LA-UR- 98-2972

Approved for public release; distribution is unlimited.

Title: MODELING THE VISCOELASTIC AND BRITTLE FRACTURE RESPONSE OF HIGH EXPLOSIVE IN AN EULERIAN HYDROCODE

CONF-980803--

Author(s): S. P. CLANCY, XCI
J. N. JOHNSON, T-1
M. W. BURKETT, XNH

Submitted to: 11TH INTERNATIONAL DETONATION SYMPOSIUM
30 AUG - 4 SEPT, 1998 SNOWMASS, CO

Los Alamos
NATIONAL LABORATORY

DISCLAIMER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

MODELING THE VISCOELASTIC AND BRITTLE FRACTURE RESPONSE OF A HIGH EXPLOSIVE IN AN EULERIAN HYDROCODE

S. P. Clancy, J. N. Johnson, and M. W. Burkett
Los Alamos National Laboratory
P. O. Box 1663
Los Alamos, NM 87545

A constitutive model that incorporates brittle-fracture-mechanics and viscoelastic material response for PBX-9501 has been developed and implemented in the two-dimensional hydrocode MESA. The hydrocode with the visco-cracking model has been applied to numerous low- rate deformation and low-speed impact events. Several low-speed impact experiments that have quantified the deformation to the explosive have been used to assess the hydrocode and model for this type of material response problem. Comparisons between MESA w/ visco-cracking model calculations and experimentally measured mechanical deformation to the explosive showed that reasonable agreement was achieved for the measured magnitude of deformation but the deformation profiles/shapes were found to be different.

INTRODUCTION

A preliminary constitutive model that incorporates brittle-fracture-mechanics and viscoelastic material response has been developed and implemented in the two-dimensional MESA[1] hydrodynamics code for studying the development of damage accumulation and localization bands within PBX-9501 high explosive. Localization band development from micro-cracking (analogous to adiabatic shear bands) can be an ignition source leading ultimately to reaction of the explosive. MESA calculations have been performed on several low-velocity (<200 m/s) deformation configurations. The simulations provided estimates of the explosive's mechanical response to the applied dynamic loading and have been compared with experiments. Also, we have plans to enhance the modeling of the structural response to predict material instabilities that could develop and lead to localization bands within the material. Ultimately, we plan to couple the explosive's deformation response with a reaction model in order to have a predictive capability for ignition resulting from cumulative damage and /or localization development.

MESA HYDROCODE

MESA is an explicit, Eulerian continuum mechanics code that is utilized to predict material deformation at elevated strain-rates. The code has been used extensively for investigating the material response in armor/anti-armor, theater missile defense, and nuclear safety problems. Some special features of MESA include a high-order advection algorithm, a material interface tracking scheme, and Van Leer monotonic advection-limiting. No significant modifications to the MESA scheme were required to accommodate the stresses provided by the generalized Maxwell model.

VISCOELASTIC-CRACKING MODEL FOR PBX-9501

The PBX-9501 plastic-bonded explosive is characterized by a shear modulus that increases monotonically with strain rate and the loss of compressive strength after strains of a few percent. Previously developed brittle-fracture mechanics models of Addessio and Johnson[2] and Dienes[3] were used to describe the brittle behavior of the explosive. Cracks are assumed to form isotropically throughout the material when the stress intensity exceeds the fracture toughness, whereas the rate of crack growth is a function of the stress intensity. A generalized Maxwell model for the deviatoric stress components was used to describe the viscoelastic behavior associated with the estane/plasticizer binder. Limited data from stress-strain measurements, Hopkinson bar tests, and ultrasonic tests for strain rates from 10^{-3} to 10^5 s^{-1} were used to assist with the development of the model parameter set for PBX-9501. However, the actual model fit extends only over three decades of strain rate (~10^2 to 10^5 s^{-1}). The rate of crack growth is a function of the stress intensity factor described by Dienes[3]. The number of nucleated cracks is assumed to be constant.

The viscoelastic-cracking model can be summarized by the following definitions and equations:

$$\dot{s}_{ij}^{(n)} = 2G_n D'_{ij} - \frac{s_{ij}^{n}}{\tau_n} - \frac{G_n}{G}\left[3\left(\frac{c}{a}\right)^2 s_{ij}\left(\frac{\dot{c}}{a}\right) + \left(\frac{c}{a}\right)^3 \dot{s}_{ij}\right] \quad (1)$$

where, s_{ij} is the total stress deviator and s_{ij}^{n} is one component of the generalized Maxwell model. The term D'_{ij} is the deviatoric deformation rate, τ_n and G_n are the relaxation time and shear modulus of the nth component of the generalized Maxwell model, respectively. Also,

$$G = \sum_{n=1}^{N} G_n , \qquad (2)$$

$$s_{ij} = \sum_{n=1}^{N} s_{ij}^{(n)} , \qquad (3)$$

and

$$\dot{s}_{ij} = \frac{2GD'_{ij} - \sum_{n=1}^{N} \frac{s_{ij}^{(n)}}{\tau_n} - 3\left(\frac{c}{a}\right)^2 s_{ij}\left(\frac{\dot{c}}{a}\right)}{\left[1 + \left(\frac{c}{a}\right)^3\right]} . \qquad (4)$$

The crack radius is c and a is a constant with dimensions of length. The crack density is related to a^{-3}. The rate of crack extension is given by the following equations and depends upon the stress intensity factor (K) and crack velocity (v_{max}):

$$\frac{\dot{c}}{a} = \frac{v_{max}}{a}\left[\left(\frac{K}{K_1}\right)^2\right]^{m/2} \text{ for } K < K' \qquad (5)$$

and

$$\frac{\dot{c}}{a} = \frac{v_{max}}{a}\left[1 - \left(\frac{K_0}{K}\right)^2\right] \text{ for } K > K'. \qquad (6)$$

The stress intensity factors have the following definitions:

$$K' = K_0\sqrt{1 + (2/m)} \qquad (7)$$

and

$$K_1 = K'(1 + m/2)^{1/m} . \qquad (8)$$

The generalized stress intensity is given by:

$$K^2 = \frac{3\pi a}{2}\left(\frac{c}{a}\right) s_{ij} s_{ij} \qquad (9)$$

or

$$K^2 = \frac{3\pi a}{2}\left(\frac{c}{a}\right)\left[s_1^2 + s_2^2 + s_3^2 + 2\left(s_4^2 + s_5^2 + s_6^2\right)\right] \qquad (10)$$

in standard Voight notation. The material parameters used to represent PBX-9501 are provided in Table I whereas Figure 1 shows the stress-strain response for PBX-9501 under uniaxial stress conditions for strain rates of 10,000, 4000, 1000, and 400 s^{-1}. (Jim should we Ref this data?)

TABLE I. MATERIAL PARAMETERS FOR PBX-9501 VISCOELASTIC-CRACKING MODEL WITH N=5.

Parameters	Values
G_1 - G_5 (units?)	944,174,521,909,688
$(1/\tau_1)$ - $(1/\tau_5)$ (μs^{-1})	0,0.00732,0.0732,0.732,2
a_0 (cm)	0.1
c_0 (cm)	0.003
V_{max} (cm/μs)	0.03
K_0 (Mbar cm$^{1/2}$), m	5×10^{-5}, 10

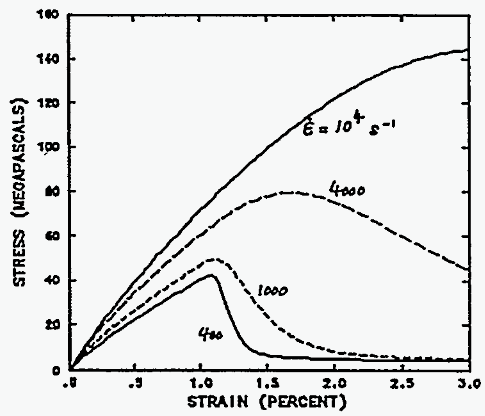

FIGURE 1 UNIAXIAL-STRESS RESPONSE FOR PBX-9501.

MESA CALCULATIONS

PBX-9501 Displacement Field Measurements/Predictions

Researchers at Los Alamos[4] have been measuring the early time deformation of PBX-9501 caused by a low-speed impact. The measurements have been made by using laser induced fluorescence to generate a speckle photographic image. Thin explosive samples were confined in a steel assembly with a sapphire window. The transparent window permits the explosive's surface to be illuminated by the laser so the displacement field can be measured at selected times during the deformation event. The experimenters controlled the deformation rate and profile by altering the velocity and shape of a projectile/plunger assembly. A brass projectile, launched from a light gas gun, was used to accelerate the plunger assembly. The average striking velocity of the projectile was approximately 200 m/s. The plunger interacted directly with the explosive. The leading edge shape of the plunger was varied to produce the different displacement field profiles.

MESA predictions of the explosive displacement field were compared with the experimental displacement field data for three plunger configurations:

- flat or infinite radius plunger
- 1.9 cm radius plunger
- 1.0 cm radius plunger

The MESA calculations were performed in Cartesian (x-y) geometry. Lagrangian tracer particles were positioned in the explosive material so displacement field predictions could be made and compared with the experimental data. Figure 2 shows the two-dimensional calculational setup (with the tracer particles in the explosive) of the experiment for the infinite radius plunger. The measured and predicted displacement field magnitudes and profiles approximately 16 μs after the projectile strikes the end of the plunger are compared in Figures 3 - 5. MESA with the viscoelastic cracking model agreed reasonably well with the measured displacement field magnitudes but did not agree with all aspects of the displacement field shapes/profiles. Specifically, comparisons between the calculations and data showed the following:

- calculations overpredicted the displacement magnitude as the depth into the explosive was increased
- the calculated displacement shapes were found to be in poor agreement with the data, especially near the edges of the plunger/explosive interface.

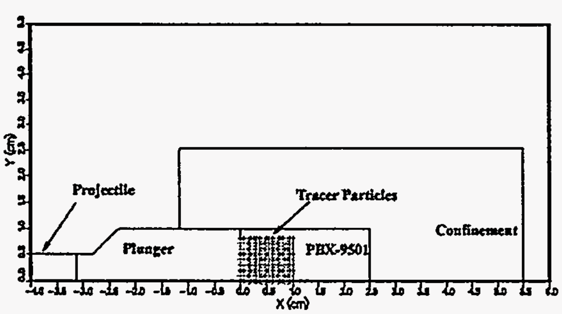

FIGURE 2 MESA INTEFACE AND TRACER PARTICLE LOCATION PLOT FOR THE INFINITE RADIUS PLUNGER.

Also, the hydrocode displacement predictions near the confined edge of the explosive were found to be sensitive to the selected spatial resolution and the material interface description at the explosive / lateral confinement interface.

Pressure-Shear Experiments/Calculations

The Army Research Laboratory (ARL) is performing tests to investigate the shear initiation of PBX-9501 under controlled pressure and loading rate conditions. Similar experiments have been performed on several different explosives of various composition[5]. This type of experiment studies the behavior of the explosive at low pressure and strain rate regimes representative of drop weight tests. Two different experimental configurations are used to investigate the ignition sensitivity of the explosive sliding against a steel surface and sliding/shearing against the explosive itself. These experiments allow a reaction/nonreaction correlation to be established for each explosive as a function of pressure and the sliding velocity.

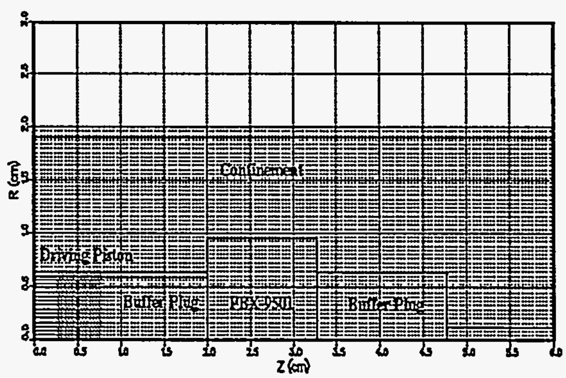

FIGURE 6 INITIAL MATERIAL INTERFACE AND VELOCITY VECTORS FOR THE MESA MODEL OF THE ARL PRESSURE-SHEAR EXPERIMENT.

The MESA calculations investigated the explosive mechanical behavior for the configuration which allows the explosive to shear and slide against itself. Only one set of pressure and sliding velocity conditions was investigated. Figure 6 shows the material locations and interfaces for the MESA calculation. The calculations provided predictions of the location and development rate of damage accumulation (crack size) within the explosive. Initially, the growth of cracks was concentrated and the interface of the buffer plug and the explosive. By ~12 μs, the explosive sample had been sufficiently loaded that cracks begin to grow on the side opposite from the location of the driving piston. Figure 7 shows a color map of the crack radius at ~30 μs.

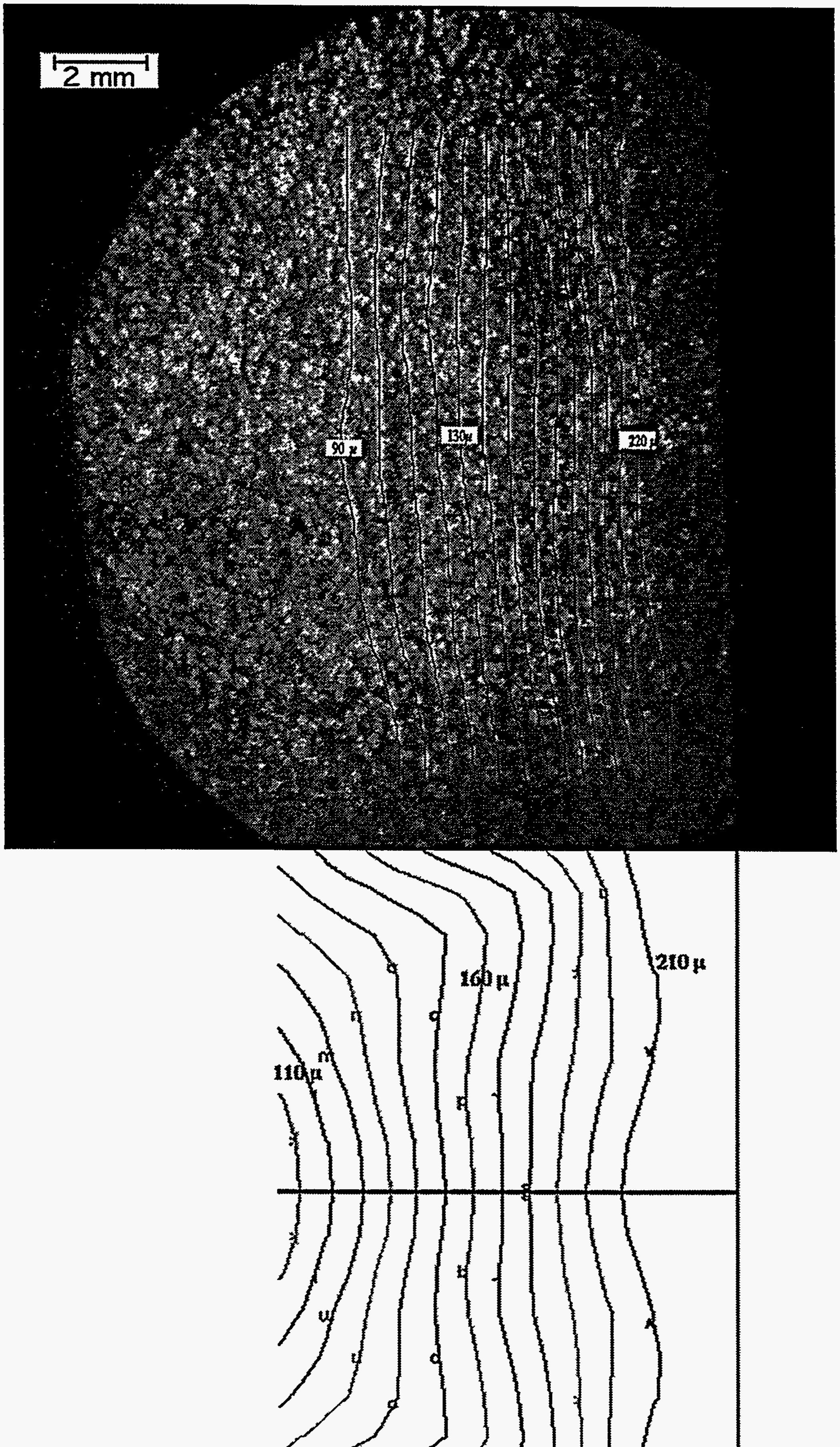

FIGURE 3 COMPARISON OF MEASURED (TOP) and CALCULATED (BOTTOM) DISPLACEMENT FIELDS FOR THE INFINITE RADIUS PLUNGER CONFIGURATION.

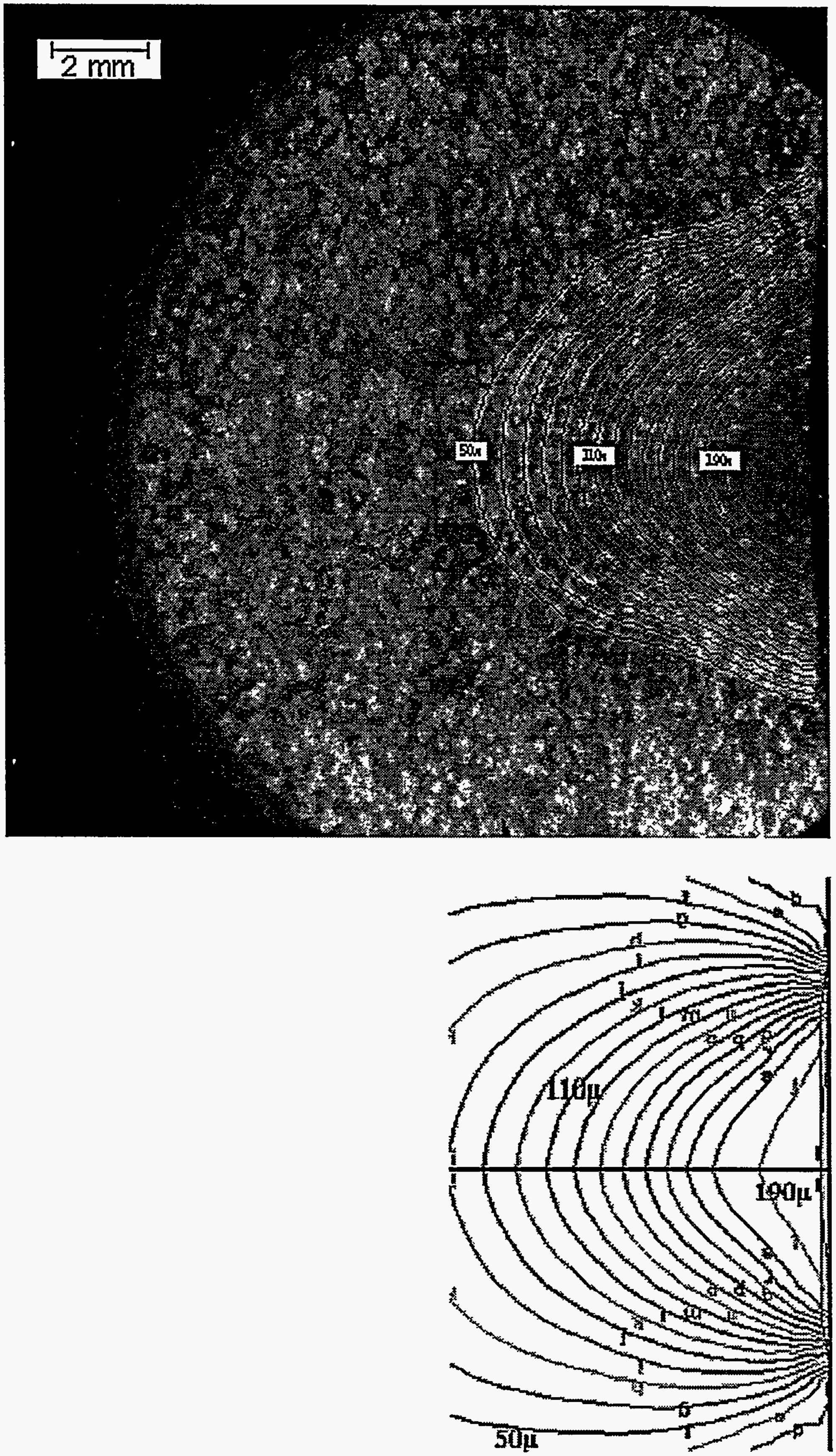

FIGURE 4 COMPARISON OF MEASURED (TOP) AND CALCULATED (BOTTOM) DISPLACEMENT FIELDS FOR THE 19mm RADIUS PLUNGER CONFIGURATION.

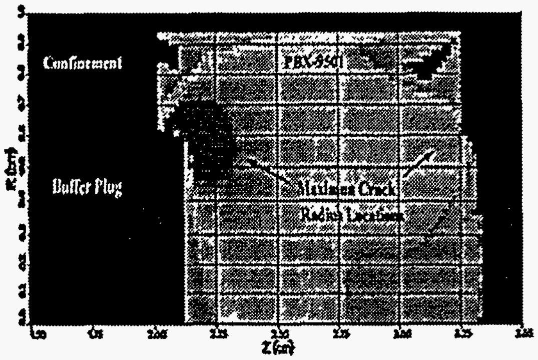

FIGURE 7 NONDIMENSIONAL CRACK RADIUS COLOR PALETTE FOR THE MESA CALCULATION OF THE ARL PRESSURE -SHEAR EXPERIMENT AT ~30 μs. MAXIMUM CRACK RADII ARE CONCENTRATED AT THE EXPLOSIVE/BUFFER PLUG AND BUFFER PLUG/CONFINEMENT BOUNDARIES ON BOTH SIDES OF THE SAMPLE.

The larger crack dimensions are concentrated at the corners of the explosive/buffer plug/confinement interface boundary where the explosive has begun to shear. The velocity field shows that the location of the shear plane is along the explosive/confinement interface (Fig. 8).

The results from these experiments and calculations could provide a methodology for incorporating a shear-to-reaction transition technique within MESA that can be coupled with our current high-explosive reaction models.

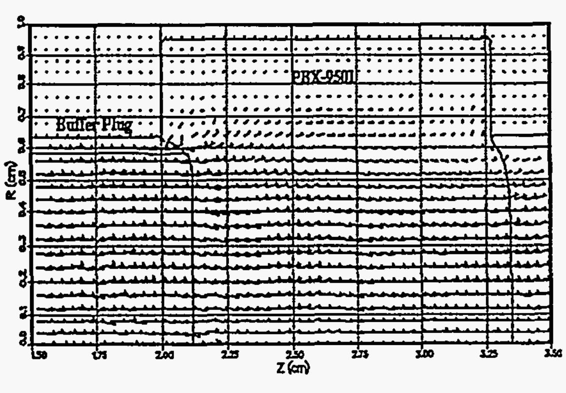

FIGURE 8 VELOCITY VECTORS FOR THE MESA CALCULATION OF THE ARL PRESSURE-SHEAR EXPERIMENT AT ~30 μs SHOWING THE SHEAR PLANE THAT HAS DEVELOPED WITHIN THE EXPLOSIVE.

Localization Band Formation

Two-dimensional, axisymmetric MESA calculations were performed on PBX-9501 in an compression loading configuration similar to the O'Donnell and Woodard instability compression experiments performed on aluminum[6]. In this type of experiment, cylindrical samples were compressed in a drop-weight apparatus where an impactor strikes the top surface of a specimen supported by a rigid base. For aluminum specimens, this configuration leads to the development of shear bands along slip planes in the cylinders.

In the previously discussed MESA calculations, we were interested in determining the explosive's structural response or the location and extent of damage that could lead to a localization type of band development depending upon the specified loading conditions. For the dynamic compression calculations, we attempted to investigate the material response with the viscoelastic cracking model and a crack radius cutoff assumption that promoted the development of localization bands instead of regions of global damage. When the crack radius reached a selected value based upon the computational cell size, the deviatoric stresses predicted by the viscoelastic cracking model were set to zero to enhance crack radius growth localization. The predicted crack radius distributions results for a MESA calculation with uniform cell dimensions of 0.05 cm and a impactor velocity of 0.0005 cm/s are provided in Figure 9.

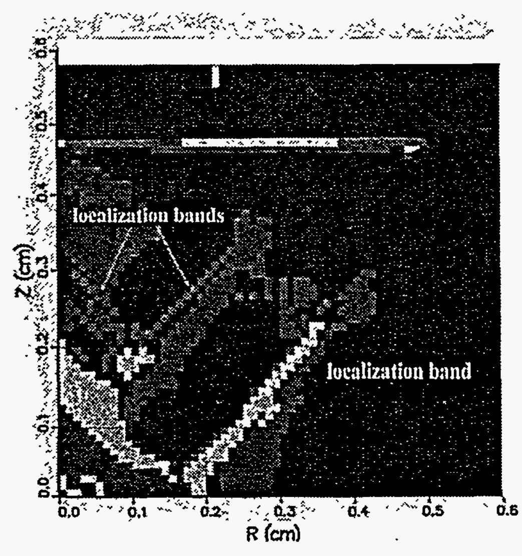

FIGURE 9 NONDIMENSIONAL CRACK RADIUS COLOR PALETTE FOR THE MESA CALCULATION OF THE COMPRESSION EXPERIMENT SHOWING THE DEVELOPMENT OF DAMAGE LOCALIZATION WITHIN THE EXPLOSIVE.

The hydrocode predicted that planes of localized crack growth would develop in the PBX-9501 under the selected crack radius cutoff assumptions. In the future we plan to implement a two-dimensional instability routine[7] so we can utilize a physically based criterion for the development of instabilities that might occur within the explosive.

SUMMARY

A preliminary constitutive model that incorporates brittle-fracture-mechanics and viscoelastic material response was developed and implemented in the two-dimensional MESA hydrodynamics code for studying the development of damage accumulation and localization bands within PBX-9501 high explosive under several dynamic deformation conditions. The simulations provided estimates of the explosive's mechanical response to the applied dynamic loading and have been compared with experiments. Comparisons between calculations and experimentally measured mechanical deformation to the explosive showed that reasonable agreement was achieved for the measured magnitude of deformation but the deformation profiles/shapes were found to be different. In calculations of material shearing under controlled pressure and sliding velocities, predictions of damage location and development in the explosive due to the growth in crack dimensions were made. Finally, we showed that planes of crack localization could develop under a crack radius cutoff assumption (based upon the calculated crack and computational cell size) for a dynamic compression experiment. In the near future we plan to enhance the structural response calculations so we can predict instabilities that could develop and lead to localization band development. A physically based material instability model will be implemented. Ultimately, we plan to couple the explosive's deformation/instability response with a reaction model in order to have a predictive capability for ignition resulting from cumulative damage and/or localization development.

REFERENCES

1. K. S. Holian, D. A. Mandell, T. F. Adams, F. L. Addessio, J. R. Baumgardner, and S. J. Mosso, "MESA: Computer Code for Armor/Anti-Armor Applications," *Supercomputing World Conference*, San Francisco, Ca, Oct. 17-20,1989.

2. *J. Appl. Phys.*,67,3275 (1990).

3. *Mech. Mater.*,4,325 (1985).

4. Blaine. W Asay, Gary W. Laabs, Bryan F. Henson, and David J. Funk, "Speckle Photography During Dynamic Impact of an Energetic Material Using Laser Induced Fluorescence," submitted to *Journal of Applied Physics*, January 1997.

5. R. B. Frey, "The Initiation of Explosive Charges By Rapid Shear," *Proceedings of the Seventh Symposium (International) of Detonation*, NSWC MP 82-334, Naval Surface Weapons Center, 1981.

6. R. G. O'Donnell and R. L. Woodard, "Instability during High Strain Rate Compression of 2024 T351 Aluminum," *Journal of Materials Science*, 23, 3578-3587 (1988).

7. H. L. Schreyer and M. K. Neilsen, "Analytical and Numerical Tests for Loss of Material Stability," *Intl. J. Num. Meth. Engin.*, 39, 1721-1736 (1996).

ACKNOWLEDGMENTS

The hydrocode applications portion of this work was supported under the Department of Energy Explosives Technology program at Los Alamos National Laboratory, Philip Howe, program manager. The constitutive model development and the displacement field experiemnts was supported by the Department of Defense/Office of Munitions under the Joint DOE/DoD Munitions Technology Development Program at Los Alamos National Laboratory, Joe Repa, program manager and Blaine Asay, project leader.