Strain field formation in plastic bonded explosives under compressional punch loading

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An inert simulant for one type of explosive formulation was subjected to low rate compressional punch deformation to determine the presence of potential strain initiation mechanisms. The presence of certain types of strain initiation mechanisms may lead to unintentional ignition in some explosive formulations. Laser induced fluorescence speckle photography was used to determine the magnitude and direction of the developing strain field during testing. Post-test SEM analyses was used to determine damage mechanisms occurring within the material. The magnitude and direction of the plastic flow lines show that a dead zone forms in the strain field immediately under the punch in agreement with Prandtl's slip-line solution of the punch problem. However, material flow patterns diverge from Prandtl's solution for other regions. Large shear strains also occur in the specimen, leading to the formation of slip bands in the hard phase constituent.

1. Introduction

PBX 9501 is a viscoelastic-plastic, granular composite material composed of high explosive granules packed in a combination of binder and a eutectic mixture of nitro-plasticizer (95 wt% HMX, 2.5 wt% Estane 5703, 2.5 wt% BDNPA/BDNPF, 0.1 wt% irganox). Mechanical stimuli, coupled with and without other stimuli, may lead to a rapid reaction or detonation of PBX 9501 [1–4]. However, the mechanisms that lead to these reactions are not well understood. High strain rate studies have shown that several factors could play a part in the formation of localized hot spots in these materials, including plastic flow, shear banding, void collapse, and particle fracture. However, relatively little work has been completed evaluating the damage that occurs in composite explosive materials at low strain rates (10^{-5} to 10^{-1} s^{-1}). Several of the same factors could contribute to hot spot formation at these low rates. For instance, if plastic flow is the operative ignition mechanism in PBX 9501, the source could lie in localized areas of relatively higher strain rates in the material during loading. In examining possible loading scenarios, the localized strains across the full field of the specimen must be understood.

One such loading scenario is that of a rigid object slowly penetrating the energetic material. In 1920 Prandtl first proposed a solution to the strain distribution on a semi-infinite, viscoelastic-perfectly plastic body during impact and penetration by a rigid flat punch [5]. Prandtl's proposed slip-line solution suggested that during low rate punch intrusion the highest strain rates occur at the boundaries of a triangular "dead zone" region directly beneath the punch. According to Prandtl's theory (see Fig. 1), the material in this area moves at the same velocity (V), and in the same direction as the punch itself. Material just outside of the dead zone flows along circular arcs extending from the sides of the dead zone to the free surface of the specimen at a velocity of 0.707 V in all directions (Fig. 1). Based on Prandtl's solution, the region of flow in an energetic material with the highest probability for the formation of hot spots occurs directly beneath the intruding punch, where the highest material velocity gradients occur.

Hill later suggested that the velocity field in Prandtl's solution was indeterminate. Instead he proposed a solution involving two separate parabolic slip-line areas extending outward in all directions from the center of the punch. Hill's solution also did not require the formation of a dead zone (Fig. 2). The resulting material flow pattern then requires flow rates twice as high as Prandtl's proposed solution (1.414V) to the sides of the punch [6]. If Hill's solution is assumed to be correct, the area of highest strain rate exists just to the sides of the punch where the plastic flow transitions to a higher velocity than the initial punch velocity.

Depending on the assumptions, finite element codes and numerical solutions by other authors have suggested the possible validity of both solutions. Various

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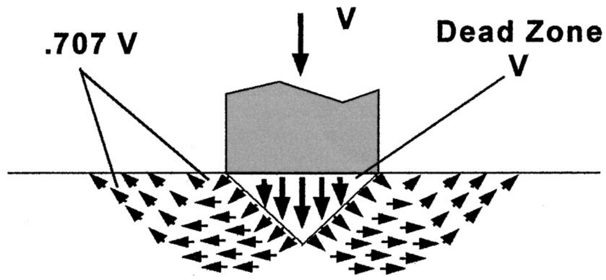

Figure 1 Prandtl's proposed slip-line solution for the flow field in a viscoelastic-perfectly plastic material during rigid punch penetration.

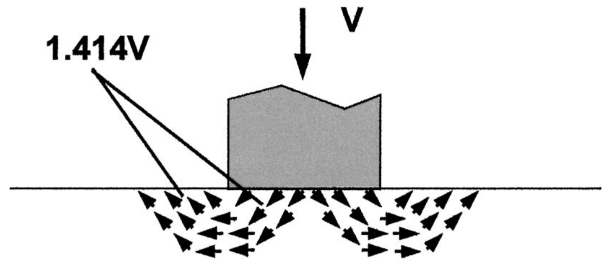

Figure 2 Hill's proposed double slip-line solution for the material flow field during punch penetration.

solutions have suggested the geometry of the velocity field is highly dependent on material properties and punch interface conditions [7–13]. Punch experiments have been performed by Sylwestrowics [13] using sand, soil and clay as the penetrated plastic body. The resulting velocity fields were similar to Hill's solution but elongated laterally as predicted by Shield [9]. However, no definitive results have yet been given for materials such as PBX 9501.

2. Experimental

To simulate punch loading for this work, a steel cell was machined to confine a 25.4 -mm by 15.85 -mm by 6.35 -mm specimen on three sides and the bottom. A sapphire window provided confinement for the fourth side as shown in Fig. 3. A tool steel punch (6.35 mm by 6.35 mm) provides penetration from the top of the specimen at a rate of 2.54 mm/minute (strain rate = 0.007 Hz) for 20 seconds (maximum strain of 0.14 strain/strain) using an Instron testing machine. The top of the specimen is otherwise open. Laser induced fluorescent speckle photography (LISP) was used to map the strain field during punch deformation of the specimen [14, 15]. Specimens were pre-soaked for 30 seconds in a Rhodamine 6G dye/dichloroethane solution. The dye dissolves only into the Estane constituent of the binder in PBX 9501 and fluoresces with absorption of 532 nm light, producing a speckled fluorescent pattern on the surface of the specimen. Specimens were then rinsed in methanol to remove any unattached dye. A Class 4 Nd : YAG laser, doubled to 532 nm, and Q-switched at 10 Hz, was used to excite the fluorescent mechanisms in the dye during the test. Digital images of the specimens were acquired at 1 Hz using a Kodak MegaPlus 4.2 digital camera interfaced to a Sun SPARC 20 during the punch deformation. A computer algorithm, written at Los Alamos National Laboratory, subdivides each image into 64 sub-images with 50% overlap. Each sub-image is then compared with the corresponding sub-image from the previous time frame by calculating the cross-correlation of the fluorescent pattern to determine motion between frames [16]. The magnitude and direction of the resulting velocity are then determined.

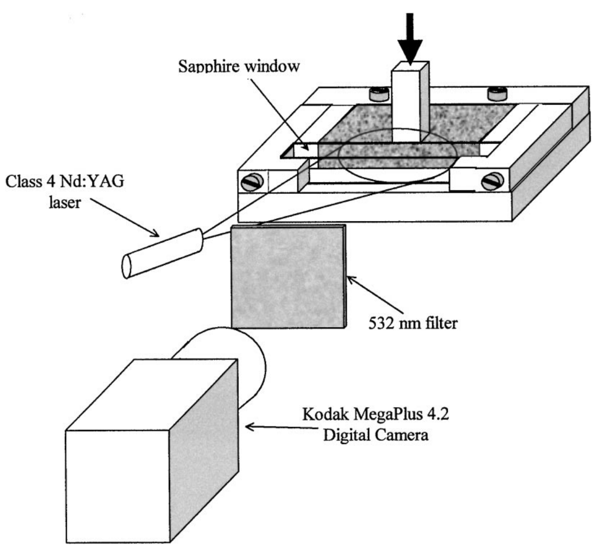

Figure 3 Tool steel confinement cell with LISP setup.

To avoid the inherent hazards associated with testing of explosives, sugar mock 9501 was used for this test. Sugar mock 9501, a volumetric match to the constituents of PBX 9501 with the hard phase explosive component replaced with inert granulated sugar, closely resembles PBX 9501 in morphology and mechanical behavior [17]. Fig. 4 shows a scanning electron micrograph (SEM) of an undamaged piece of mock explosive containing large hard phase sugar particles surrounded by soft phase binder.

3. Results and discussion

A series of 20 images was taken at one-second intervals as part of the experiment. Fig. 5 shows the 8th picture in the series, occurring 8 seconds into the test. Viscoelastic-plastic flow has occurred within the sugar mock PBX 9501 during punch penetration. The magnitude and direction of the current flow is represented by vectors, which are overlaid on the original image. An obvious triangular dead zone fully forms in the material after minimal punch penetration (0.3454 mm, 5% strain, 8 seconds). This dead zone continues to move through the material at a velocity equal to the punch throughout the remainder of the test.

After 0.5181 mm of deformation (8% strain, 12 seconds), the dead zone is completely formed (Fig. 6). This zone is in agreement with Prandtl's flow prediction for a rigid flat punch penetrating a semi-infinite elastic perfectly plastic material. To the sides of the dead zone are transition zones where the displacement field in the material changes from a downward direction to a direction perpendicular to the punch. However, there is no evidence of flow in these areas back to the surface of the specimen. Back flow does occur, but in regions approximately one punch width to the side of the punch. These characteristics diverge from both Prandtl's and Hill's solutions.

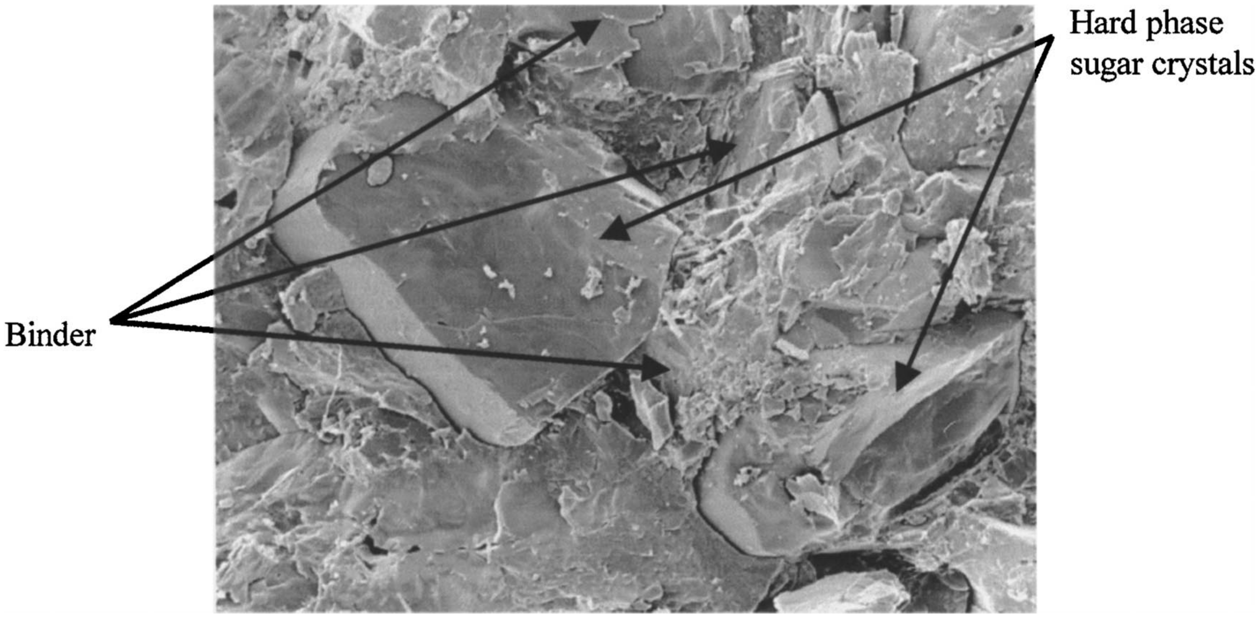

Figure 4 SEM of undamaged sugar mock explosive 9501 (200×).

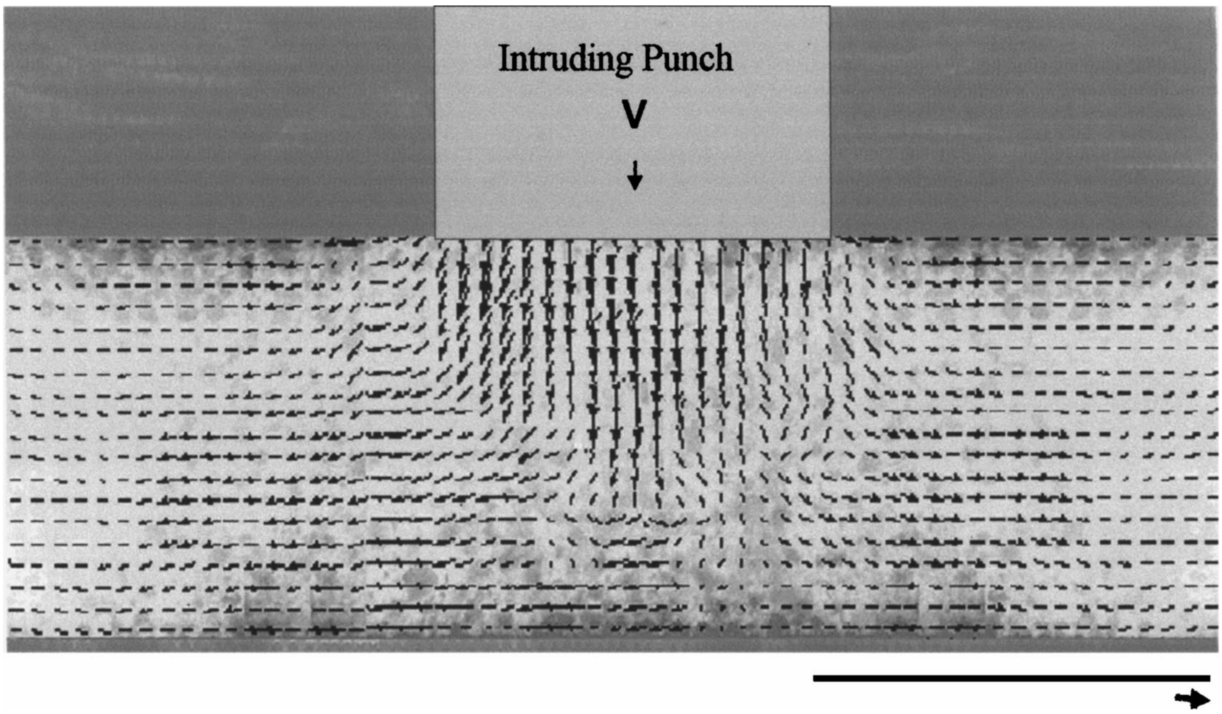

Figure 5 Overlay of test image with the velocity field from the speckle photographic results after 8 seconds (0.0136 inches of deformation). Bar = 0.25 inches. Arrow = 0.0423 mm/sec.

Differences in the displacement geometry from Prandtl's profile could arise from the steel confinement. The experimentally measured back flow phenomena could be caused solely by the interaction of the material flow with these rigid supports. However, the confinement is 1.5 punch widths to the side of the punch, whereas back flow begins only one punch width to the side of the specimen.

The accuracy and sensitivity of speckle photographic techniques are directly linked to the speckle size that can be resolved by the imaging system [18]. For the camera system used in this study, the maximum resolution is 9 μm. Additional differences between current LISP results and those suggested by Prandtl or Hill could occur due to the interface between the mock explosive and the sapphire window. The sapphire window necessarily provides a more rigid support than the distant steel confinement in order to prevent out of plane motion and resulting speckle decorrelation. More rigid confinement in one direction would result in a slight increase in the magnitude of the material flow rate in all other directions.

SEMs were taken from within the damaged region under the punch to determine the extent of the plastic flow and damage that occurred in the material. To avoid effects from added fracture stresses and possible contact distortions to the material as it pushed against the sapphire, the mock explosive was cooled in liquid nitrogen and fractured to provide information on the damage mechanisms occurring within the specimen.

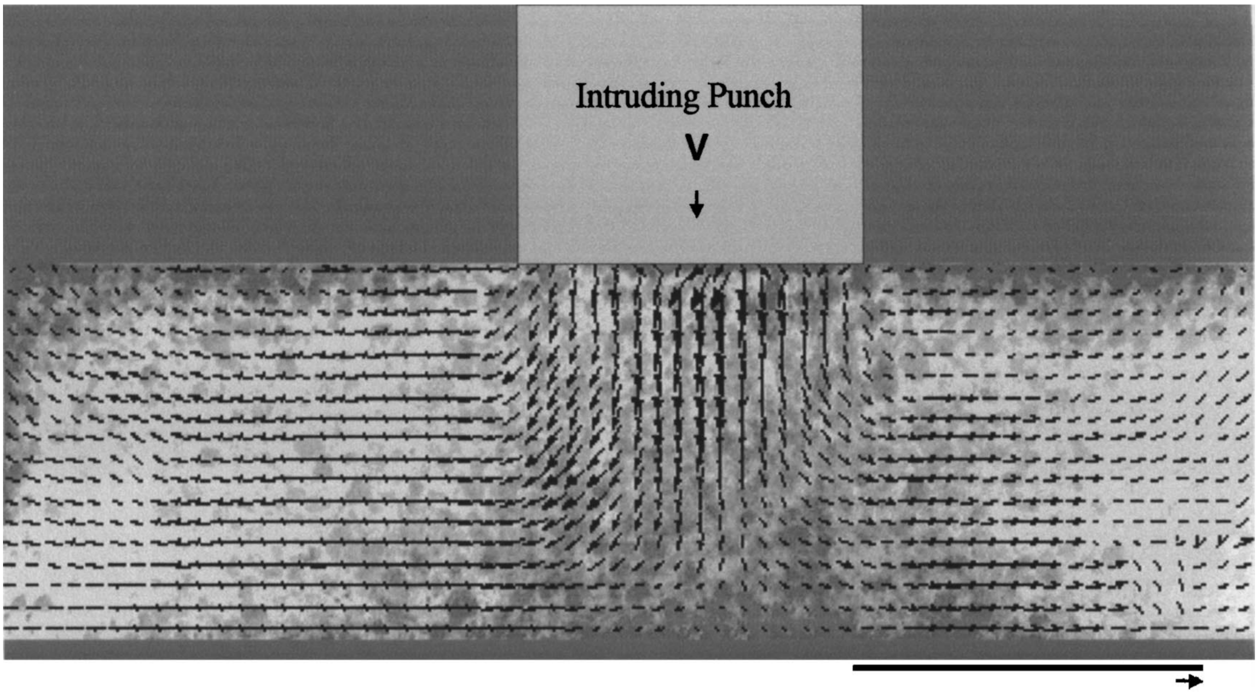

Figure 6 Overlay of test image with the velocity field from the speckle photographic results after 8 seconds (0.0136 inches of deformation). Bar = 0.25 inches. Arrow = 0.0423 mm/sec.

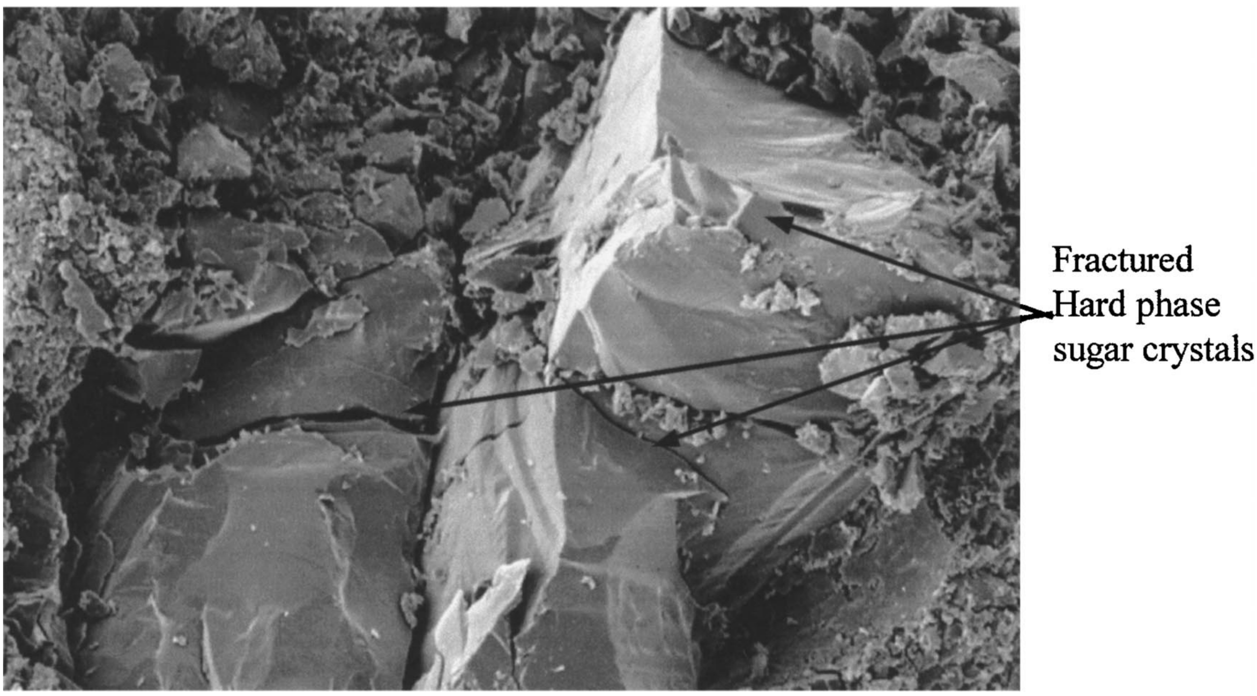

Figure 7 SEM micrograph (200×) of damaged sugar mock 9501 showing fractured hard phase sugar crystals.

One such region is shown in Fig. 7. In these regions hard phase sugar granules have migrated together and the binder has flowed under compressive loading [19]. No debonding is seen between the hard phase granules and soft phase composite binder. During loading, however, stresses have been produced within the material with magnitudes high enough to cause brittle fracture of the hard phase. As no evidence can be found of Hill's higher velocity regions, these high strains cannot be linked to magnified plastic flow in localized areas.

In the Prandtl punch damage scenario, the shear strain rates should be low enough to avoid problems related to shear band formation as the flow gradually transitions from the vertical punch direction to horizontal side flow. However, samples of the sugar mock 9501 from the areas of highest shear strain, directly to the side of the intruding punch, show evidence of shear banding in the hard phase sugar (Fig. 8). Although volumetric strain rates are small at these low punch velocities, the presence of shear bands suggests that large shear stresses occur within regions of the specimen during punch penetration. Highest shear strain rates occur immediately to the sides of the intruding punch where flow velocity gradients are maximized as shown in Figs 5 and 6. Further examination of the other regions of the post test specimen revealed no evidence of shear banding outside

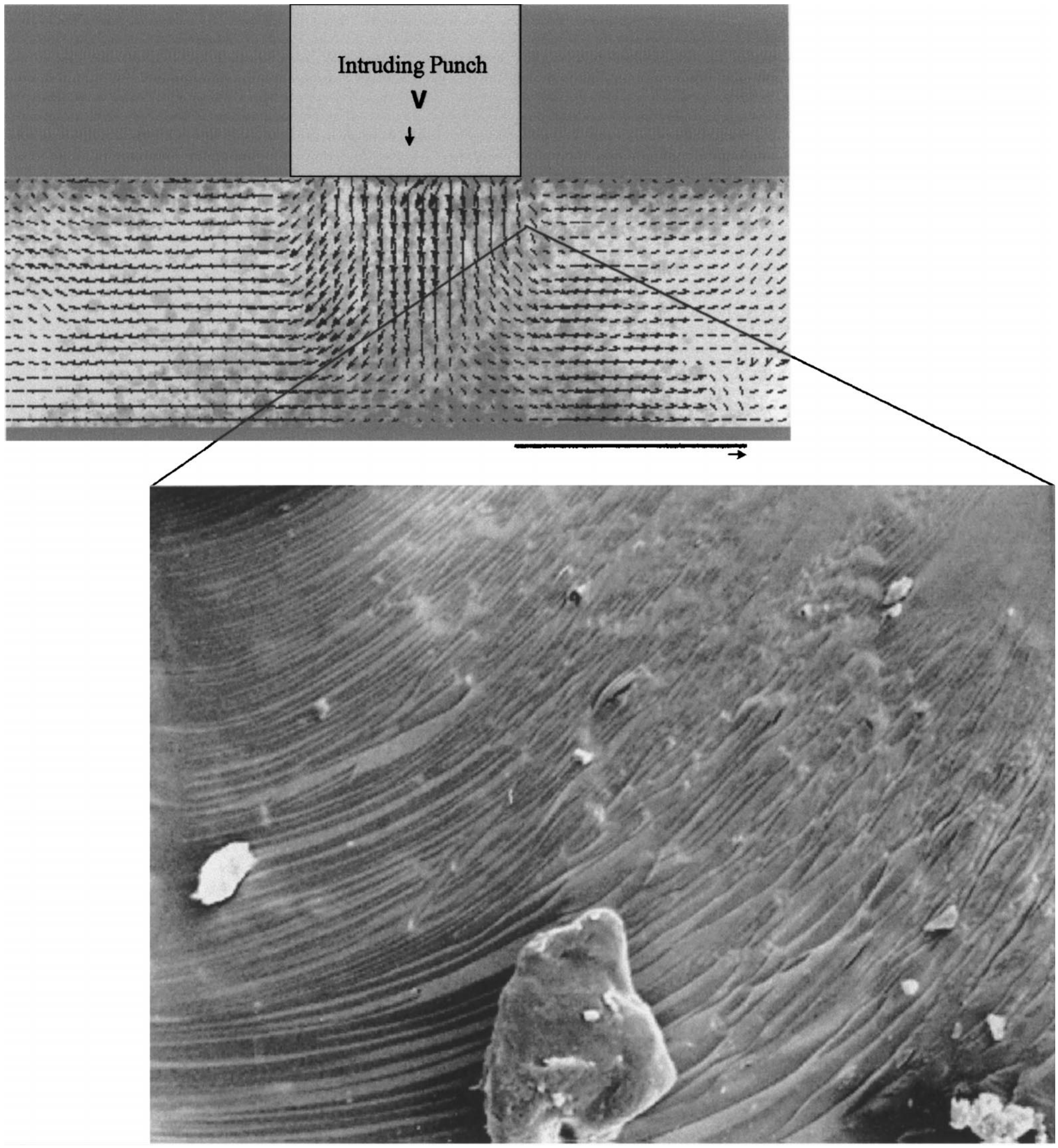

Figure 8 Shear bands in a hard phase sugar crystal (1000×) after punch deformation of mock PBX 9501.

of the transition region immediately to the sides of the punch.

Although the hard phase HMX has been replaced in this mock with sugar, the mechanical properties of the sugar closely resemble those of the HMX and behavior should be similar. For hot spot formation to occur within an explosive, pressure and temperature must reach critical levels at localized points within the material. Other recent studies have shown that the formation of shear bands occurs as plastic shear strains become large, leading to very high localized temperatures within a material. Mason *et al*. [20] suggested that thermal softening occurs within shear bands at the tip of propagating cracks in C-300 steel. Zhou *et al*. [21] showed the formation of shear bands within W-Ni-Fe alloy leads to thermal softening even at rates as low as $10^{-4}\ s^{-1}$. The localized high temperatures associated with this thermal softening in metals increase with impact velocity. Zhou, Rosakis, and Ravichandran [22] showed, using high-speed infrared detectors, that localized temperatures within C-300 steel can reach in excess of 1400 °C.

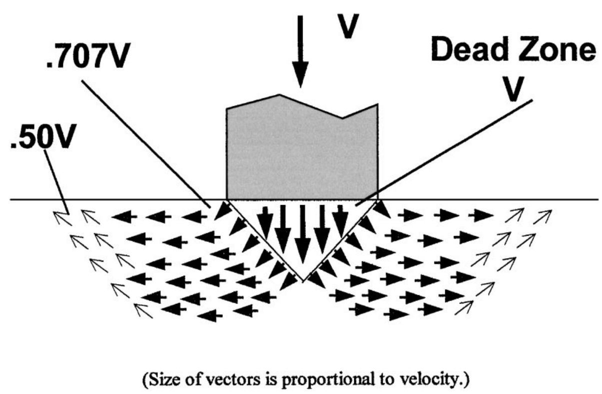

Figure 9 Image depicts the experimentally determined material flow field for punch deformation in PBX 9501.

Explosives have a much lower compressive strength than metals and therefore such high localized temperatures would not be expected. However, it has been shown that localized temperatures of even 200 °C can initiate a reaction in some explosives [23]. The formation of shear bands within an explosive formulation has been shown to occur even at sub-critical rates [24] and under unconfined loading conditions [23]. These high strains along with the elevated pressures and temperatures within the shear bands could lead to the formation of hot spots in PBX 9501 under compressive loading even at lower strain rates.

4. Conclusions

Overall, conclusions can be drawn from this work in two areas: 1) experimental verification of the flow field within a specimen under low rate punch loading, and 2) the possibility of hot spot formation and explosive initiation due to plastic flow and shear banding within PBX 9501. The results of laser induced fluorescent speckle photography support the following conclusions concerning the flow field behavior during Prandtl punch penetration as shown in Fig. 5.

1) At a strain rate of 0.007 s^{-1}, clear evidence can be seen of Prandtl's triangular dead zone directly beneath the punch. The mock explosive material moves in this region at the speed of the intruding punch. Volumetric strain rates will be proportional to these velocities.

2) The boundaries of the dead zone are the area of highest volumetric strain in the entire specimen. To the sides of the punch, near the front edges of the dead zone the material flows plastically in arcs. These arcs show a gradual transition from the directly downward flow in the dead zone to flow perpendicular to the intruding punch approximately half a punch width to the sides of the dead zone. The plastic flow, and therefore the volumetric strain in these regions, is less than that of the dead zone by approximately 30%. This also agrees with Prandtl's proposed velocity of .707V for these regions (See Fig. 9).

3) The flow field for the areas along the top surface of the specimen and directly to the side of the punch differ from both Prandtl's and Hill's proposed solutions. Both Prandtl and Hill theorized flow moving back toward the surface directly to the sides of the punch. However, these areas show little motion—the only significant motion being once again perpendicular to the intruding punch. Back flow does occur in the specimen, but begins a complete punch width to the sides of the punch. This back flow is at a lower rate than the punch velocity by more than 50%. Both the rate and location of this flow differ from both Prandtl's and Hill's solutions.

4) Overall, no diagnostic evidence of Hill's strain field is found in sugar mock 9501 using LISP.

In considering the material behavioral mechanisms within an explosive undergoing low velocity punch penetration, the rate of plastic flow does not appear to be large enough alone to have a significant influence on hot spot formation at low punch velocities. At higher rates, heat generated from plastic flow could reach levels capable of initiating a reaction in the explosive, but at these higher rates other ignition mechanisms such as shear banding and void collapse will dominate the reaction and lead to ignition of the explosive. Shear stresses, as shown by the formation of shear bands within the specimens, are of much higher magnitude than initially thought. Even at volumetric strain rates as low as 0.007 s^{-1}, the shear strains are significant enough to lead to shear banding in the hard phase constituent of PBX 9501.

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