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Proton Radiography: A New Window into Shock Wave Processes

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The ability to obtain direct density measurements of materials under extreme conditions of stress (>10 kbar) and strain rate (10^6 s^{-1}) for a wide range of materials has eluded researchers for decades. In the past, x-radiography has been used to directly observe phase transition waves [1] or dynamic damage processes [2], but has not been used to quantify density. Proton radiography (pRad) is a powerful new diagnostic with the potential of producing accurate (1%) direct density measurements from dynamically loaded materials. Because protons are charged particles, a lens system can be constructed using magnets to focus the protons on the target and reconstruct the image at the detectors producing images with much higher contrast and sharpness than X-rays with little or no parallax [3]. In addition, multiple images can be obtain during a single dynamic experiment. Here, we will describe experiments to quantitatively determine density in shock compressed materials by coupling proton radiography measurements with plate impact experiments. Plate impact experiments using gas and powder driven guns are well suited to investigate dynamic compression of solids because they produce well-characterized, one-dimensional loading in shocked samples [4]. To that end, we have designed and built a 40 mm powder-driven gun to launch planar flyer plates up to velocities of 1.75 km/s that can be coupled to the proton beam.

The proton beam used for these experiments is generated at the Los Alamos Neutron Science Center's (LANSCE) linear accelerator at Los Alamos National Laboratory. This accelerator operates on a 20 Hz cycle producing square pulses of protons 1 ms long. Each pulse can be further subdivided into "micropulses" 50 ns long and a minimum of 200 ns (user selectable) apart. However, since the typical system time of a powder-driven gun (from trigger signal to impact of the projectile with the target) is greater than 5ms, careful synchronization of the gun with the proton beam cycle is necessary to ensure that protons are available at the target at the time of impact. This presents a unique set of challenges to overcome to ensure success. In addition, to produce the highest quality radiographs, it is necessary to ensure that other materials are not in the beam path to scatter protons away from the target. This results in decreased contrast at the image plane and greatly complicates the relationship between proton intensity at the image plane and density of the material being investigated. Great care was taken to "suspend" the target in front of the powder gun while maintaining precise alignment of the target to the gun and proton beam axis. Figure 1 schematically shows the experimental configuration used to obtain radiographic data from shocked samples. Details of how targets were suspended will be presented.

Aluminum 6061-T6 and Oxygen Free High Conductivity (OFHC) copper were chosen for the initial experiments because of the large body of shock-wave data that exists on these two materials. Existing material models have proven effective in describing the dynamic response of both 6061-T6 Al [5, 6], and OFHC Cu [7] when subjected to one-dimensional shock-wave loading. Therefore, provided that the experiments were designed carefully and that the

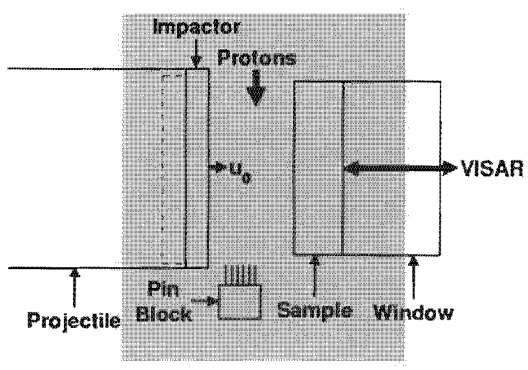

FIG. 1: Representation of the experimental configuration used. The "pin block" is used to trigger the cameras and proton micropulses as well as to measure projectile velocity

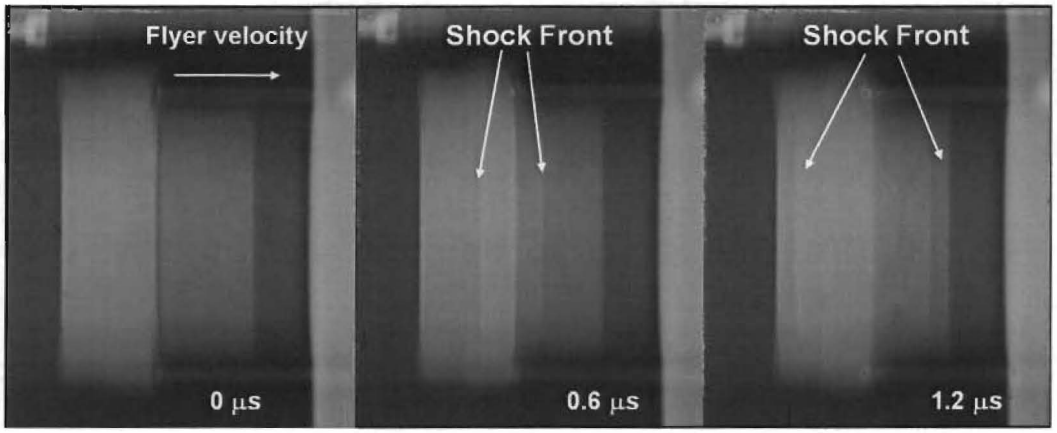

FIG. 2: Radiographs from a single dynamic experiment with aluminum impacting aluminum at 1.45 km/s. Frame 1 was taken just before impact of the projectile with the target, while frames 2 and 3 are taken after impact and show the traversal of the shock wave across the target and impactor.

projectile velocity was measured during the experiment, the final density in the shocked state could be calculated with a high degree of confidence and compared directly to the density measurements obtained from the radiographs. Figure 2 shows a sequence of radiographs obtain from an aluminum experiment and clearly shows the progression of the shock front through the target impactor. Detailed results from all experiments performed will be presented, but in all cases, agreement between measured and calculated densities behind the shock front were better than 0.5% [8]. Furthermore, since good agreement was obtained from two materials with very different starting densities we believe this technique will be applicable to a wide range of materials and the extension of this technique to examine materials that undergo phase changes under shock loading will be presented.

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