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Dynamic Measurement of the Influence of Projectile Radius and Velocity on Strain Localization During Impact of an Energetic Material

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A new technique for measuring the dynamic displacement fields during deformation has been developed. The method uses high speed laser-induced fluorescence speckle photography. We report the effect of projectile velocity and radius on the strain fields in a quasi-two dimensional confined sample of PBX 9501.

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, 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. There are two basic types of speckle photography, laser and white light speckle, which are now briefly described.

When coherent light (i.e., laser light) strikes an optically rough surface the reflected light constructively and destructively interferes, because of the unequal path lengths. When imaged, this interference gives rise to a speckle pattern formed at the image plane.¹ When viewed through a lens, the speckle size is controlled by the limiting stop of the system and the wavelength of the laser used, with optimal sizes required to obtain the highest resolution and accuracy.² The speckle pattern is a unique function of the surface structure; as the surface is displaced laterally, the speckle pattern also moves proportionally. The displacement of individual speckles is then correlated, and this relates directly to surface displacement. While out-of-plane motion changes the size of the imaged speckle, if

the motion is uniform, relatively small, and the depth of field of the optical system is sufficient, this effect is negligible.

However, if the surface is confined and the out-of-plane motion causes a fundamental change in the surface structure, then significant decorrelation results.

In conventional laser speckle photography, the speckle pattern from the undisplaced surface is first recorded on film. The surface is then deformed in the plane perpendicular to the recording axis, and another photograph is taken on the same film, creating a double exposure. Often, one translates the film or object between exposures to eliminate the ambiguity that arises in the analysis of the resultant fringes (see below). This combined image is then analyzed with a laser probe³ and either whole-field or point-wise sampled to yield fringes that result from the interference of the diffraction cones generated by the speckles. The amount of motion is inversely proportional to the fringe spacing, and the direction of motion is along the vector that lies perpendicular to the fringes. Herein lies the source of the ambiguity mentioned above; two direction vectors can be overlaid on the fringes in directions 180 degrees opposite each other. Translation between frames can resolve the ambiguity if the motion is larger than the displacement measured and the direction is known. Automatic fringe analysis has been demonstrated using translators and charge coupled device (CCD) cameras with both one dimensional and two dimensional (1-D and 2-D) fast Fourier Transform (FFT) analysis of the fringes.³⁻⁶ A CCD array can also be used to record the images (in place of film) and the entire analysis is performed digitally⁷ with submicron displacements accurately mapped. If, during deformation, the

surface structure giving rise to the speckle pattern changes, the correlation between the deformed and undeformed state will be destroyed, and no useful data are obtained. This method thus works best at relatively low total strains (<2%) and on free surfaces.

Alternatively, a surface can be painted or otherwise marked to achieve a speckle-like appearance which is independent of the surface roughness, and an incoherent source (i.e., a white light source) can be used for illumination. These artificial speckles (sometimes called "white light speckles") then serve the same purpose as laser generated speckles, and the analysis is the same. The white light speckle method is much more robust and not as sensitive to decorrelation arising from out-of-plane motion of the specimen,⁷ because changes in surface structure, whose size is on the order of the wavelength of the coherent source, have no effect on the speckle pattern itself. Measurement of strains in excess of 5% are possible⁸. However, the method is also not as accurate as the technique using laser speckles, in part because the speckle size cannot be tuned to achieve optimal resolution, and in general the white light speckles are larger than required to satisfy optimal sampling theory.⁹

Laser speckle photography has been performed in quasistatic experiments using explosives,¹⁰ and high speed measurements have been made in polymethylmethacrylate (PMMA) using spherical projectiles^{10, 11} in brittle steel using a hopkinson bar,¹² and in the measurement of dynamic crack tip displacement fields.¹³ To the best of our knowledge, neither high speed laser nor white light speckle photography has been performed elsewhere using energetic

materials. These measurements are very difficult because of the low strength (yield strength $\sim 8\text{-}80\text{ Mpa}^{14}$) and because significant out-of-plane motion and surface disruption occurs during fracture, which occurs early during the deformation process.

We have developed a novel technique to perform speckle photography of explosives during dynamic deformation using 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. We use a sapphire window to confine the observed surface to reduce three dimensional effects. This confinement made the use of conventional laser speckle methods difficult because of dynamic surface changes which occur when an object is deformed. The movement of the (relatively) soft surface across the confinement window irreversibly changes the origin of the speckle pattern, resulting in decorrelation, in the case of laser speckle, and obscuration of the painted surface during white light speckle photography. As demonstrated by this work, observation of the white light speckle pattern via laser induced fluorescence has eliminated these problems. An earlier publication¹⁵ presents the first successful implementation of this technique. We have subsequently made important modifications and improvements that will be detailed here, and we also present additional quantitative data which show the effect of projectile curvature on strain field evolution. First however, we present a general overview of the technique.

EXPERIMENTAL TECHNIQUE

White light speckle photography requires a surface with an optically resolvable structure. Typically this is accomplished by applying a light coat of paint or ink. If however, the surface is heterogeneous, a surface treatment may not be needed. PBX-9501 is a heterogeneous explosive consisting of 95 wt.% HMX (octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine) crystals (typical grain size $\sim 100\mu\text{m}$) embedded in a binder consisting of 50% estane (a polyurethane) and 50% BDNPA/F (bis (2,2-dinitropropyl) acetal/bis (2,2-dinitropropyl) formal, 50/50 wt.%). The density of the pressed compact is typically 1.89 g/cm^3 . The photographic contrast between the grains and the binder is insufficient without surface treatment. We have used both ink and paint to create the speckles, and this method works well for unconfined samples.¹⁶ However, when confinement is required, each of these materials tends to smear and disrupt correlation.

To improve the contrast, we add a solution of Rhodamine 6G/dichloroethane to the front surface of the explosive. Rhodamine 6G fluoresces from 550-590 nm when illuminated with 532 nm light. We originally used front lighting and a low pass filter to block the 532 nm light reflecting from the target. We have subsequently found that by using the dye and backlighting the contrast is improved significantly. Thus, in this case, the dye is most likely acting more as an absorbing medium. The binder is soluble in dichloroethane and thus the dye is carried preferentially into the binder component of the matrix. Illumination of the rear surface of the sample is provided by a frequency doubled, pulsed Nd:YAG laser (New Wave Research Corp., Minilase). The

pulse width is ~ 10 ns and output power ranges from 0-14 mJ. The power is adjusted by varying the delay between the lamp flash and the Q-switch, with the maximum output obtained with a delay of 240 μ s. This delay is significant as it must be incorporated into the timing of a dynamic deformation experiment. The power is relatively constant for delays from 230-250 μ s, but drops significantly outside of those limits. Thus, to insure adequate and reliable exposure, the laser is operated with a Q-switch delay of 240 μ s. The laser light is conducted to the rear of the target using a set of mirrors, and the front surface is photographed.

The data presented in this paper were all obtained with an Imacon 468 camera with eight CCD channels. A Tamarand telephoto lens with bellows attachment was used to image the target.

Deformation of the explosive was obtained by firing a projectile from a specially designed light gas gun, which has timing jitter of less than 50 μ s.¹⁷ The explosive target was confined in a steel assembly equipped with a sapphire window, 6.35 mm thick (see Figure 1).

Sapphire was used because of its strength and also because of its transmissivity in the 3-10 μ m region. Simultaneous IR temperature measurements were made that are being reported elsewhere. The brass projectile (velocity ~ 195 m/s) from the gas gun impacted a steel pusher which was in contact with the explosive. Pushers of different radii were used to produce variable strain fields. The reaction products and debris were contained by enclosing the target assembly in an aluminum box. The entire experimental configuration is depicted in Figure 2.

FIGURE 1. SCHEMATIC OF TARGET ASSEMBLY

FIGURE 2. SCHEMATIC OF EXPERIMENTAL CONFIGURATION

We conducted tests using pushers with front surfaces machined to 10- and 19 mm radius, as well as one that was flat. Nominal velocities of 196 m/s were used in experiments with each of these, and the pusher having 10 mm radius was also fired at 157 m/s. A full treatment of all the data is beyond the scope of this paper. The major utility of data of this type, is that they can be used to compare with finite element calculations and assist in the creation of materials models.¹⁸ Examples of the kinds of information that are available with this technique are provided here.

DATA ANALYSIS

During deformation of the explosive, images of the target were acquired at prescribed times. Typically eight frames were obtained. The images were then analyzed using the commercial software package Visiflow (AEA Technology, Oxfordshire, UK), using cross correlation between the static and dynamic images. The software was written specifically for particle image velocimetry applications, however, it works well with speckle photography as well, as would be expected. The analysis results in a series of vectors, each representing the two dimensional cumulative displacement at preselected locations.

The displacement information is useful in its own right, in that it can be used to compare with finite element computer models that are calculating the deformation history of explosives¹⁸. However, further analysis can also be done to provide information regarding the localization of strain which can lead to initiation of the explosive.

Strain is defined as

$$\begin{aligned}\epsilon_x &= \frac{du(x,y)}{dx} \\ \epsilon_y &= \frac{dv(x,y)}{dy} \\ \epsilon_{x,y} &= \frac{1}{2} \left[\left(\frac{du}{dy} \right) + \left(\frac{dv}{dx} \right) \right]\end{aligned}\quad (1)$$

where $u(x,y)$ and $v(x,y)$ are x and y components of the displacements respectively. The volumetric and effective shear strains are defined as

$$\begin{aligned}\epsilon_v &= \epsilon_x + \epsilon_y \\ \gamma &= \sqrt{2[\epsilon_x^2 + \epsilon_y^2 + 2\epsilon_{xy}^2]}\end{aligned}\quad (2)$$

The volumetric strain comprises the dilatation of the process at each point while the effective shear strain measures the overall shape change. In pure shear, the volumetric strain will be zero.

Each of the above values was calculated for each test. This results in a large amount of data which can be analyzed and used to track specific behavior. One problem results from the fact that strain is calculated from the derivative of the displacement data. Taking derivatives of experimental data necessarily results in additional noise, beyond that which naturally occurs. The raw displacement data were smoothed using a kernel algorithm. The strain data that are presented had no further smoothing performed.

RESULTS

Two examples of the data are shown below. Figure 3 shows a surface plot of displacement for one of the experiments which used the 10 mm pusher, and Fig 4 is the corresponding shear strain surface. Impact occurred at the left of each figure. Positive displacements are seen, with the maximum in this case of approximately 400 μm , and a good degree of symmetry was obtained. The shear strain ranges from near zero to approximately 0.15 near the center of the field. These data were acquired 35.5 μs after impact. A total number of eight frames of data covering the times from 30.5 μs to 41 μs was acquired, and the temporal evolution of each of these quantities can be observed.

FIGURE 3. DISPLACEMENT SURFACE FOR 10 MM RADIUS PUSHER, 35.5 μ s AFTER IMPACT

FIGURE 4. SHEAR STRAIN SURFACE FOR 10 MM RADUS PLUNGER 35.5 μ s AFTER IMPACT.

To facilitate comparison of material response, a slice was taken at an axial position approximately 7 mm from the impact point. The precise location varied for the different experiments because of placement differences. Also, the data using the flat pusher was taken 0.5 μ s earlier than the others. The displacement and shear strain were then plotted for each experiment. Data from all 5 experimental conditions 32 μ s after impact are presented in Figures 5 and 6, where the effects of density, velocity and pusher curvature are observed.

FIGURE 5. DISPLACEMENT IN X DIRECTION 32 μ s AFTER IMPACT.

FIGURE 6. SHEAR STRAIN PROFILES 32 μ s AFTER IMPACT.

Considering displacement at a constant velocity, the pushers having different radii show a predictable pattern, with the flow from the 10 mm pusher showing the most divergence. Comparing with finite element calculations shows that this increased divergence arises from hydrodynamic effects as well as an accumulation of damage at the pusher

face, which is much greater for the pusher having the greater curvature. Reducing the velocity predictably reduces the magnitude of displacement in the x direction, while lowering the density serves to accentuate the damage at the pusher/HE interface, and reduce the displacement in the far field.

The shear strain results also show predictable behavior, with the 10 mm pusher effecting the largest amount of shear strain and the flat pusher, the least. Lowering the density reduces the shear strain as well.

No ignition was noted in any of these experiments. Neither the bulk compression nor the shear was sufficient. However, at these velocities using blunt pushers, we have observed ignition. Thus, with higher amounts of shear strain even at the same penetration rates, temperatures exceeding those required for ignition are obtained. These experimental techniques are going to be extended to cover these regimes so that specific shear strain conditions can be examined.

Others¹⁹ using spigot intrusion tests have noted that when the density in PBX 9501 is decreased the velocity required to obtain initiation is increased. Since the primary mode of heating in these experiments is through the mechanism of shear, our results showing a decrease in shear strain with density lend support to those findings. However, much further work is required to substantiate these preliminary results.

CONCLUSIONS

We have developed a reliable method for the direct observation of displacement fields during dynamic deformation of a heterogeneous explosive. Values of volumetric and shear strain can be calculated from these data which can

then be used to dynamically quantify shear ignition mechanisms, through careful analysis utilizing finite element calculations under development.

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