SHEAR DEFORMATION AND SHEAR INITIATION OF EXPLOSIVES AND PROPELLANTS

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Shear deformation of explosives and propellants is important in many impact scenarios. But to date, progress has been slow in developing useful shear initiation criteria because it is difficult to set up an experiment that exposes the energetic material to a well-defined shear stimulus for the duration of the initiation. Recently however, the U.S. Army Research Laboratory (ARL) developed a shear-punch experiment using a modified split-Hopkinson bar, in which shear rate and duration are controlled by varying striker bar velocity and length. Shear velocities approaching 100 m/s and durations as long as 200 μs are possible. Experiments to determine the critical shear velocity and critical duration of loading for initiation are reported for a modified double-base propellant. At subcritical conditions, thin sections along the axis of the sample were cut from samples that did not ignite. For these samples, microscopy was used to probe for evidence of

INTRODUCTION

Sensitivity rankings of energetic materials are not generally consistent across a range of stimuli–shock, shear, and thermal. Ultimately, one desires an initiation criterion and fundamental understanding of each. For thermal and shock stimuli, several useful models and experiments exist. However, many hazard scenarios lead to “shear” initiation in which the energetic material experiences a complex and poorly understood flow field. Energy is deposited in local regions in the material over short timescales. Thus, temperatures quickly rise to high values leading to a precarious competition between the energy input between deviatoric strain energy and chemical energy and energy loss due to heat conduction.

Frey [1] provided a basic analytic model of this process using simple Arrhenius kinetics and constitutive behavior more than two decades ago. Today’s computer codes are fully three-dimensional and can handle much more complex behavior. However, to date, shear initiation is not commonly modeled because no clear test has arisen as a benchmark for the modeling. Whereas shock initiation occurs over microsecond time-scales, shear-initiation frequently takes tens or hundreds of microseconds, thus leading to uncertain experimental boundary conditions and widely varying loading conditions.

Previously, one test that closely represented conditions of interest was the activator-punch test [2]. However, the pressure on the shear surface was not well known, and controlling the shear velocity independent of pressure was difficult. For this reason, the shear-punch test was developed. This test uses a modified split Hopkinson bar technique to better control input and measure results.

The objectives of this test are two-fold: (1) establish quantitative ignition thresholds in pressure-shear-duration space, and (2) provide samples for analysis of damage and chemical reaction below the initiation threshold. This paper reports initiation data and samples analysis results for a modified double-base propellant, P1. In addition, some data for TNT and an energetic-thermoplastic-elastomer/RDX propellant (ETPE/RDX) are shown for comparison purposes.

Though quantitative thresholds have been established for TNT, its brittle nature made it impossible to study the shear region on samples that did not ignite. For ETPE/RDX, the levels of stimuli provided by the shear-punch apparatus were too low to induce any ignition of the sample. A quantitative threshold has been established for P1 along with microscopy analysis of the shear region. For this reason, this paper focuses on the shear initiation and deformation of P1.

Optical and scanning electron microscopy (SEM) has been used to analyze these energetic samples subjected to various levels of shear loading.

EXPERIMENTAL DESCRIPTION

The apparatus used is modified split-Hopkinson pressure bar (SHPB). Figure 1 shows a schematic of the setup. The striker, input, and output bars are 12.7-mm diameter 350-maraging steel. The bars were heat treated to ~340 kpsi ultimate tensile strength. The input and output bars are 1.5-m long. Currently, three lengths of striker bar are available–0.25, 0.5, and 0.55 m–, which give nominal pulse durations of 100, 200, and 220 μs.

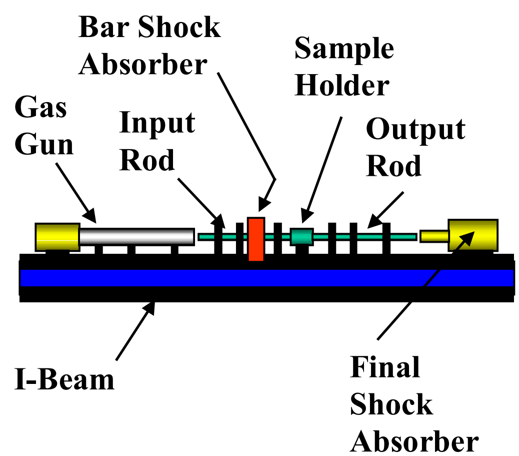

FIGURE 1. SCHEMATIC OF PRESSURE-SHEAR EXPERIMENT (NOT TO SCALE).

Impact velocity is measured using three sets of pitch-and-catch fiber optics near the end of the barrel and connected to a light source and optical detectors. Two strain gages are mounted 180° apart near the center of both the input and output bars to measure the incident, reflected, and transmitted strains. A 0.13-mm (5-mil) copper and 0.08-mm (3-mil) Kaptan disk is place between the striker and input bars for ringing and momentary electrical isolation at impact.

When samples react violently, the input and output rods are driven away from the sample at high velocity. As with most SHPBs, the output rod is slowed by a shock absorber, but a special bar shock absorber had to be designed to stop the reverse motion of the input bar without significantly affecting the quality of the incident strain. This is shown in Figure 2, in its compressed state. The input rod can be seen passing through the center of the shock absorber. A shallow angle metal cone was rigidly attached to the rod. When the rod is driven backwards, the cone engages a mating cone in a polyethylene buffer that in turn compresses alternating layers of foam rubber and polyurethane. The rubber is resilient, and the polyurethane serves as crush elements.

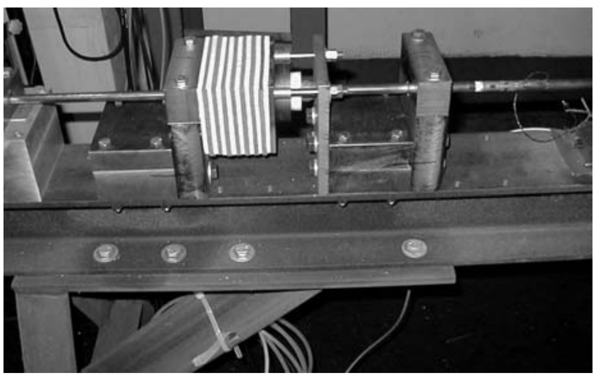

FIGURE 2. INPUT-BAR SHOCK ABSORBER

The sample section is what sets this test apart from normal Hopkinson bars. Figure 3 shows the sample holder assembly, not drawn to scale so that the important elements may be more clearly seen. The most significant feature of Figure 3 is the sample. Unlike with most SHPBs, the sample is of a larger diameter than the bar. It is held in a holder that is rigidly fixed to the I-Beam. Thus, the sample is effectively sheared during the experiment, ideally along the radial plane shown in Figure 3.

The sample itself is 19.05-mm diameter x 12.7-mm long. It is held within a three-piece holder, made from 17-4 PH stainless steel, hardened to Rockwell C 42, and bolted together with six high-strength bolts. The two short hardened steel bars in contact with the sample serve as transfer pistons. The input bar and output bar are fit snugly against these pistons just prior to a shot. These bars are expendable if the sample reacts with extreme violence.

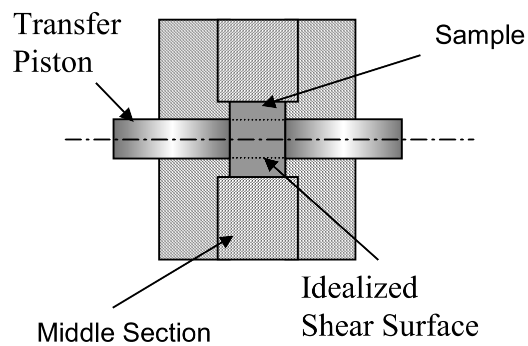

FIGURE 3. SAMPLE HOLDER ASSEMBLY

The holder in Figure 3 was used for the testing reported in this paper. A second holder, described in reference [3] permits the user to hydraulically apply radial pressure prior to the experiment, but data with that setup are limited.

In operation, a sample is loaded into the sample holder and is placed into its mount. Pressed or machined samples fit very well but some ductile laminated-and-punched samples are of poorer tolerance. Thus, vacuum grease is applied to all samples before insertion to fill any voids that may be present. Experience has shown that without grease, samples of poor tolerance are prone to ignition at their outer radial edge due to either friction against the sample holder or adiabatic compression of voids. In early shots, there was evidence of sample extrusion between the transfer pistons and holder; so 0.76-mm-thick (30 mil) polyethylene disks were added as seals between the transfer pistons and the sample. With grease and seals, indications are that all initiations occurred because of the shearing within the energetic material.

STRAINS SIGNALS

Two striker bar lengths were used, 0.25 and 0.50 m, resulting in ~100 µs and ~200 µs pulse durations respectively. Because the sample configuration in Figure 3 is different than that of traditional SHPBs, so are the resulting measured strains. Typical input, reflected, and transmitted strain pulses are shown in Figure 4. Strains are shown for P1, ETPE/RDX, and polycarbonate with the 0.5-m bar at velocities from 26–29 m/s. Because the velocities were not equal, the strains were normalized by the nominal input strain. Also shown in Figure 4 are the combined input-plus-reflected-minus-transmitted pulses.

Analysis of Figure 4 illustrates some important features of this experiment. These result from an intentional violation of two fundamental tenets of SHPB testing. First, the 12.7-mm sample thickness —desired to achieve long shear distances—precludes rapid stress equilibration across the sample. For a nominal sound speed of ~2 to 3 mm/µs for this class of materials, three complete wave reverberations across the sample would take ~38–25 µs, a substantial part of the pulse duration. Second, the sample geometry—designed to generate a shear load parallel to the motion—means the sample will never truly be in axial stress equilibrium.

Figure 4a shows that repeatable input strain pulses are obtained from the experiment. Figures 4b and 4c show that all three materials result in the same general trends in the strain pulses. To understand these curves it is worth discussing an idealized scenario where a sample of impedance lower than the bars is sheared instantaneously at time zero along the expected shear plane. Furthermore, assume that the shear surface is frictionless after it is created and the incoming incident pulse is a square wave and the sample is elastic.

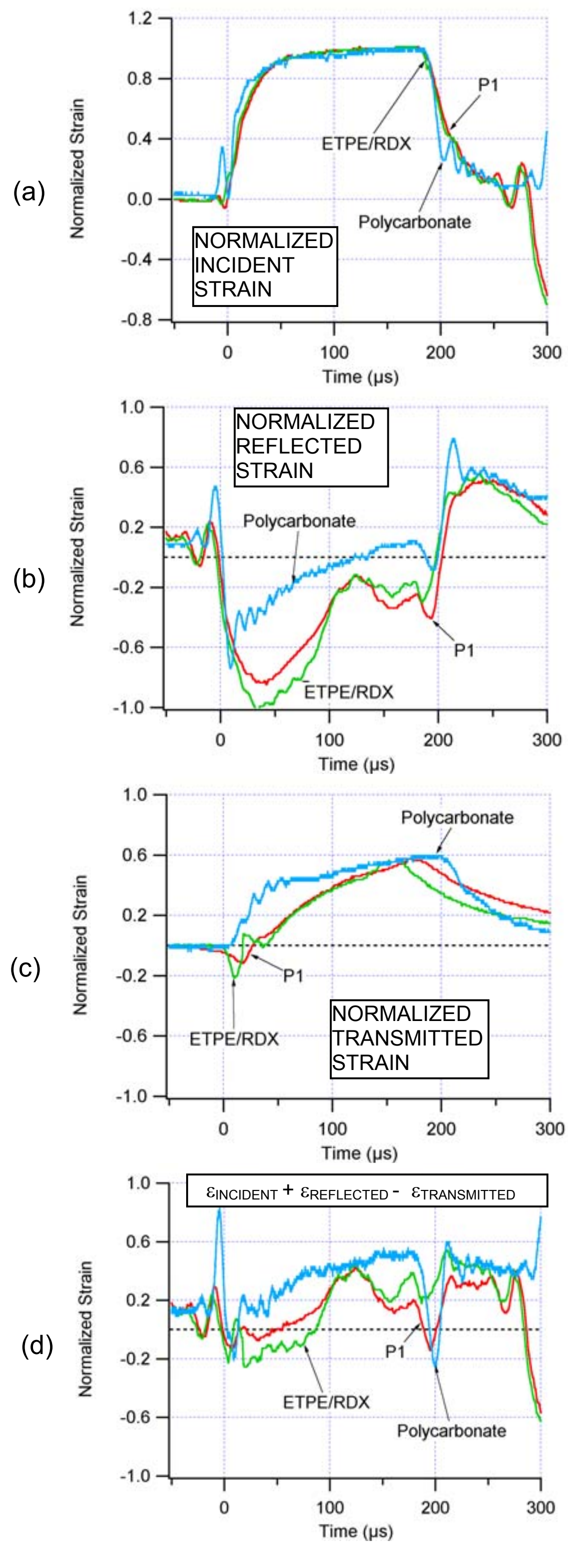

FIGURE 4. NORMALIZED INPUT, REFLECTED AND TRANSMITTED STRAINS FOR FOUR MATERIALS.

In this scenario, an initial tensile wave would be reflected; the magnitude of this wave would be determined by the relative densities and sound speeds of the samples and bars. In Figure 4, this behavior is evident. There is an initial large reflected strain, with a rise time on the order of the rise time of the incident pulse, which is not really a square wave. For these materials, the reflected tensile strain is 70–90% of the incident strain, which is expected base on the density and sound speeds of the materials relative to the steel bars.

In the idealized scenario, the reflected stress would then drop to zero and the transmitted stress would increase to the incident value over time associated with the "ringing" up of the sample, effective ~25–38 μs. This general behavior is also seen in the actual samples. After the initial large reflected tensile pulse, the magnitude of the reflection decreases; during the entire process the magnitude of the transmitted pulse increased.

In the idealized scenario, the magnitude of the incident plus reflected strain will equal the transmitted strain once the sample achieves stress equilibrium. In actual application however, the strain pulses do not cancel and do not approach their ideal values because the load on the effective shear surface affects their values. The combined strain signals in Figure 4d illustrate this. Their values are an indication of the effective shear force acting on the sample. Indeed, this nonequilibrium strain provides an estimate of the effective shear force on the sample through the multiplication

$$F_{SHEAR} = -AE[(\varepsilon_{INCIDENT} + \varepsilon_{REFLECTED}) - \varepsilon_{TRANSMITTED}] \quad (1)$$

where A is the bar cross-sectional area and E is its modulus of elasticity. Figure 5 depicts a typical shear force history for P1. At these velocities, the axial stress in the bar is ~5 kBar and the compressive force in the incident bar is about 60 kN. Figure 5 shows that the shear force peaks out at about 30 kN.

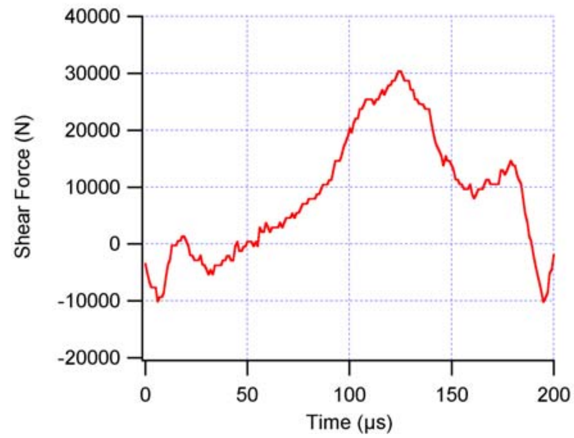

FIGURE 5. TYPICAL EFFECTIVE SHEAR FORCE HISTORY

There are several notable features in Figure 5. To begin, the shear force appears to start in an erratic fashion. There are contributing factors for this behavior. First, even in the idealized scenario with no friction the normalized $\varepsilon_{INCIDENT} + \varepsilon_{REFLECTED} - \varepsilon_{TRANSMITTED}$ will oscillate about zero with a frequency associate with the transit time across the sample; the magnitude will be as much as 0.20 while the sample equilibrates of several tens of microseconds. Due to the extended rise time of the pulse will decrease both the frequency and magnitude. The slight initial ringing in the incident strain wave may also contribute to the initial oscillation of the nonequilibrium strain.

A second significant feature of Figure 5 is the magnitude of the effective shear force. The time-averaged effective shear force acting on the sample is 8.56 kN. The implication is that a large amount of initial kinetic energy of the striker bar is dissipated into the sample.

SAMPLE DEFORMATION

The difference in the strain values for different materials results in different shear displacements. After each test, the extent of shear is measured for each non-ignited sample. Because the outer diameter and the outside portion of each end of the sample were constrained (see Figure 3), the only sample deformation possible was a physical dent caused by the penetration of the input transfer piston and the related punchout on the sample output side. The average of the dent and punchout distances for tests with the 0.5-m striker bar is shown in Figure 6 for four sample materials. A comparison of deformation for two different striker bars is given in Figure 7.

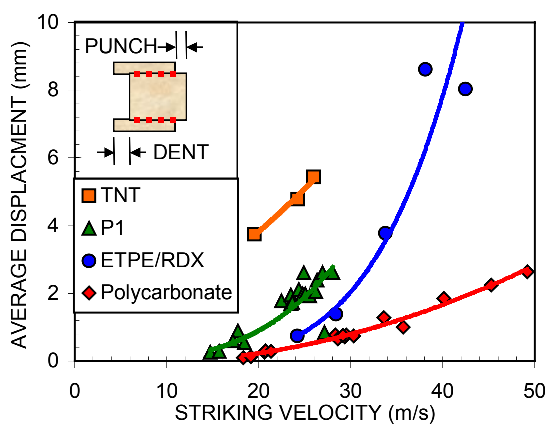

FIGURE 6. AVERAGE DISPLACEMENT FOR FOUR MATERIALS WITH THE 0.5-m STRIKER

The average of the dent and punchout are plotted in Figures 6 and 7. In practice for TNT and P1, the punchout was greater than the dent. For TNT, the extremely brittle nature of the material makes it difficult to assess the punch at large displacements because the sample actually failed in tension on the output end. For P1, the punchout averaged 0.3 mm (12 mils) greater than the dent depth with a maximum of 1.17 mm (47 mils) greater. This is due to the samples not fitting perfectly in the holder. Slightly oversized samples are compressed when the

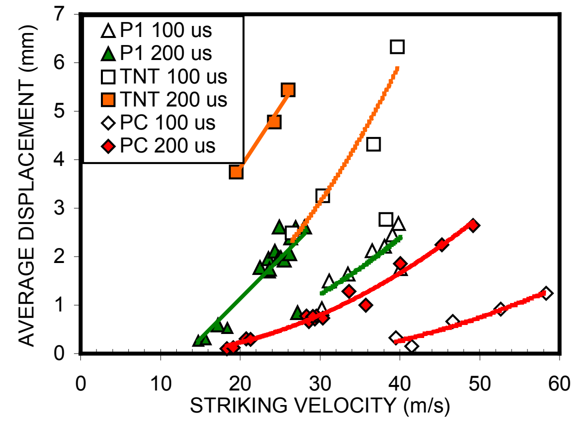

FIGURE 7. COMPARISON OF DENT AND PUNCH WITH A 0.25 VS. 0.5-m STRIKER BAR.

holder is assembled. This results in an initial negative dent and positive punch on the sample before the test. These initial displacements are superimposed on the test-generated displacements, but they have negligible affect on the average displacement. An initial over-sized sample by 0.1 mm radially or 0.13 mm axially would result in an initial axial length increase commensurate with the average 0.3-mm discrepancy in punch out and dent depth. For polycarbonate samples, which were machined to more precise fits in the holder, the punch still exceeded the dent in most tests, though the average was only 0.03 mm (1 mil) with a maximum of 0.1 mm (4 mils).

The average displacement is an indication of the displacement over which the shear force is applied. If the average 8.56 kN force from Figure 5 is applied over a nominal 2-mm displacement from Figure 6 for P1, this translates into 17 J of energy dissipated in the sample. If the material shears while at peak force, the energy dissipated would be ~60 J. A more accurate estimate is possible using the strain gages to estimate displacement, but this is not shown here. When the dissipated energy is isolated in a thin shear layer, that layer can be adiabatically heated to temperatures required for initiation.

INITIATION AND DECOMPOSITION

Indeed, the main purpose of this experiment is to study shear initiation. For P1 and TNT, ignition thresholds were measured with the 0.25-m and 0.5-m bars. Ignition here is defined as a self-sustained burn consuming significant amounts of material. Depending on the sample type and rate, in some tests the burn quenches when the bars are ejected from the holder and the pressure rapidly decreases. These are considered ignitions.

To determine a threshold, striker bar velocity was varied to determine critical shear velocity. Each test was qualitatively assessed a GO or NOGO (NG) result. The Langlie "Up-Down" Method [4] was used to determine the target striker bar velocity for each subsequent shot. For the resulting data sets, the maximum likelihood method [5] was used to calculate the resulting critical shear velocity. Figure 8 depicts the trend of critical velocity with pulse duration for P1 and TNT. Critical velocity decreases with increasing duration of loading, or conversely, critical duration of loading decreases with increasing shear velocity.

Figure 8 shows that fairly clear thresholds are obtained in this experiment, with uncertainties in the threshold velocity typically on the order of a few percent. The TNT appears to be slightly more sensitive to shear in this test than does P1; however, the ETPE/RDX material could not be made to react at velocities up to 48.2 m/s. Hence, the individual NG points are plotted. The insensitivity of this material to shear is attributed to its elastomeric binder.

Initiation in this experiment is due to the energy dissipated in the sample leading to localized heating and ignition. This effect was examined on samples that did not fully ignite but did undergo some decomposition. Microscopy was used on these P1 samples. They were cut into thin slices along their axis and examined. Figure 9 illustrates a typical decomposition pattern. This particular sample was subjected to a 39.10 m/s shear velocity for a duration of ~100 μs.

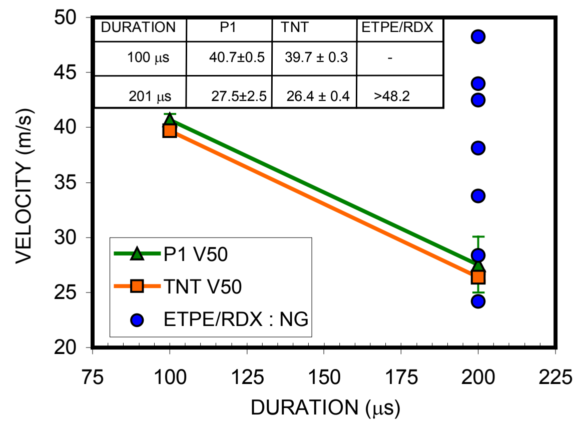

FIGURE 8. CRITICAL VELOCITY FOR P1 AND TNT, AND NONREACTING ETPE/RDX TESTS

The darkened areas in Figure 9 represent regions of decomposition. There is a general alignment of these regions with the expected direction of shear. However, the individual bands of decomposition run parallel to the expected shear plane. This is believed to be a result of the ductile nature of this material. Whereas a brittle material like TNT may exhibit a clear region of shear failure, a material like P1 may experience what more closely resembles an extrusion process during deformation. This may result in flow lines wrapping around the edge of the sample holder on the output side in a pattern as illustrated in Figure 9. This effect may be facilitated by the output side of the sample being effectively at a lower pressure during the experiment. Because the effective shear force can be thought of as applied over the sample, the compressive load at the output bar must be less than at the input bar. The lower pressure may allow flow to occur more readily at the output side of the sample, thus resulting in preferential decomposition.

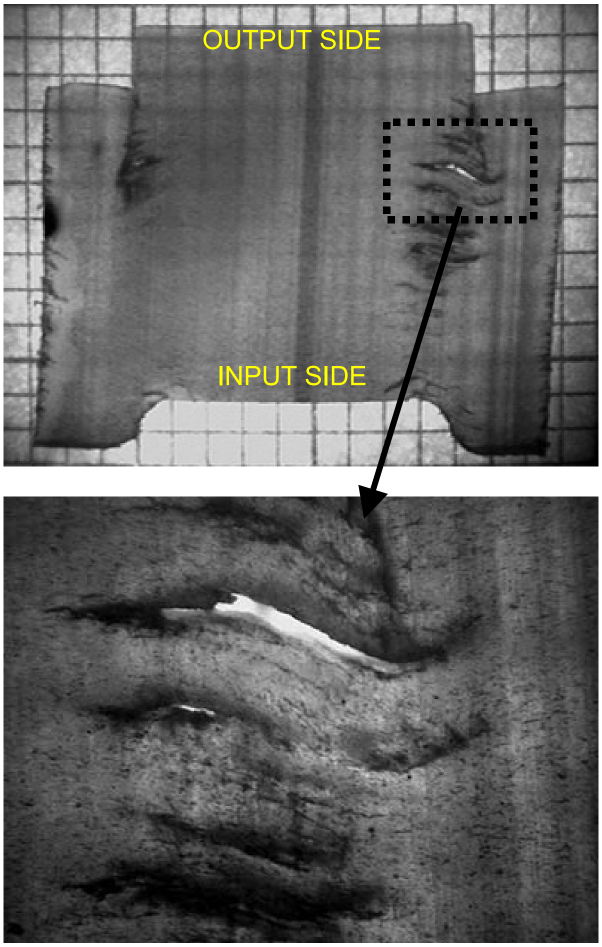

FIGURE 9. TYPICAL P1 DECOMPOSITION

SUMMARY

A shear punch test has been developed at ARL to study the effects of shear loading on various energetics. To date ignition thresholds have been determined for a modified double base propellant and TNT with two different pulse durations. As expected, the critical pulse duration decreases with increasing shear velocity.

Initial calculations of the sample loading based on strain gage data indicate a large amount of energy dissipated in the sample during the experiment. This energy dissipated leads to ignition. For some samples, decomposition has been examined in experiments just below the ignition threshold. For the double base propellant, the general direction of the decomposition is along the expected shear plane, but the direction of the individual shear regions is perpendicular to the expected shear direction.

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