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# DIRECT MEASUREMENT OF STRAIN FIELD EVOLUTION DURING DYNAMIC DEFORMATION OF AN ENERGETIC MATERIAL

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We previously reported results showing displacement fields (at a single instant in time) on the unconfined surface of an explosive during deformation using white light speckle photography. We have now successfully obtained similar data in confined samples showing the evolution in time of the strain field using laser-induced fluorescence speckle photography. A modified data analysis technique using methods borrowed from particle image velocimetry was used in conjunction with an eight frame electronic CCD camera. For these tests, projectiles of varying shape were fired into an explosive sample. Localization of strain was observed in all cases and was found to be a strong function of the projectile shape, with ignition occurring in those cases where shear appears to play a dominant role. Results from this and continuing studies provide experimental evidence for strain localization, and for the first time allow the direct comparison to computer model predictions. The data are also being used in the design of more realistic and reliable constitutive models.

## INTRODUCTION

Optical methods have been used for many years to measure both in-plane and out-of-plane motion of materials during quasi-static and dynamic loading. These techniques include laser speckle interferometry, coherent gradient sensing, laser speckle photography, white light speckle photography, high resolution moiré photography, and digital speckle pattern interferometry, among others. Each method has its particular strengths and weaknesses, and the choice of which technique to use rests upon careful analysis of a host of issues. Among these is the nature of the material to be studied (e.g., viscoelastic or brittle), rate of deformation, magnitude of three dimensional effects, resolution required, cameras and optics available, availability of lasers and other illumination sources, computational capabilities, and analysis response time requirements.

The many applications of laser speckle photography have been well documented (1). These include the visualization of stress concentration, thermal stress development, and fracture mechanics. It is a useful technique for noncontact strain measurements and has been used extensively in metrology. However, many of these applications are used in quasistatic environments and are not suitable for dynamic measurements.

We have developed a novel technique to perform speckle photography of explosives during dynamic deformation. We are interested in such measurements because we wish to identify energy localization mechanisms which cause ignition at low- to moderate rates of deformation. These measurements are particularly difficult because the material has a low yield strength (~8-80 MPa) and

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because significant out-of-plane motion and surface disruption occurs during fracture, usually early during the deformation process. We have performed conventional white light speckle photography using coherent illumination and unconfined explosives (2) and more recently developed a technique wherein we use a coherent illumination source and the laser-induced fluorescence from a dye molecule dissolved in a portion of the surface to create the speckle pattern (3) on confined surfaces. We here report a variation of that method which increases contrast and thus improves the accuracy of the data. We have also been able to implement the technique using an eight frame CCD array which permits observation of the evolution of the deformation field.

## EXPERIMENTS

A full explanation of the method is provided elsewhere (3). A general description will be given here along with the modifications. A rectangular (10 x 25 x 5 mm) PBX 9501 sample is dipped into a solution of Rhodamine 6G dye for 10 s and then rinsed in dichloroethane. The dye is preferentially absorbed into the binder. The explosive is then placed into a steel fixture which permits observation through a 25.4 mm sapphire window on the front and illumination from the rear through the sample (see Fig. 1). We found that by back-illuminating rather than front illuminating as before, we obtained improved resolution and contrast. This configuration maintains a two dimensional confinement for the times of interest. Plungers of different radii are then placed in contact with the explosive. For these experiments we used two plungers, one of 10 mm radius and the other having a 19 mm radius.

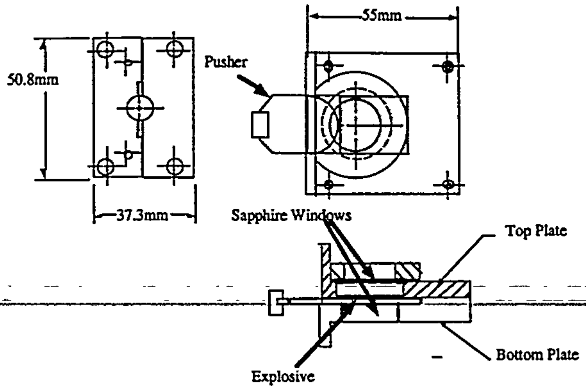


**FIGURE 1.** Confinement assembly showing explosive containment and optical access.

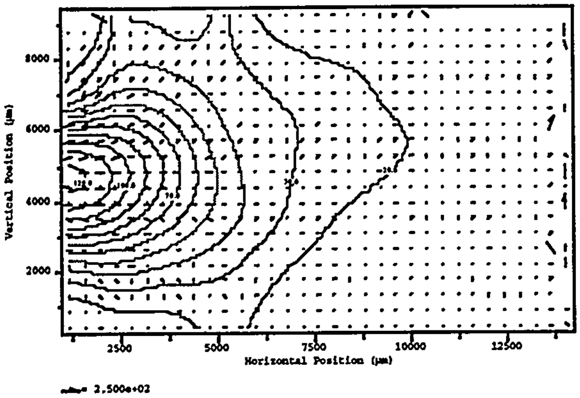
The assembly is placed at the end a gas gun and the plungers are impacted with brass projectiles having nominal velocities of 190 m/s. This introduces a reliable and reproducible strain field into the explosive. Eight (15 mJ) Nd:YAG lasers are focused into a fiberoptic taper and conducted onto the rear of the target, each at a preselected time. The resulting white light speckle pattern is then imaged with an Imacon 468, eight channel CCD camera (22 μ pixels, 586 x 385) at a magnification of 0.875. We found that the 532 blocking filter used in previous front-lit tests was not needed in the back-lit mode. Images were acquired at 3 μs intervals with exposure times determined by the laser pulse width, which is approximately 10 ns.

We previously used a modified CASI data reduction technique (3, 4). Subsequently we have been using a proprietary software package called Visiflow (AEA Technology) originally developed for use in particle image velocimetry. This software has many more capabilities than were originally available to us, and performs a wide range of analyses.

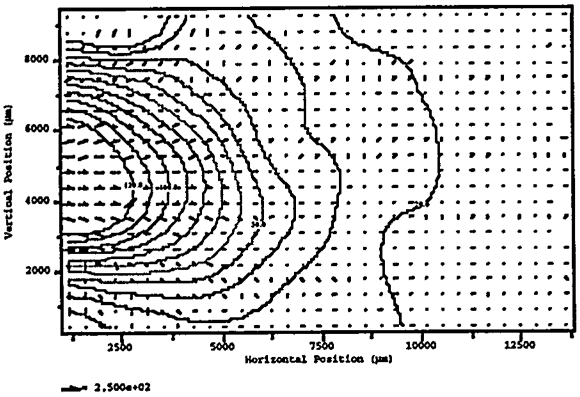
Because the CCD arrays are slightly misaligned with respect to one another, static images were analyzed along with the dynamic images, and apparent motion was removed by subtracting the one from the other. Cross correlation using 32x32 blocks with 50% overlap was used to reduce the data presented here.

## RESULTS AND DISCUSSION

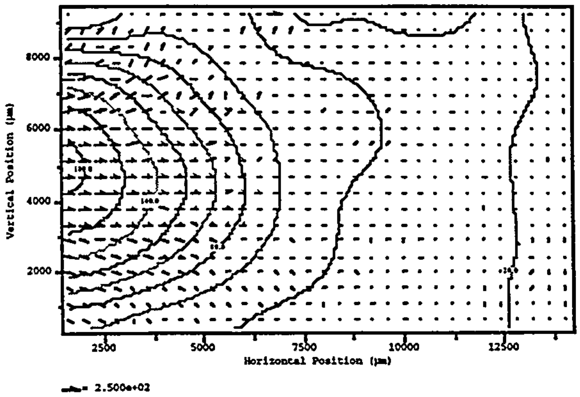
We here report a sample of the results obtained with the current method. Figure 2 shows x-component displacement vectors and contours from the experiment at three different times, 3 µs apart, using the plunger of 10 mm radius. Impact occurs at the center of the left edge. The vectors are as-measured while the contours were taken from data which were subjected to a kernel smoothing algorithm. The evolution of the displacement field is clearly demonstrated by these data. Note the change inthe contour levels in Fig. 2c.



(a)



(b)



(c)

**FIGURE 2.** Vector field with contour overlay showing displacement after impact with projectile of 10 mm radius at three successive times, 3 µs apart.

Figure 3 shows another representation of the data found in Fig. 2c. The large amount of curvature in the displacement front can be more easily seen when the two figures are compared.

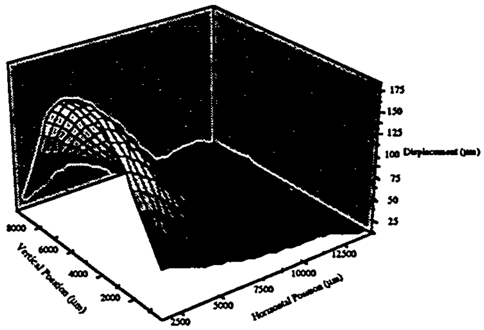


**FIGURE 3.** Surface plot showing displacement as a function of position. These data are the same as represented in Fig. 2c.

Strain localization is more easily observed by taking selected vertical slices through the displacement data. Figure 4 shows $\varepsilon_x|_y$ taken 2.005 mm from the left side of the target at four different times, 3 µs apart, after impact by the 19 mm plunger. The development of the strain with time shows a steepening of the curves which represents a localization. Such localizations can lead to shear bands and other structures which can result in high temperatures and ignition.

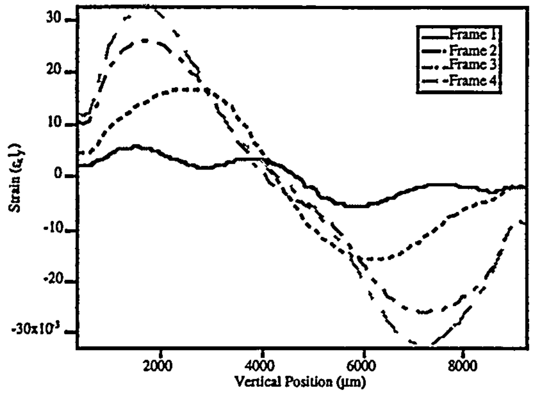


**FIGURE 4.** Strain ($\varepsilon_x|_y$) computed along a vertical slice of the displacement field 2005 µ from left edge of target after impact by plunger with 19 mm radius. Frames are 3 µs apart.

Figure 5 compares the strain field at the same location as Figure 4, but compares the results from fields resulting from impacts by the two different plungers. The plunger with the smaller radius provides a much higher level of strain in the same volume. Decreasing the radius further is expected to lead to ignition of the explosive.

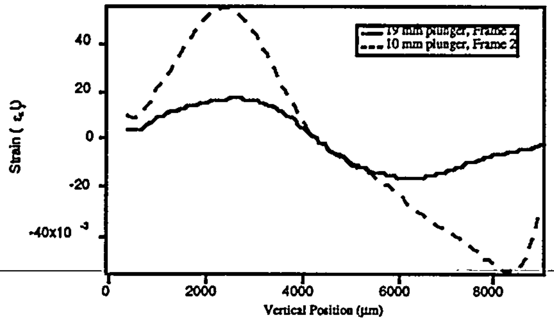


**FIGURE 5.** Comparison of strain ($\varepsilon_x|_y$) computed along a vertical slice of the displacement field 2005 µ from left edge of target after impact by plungers with 19- and 10 mm radius.

## CONCLUSIONS

Understanding the ignition of explosives by events which do not produce a strong planar shock is very important if we are to adequately address the safety of systems. This understanding cannot come without accurate and reliable models which have been fully tested against resolved dynamic data. We believe that measurements of displacement fields such as those reported in this paper, measurements of temperature fields (5), and similar studies, coupled with three dimensional computer modeling (6) will yield such an understanding. Future work in our laboratory will provide detailed measurements of shear band formation and ignition.

## ACKNOWLEDGMENTS

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