such as multiple shocks, decaying shocks, and isentropic ramp waves.) However, using a laser to induce the initial shock wave can make it easier to apply new diagnostics, because synchronization is generally more straightforward than with shocks launched by explosives or a flyer impact. Also, compared with other techniques, it is often easier to recover shocked samples from laser experiments.[6]

Several interesting discoveries have emerged from laser-induced shock experiments on nanosecond time scales at Trident. Shocks along the ⟨100⟩ crystal directions in silicon show no evidence of plastic flow.[2] The stress at which plastic flow occurs on these time scales has been investigated for single crystals and polycrystalline foils of materials, including beryllium, iron, tantalum, nickel-titanium, nickel aluminide, and ruthenium aluminide. The results have contributed to the development of time-dependent plasticity models and of simulations with explicit treatment of the motion of dislocations.[4,7,8,9] In the rest of this article, we will review recent advances in dynamic loading by laser ablation and in TXD.

Dynamic Loading Induced by Laser Ablation

Shocks and other loading histories can be induced in samples of material by surface ablation resulting from the absorption of laser energy. At the start of the laser pulse, energy is deposited in the skin depth at the surface of the sample. Material at the surface ablates in the form of plasma; subsequent laser energy is deposited in this plasma. Reaction and the plasma itself apply pressure to the remaining material in the sample, until the laser pulse ends and the plasma cloud dissipates (Figure 1).

A laser pulse of constant irradiance does not induce a constant pressure in the sample. We see a pressure spike in the first ~ 100 ps while the ablation plasma is established, followed by a period in which the plasma profile close to the sample is roughly constant and acts as a rocket. If a constant pressure shock is desired—necessary for accurate measurements of the EOS—then we must adjust the irradiance history of the laser pulse. At Trident, optical zone plate arrays are used to distribute the laser energy uniformly over a spot on the sample. For dynamic-materials work, we have mainly used a zone plate giving a 4-mm spot. At this scale, Trident can deliver irradiances up to ~ 10 PW/m^2, inducing pressures of up to several tens of gigapascals. For laser-pulse durations around 1 ns, the sample thickness is 10 to 500 μm, so the drive is safely one dimensional over most of the area of the spot.

In nanosecond mode, the Trident laser pulse consists of 13 sequential elements each 180 ps long whose amplitude can be controlled independently. As well as being able to set the irradiance history to produce a constant pressure, we have also generated decaying shocks (analogous to the von Neumann spike or Taylor wave induced by detonation waves in chemical explosives) and isentropic compression waves (starting with a low irradiance and increasing

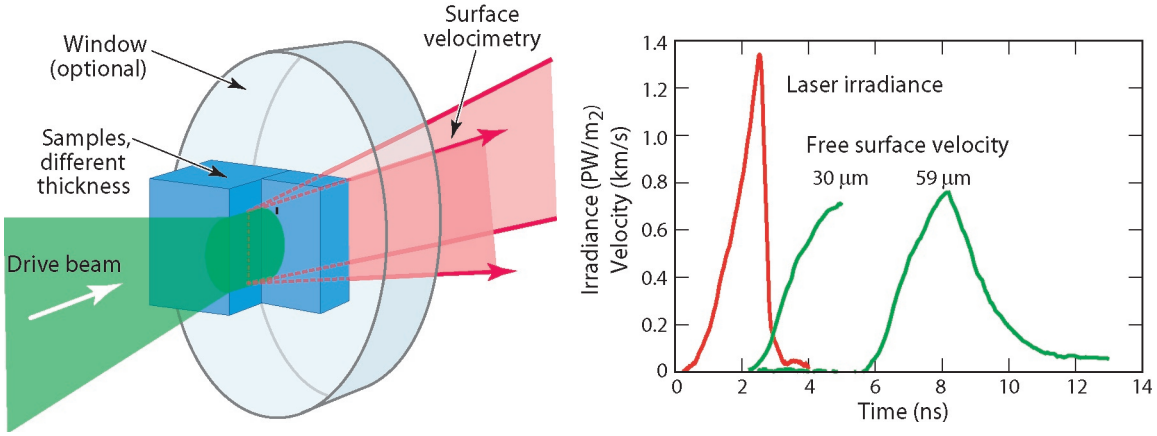

Figure 2. Schematic of side-by-side targets of different thickness used for laser-induced isentropic compression experiments (LICE) (left) and example results from Trident shot 15018 (silicon crystals) showing ramped laser pulse and smooth acceleration history at the surface of each sample (right).

gently to drive a smooth ramp wave through the sample). Isentropic compression experiments (ICE) driven by pulsed electrical power on microsecond time scales have been used to measure the EOS in beryllium and lead; we have used the laser-driven equivalent (with the unfortunate acronym of LICE) to generate ramp waves on nanosecond time scales in aluminum, silicon, iron, and tantalum (Figure 2).

Transient X-Ray Diffraction

In TXD, a source of x-rays is used to infer the state of the crystal lattice by diffraction during the passage of a shock wave. We have used a laser-generated plasma as the x-ray source by focusing a beam delivering ~ 200 J in ~ 1 ns to a spot ~ 100 μm in diameter on a foil around 10 μm thick. For titanium and manganese foils, the resulting plasma emits predominantly helium-like line radiation (i.e., from atoms stripped of all but one electron) whose wavelengths are 2.61 and 2.006 Å, respectively—useful for experiments on a variety of materials. We have recorded the diffracted x-rays with two-dimensional time-integrating detectors (x-ray film and image plates) and one-dimensional time-resolving detectors (x-ray streak cameras). The coverage in terms of solid angle is typically quite small, so usually a particular small set of diffraction lines is followed as a function of drive pressure, rather than uniquely identifying a complete diffraction pattern from each experiment.

Previously, experiments have been performed on shocks in single-crystal samples, demonstrating the onset of plasticity and solid-solid phase transformations.[2,10] We have now performed some initial TXD experiments on dynamic melting in single crystals of gallium, which we use as a convenient melt prototype because its low melting temperature (29.8°C) makes it easier to distinguish the effects of melt from plasticity and phase transitions (Figure 3). Our ultimate application is beryllium for ICF capsules, where, in addition to plasticity and a possible solid-solid phase change, melt is expected to occur at ~ 150 GPa, requiring TXD to be performed over a wide range of diffraction angles.

We have also demonstrated time-resolved diffraction from rolled polycrystalline foils of beryllium, using a collimator so that only a small region of the sample was illuminated (Figure 4). For single crystals, the position on the sample surface at which diffraction occurs moves as the lattice is compressed. Polycrystal TXD allows a greater variety of samples to be used and also makes it easier to perform experiments at higher pressure, where the single-crystal diffraction point would move too far across the surface of the sample.

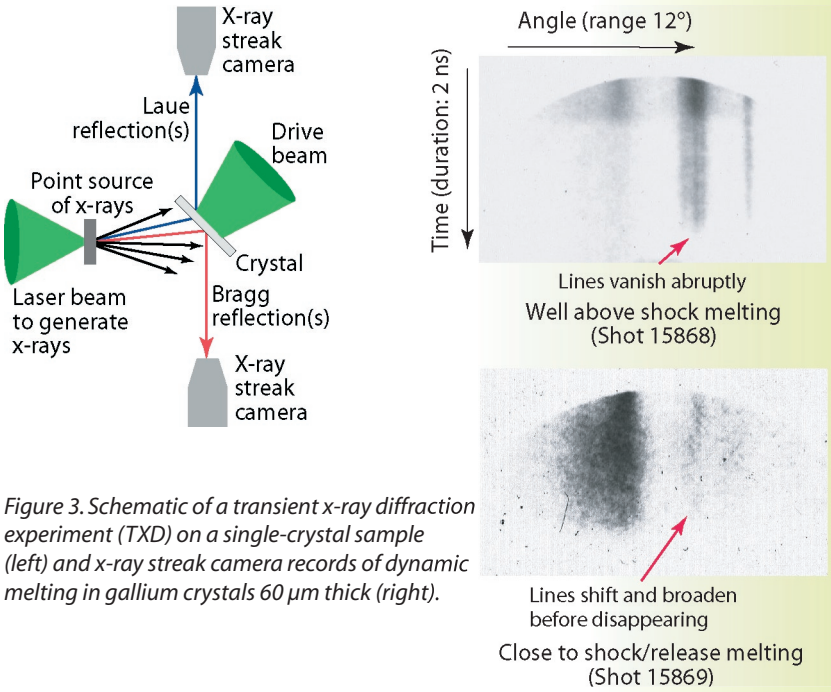

Figure 3. Schematic of a transient x-ray diffraction experiment (TXD) on a single-crystal sample (left) and x-ray streak camera records of dynamic melting in gallium crystals 60 μm thick (right).

Conclusion

Dynamic loading by laser ablation has provided valuable insights into the detailed response—plasticity and phase changes—of materials on nanosecond time scales and pressures to tens of gigapascals. This regime is important in the development of improved material models for weapons and ICF applications. The use of lasers has made it easier to develop new diagnostic techniques, providing subnanosecond temporal resolution and greater ease in synchronizing the measurement with the drive. We expect to develop these techniques further and apply them to a wider range of materials, working more closely with the development of advanced, physically based models.

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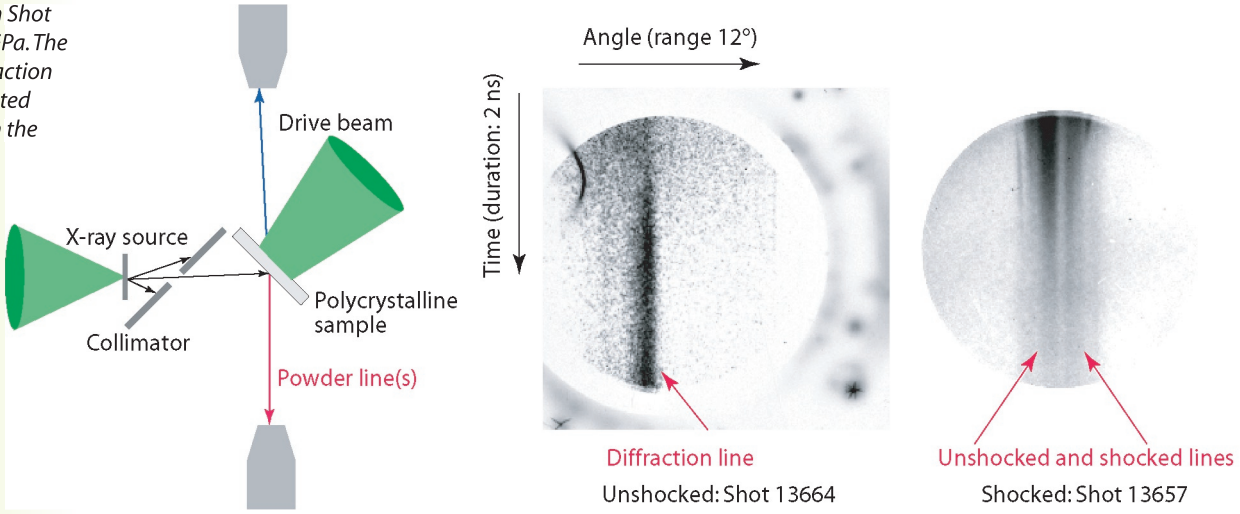

Figure 4. Schematic of transient x-ray diffraction experiment on a polycrystalline sample and x-ray streak camera data demonstrating powder lines for 125-μm-thick beryllium foils (left). The shock in Shot 13657 was ~ 20 GPa. The width of the diffraction lines was dominated by the aperture in the collimator (right).

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