Characterization of Shear Ignition Threshold of Energetic Materials Using Hybrid Drop Weight-Hopkinson Bar

V.S. Joshi and R. H. Guirguis
Research and Technology Department
Naval Surface Warfare Center Indian Head Explosive Ordnance Division
4104 Evans way, Suite 102, Indian Head, MD 20640-5035
vasant.joshi@navy.mil

Abstract

Sensitivity of energetic material to impact is important in determining hazards associated with accidental mechanical stimuli during transportation and handling of material. In any hazard scenario, there may be significant contribution of shear associated with the impact which must be understood to determine if a certain threshold could initiate the explosive and cause catastrophic destruction. Characterization of sensitivity of explosive is traditionally evaluated by a go-no-go ignition condition in a conventional drop weight test, using sand paper to pin the sample in place. While drop weight test offers a comparison for different materials, individual contribution of shear, strain, strain rate and friction in attaining ignition cannot be separated in the drop weight test. We have conducted experiments in an instrumented Hybrid Hopkinson bar, wherein lubricating the samples provides pure shear conditions which allow use of equations to obtain combination of shear and strain rate, for quantifying ignition threshold conditions. Full scale testing of munitions to determine ignition threshold may be very expensive, hence small scale testing combined with modeling which can be applied for large scale actual tests offer a low cost solution. In series of experiments conducted on explosives, the ignition threshold was determined as a boundary between ignited and non-ignited points in energy vs. energy rate plot. Data generated by experiments on different sizes of samples impacted at various velocities, using real time diagnostic techniques to simultaneously quantify mechanical properties and ignition threshold conditions, together with modeling of the experiment are presented.

Introduction

Prevention of unintentional ignition of energetic materials is one of the primary interests in ordnance technology. Development of insensitive compositions is one of the focus areas of research, aimed at preventing accidents during transport and handling of munitions. Characteristics of hazard scenarios in energetic material usually include a significant amount of shear in addition to high pressure, which result in hot spots leading to localized ignition. In addition to the static and dynamic properties of materials which are required for modeling of mechanical stimuli, initiation conditions are also important in transitioning response of material from pure mechanical loading to ignition and growth. Therefore, understanding of sensitivity and ignition and quantifying sensitivity to shear in an energetic composition is essential in developing insensitive munitions. Accurate simulation of any event needs a robust model based on experimentally calibrated material response.

Background

Mechanical behavior of energetic material is significantly different from metals and structural composites and the assumption of isotropic behavior may not be valid beyond a finite strain. Since impact conditions are essentially high strain rate phenomena, we have used a Split Hopkinson Pressure Bar (SHPB) to obtain mechanical properties of HMX and polymeric binder HTPB based soft and compliant explosives [1-3] at high strain rates. For obtaining quality results and reliable data, several issues had to be addressed by customizing of various aspects of setup, diagnostic methods, data reduction techniques, selecting superb bandwidth and signal to noise ratio amplifier, optimizing sampling rate and bit resolution, gage resistance and excitation voltage, and proper lubrication [4]. In addition to this, dispersion correction, validation of data using 1-, 2-, and 3-wave analysis and high-speed imaging were applied to obtain stress-strain curves in PBXN-110 explosives, at strain rates up to 5,000/sec [5].

Ignition has not been observed in these PBXN-110 explosive SHPB tests, even in small explosive samples. In order to obtain ignition, much higher strain rates are required, and have been achieved in recently developed new apparatus, which is a hybrid between the Split Hopkinson Pressure Bar (SHPB) and the conventional Drop-Weight test. It has also been demonstrated that shear induced ignition can occur in extremely insensitive explosives and the threshold for such ignition can be quantified in terms of several parameters, suitable for modeling. [6]. Earlier efforts to accurately determine mechanical behavior of soft explosives by SHPB is now complimented with higher strain rate testing up to onset of ignition.

Hybrid Drop Weight Hopkinson Bar Setup

The setup consists of a gas driven projection system, capable of launching a bar at velocities in excess of 20m/s, sufficient to cause high strain rate compression of sample, as illustrated in Fig. 1. It consists of two 300 mm long, 25.4 mm diameter striker and incident bars, made of hardened AISI 4340 steel. The sample is placed between the incident bar and a fixed anvil. As result, energy can be transmitted to the explosive sample, and very high strains and strain rates can be achieved. For small sample thickness, the strain rate does not remain constant, but increases as the sample gets compressed. Increasing both strain rate and strain also increases the likelihood of ignition, which is important when trying to make measurements of the mechanical and ignition behavior of explosive samples simultaneously. Mathematical equations describing the pure shear loading conditions, elaborated elsewhere [6-8], are the basis for obtaining ignition conditions in shear loading.

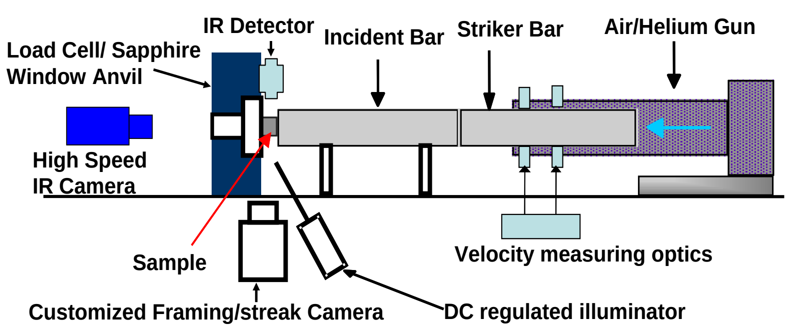

Fig.1. Schematic of Hybrid Hopkinson Bar system

The system diagnostic consists of three major elements-load cell, streak/framing camera and IR detector, which are synchronized to obtain mechanical properties and detection of ignition in one experiment. Each test represents a single point in the energy vs. energy rate space. By conducting a number of tests below as well as above the ignition point, a threshold level is determined. A new full frame IR thermal imager was recently added to the diagnostic, which cannot operate simultaneously with the load cell, since the anvil carrying the load cell must be replaced by another anvil with a sapphire window for thermal imaging. For experiments with load cell removed, the velocity matching is the only method to confirm the consistency of loading conditions.

The sapphire window has a tall cylindrical geometry, with diameter identical to the bar diameter. This prevents uneven loading. To prevent the sapphire window from breaking, part of the cylinder was press fitted into the anvil, leaving half of the window unsupported for application of reflectors for real time strain measurements, as shown below.

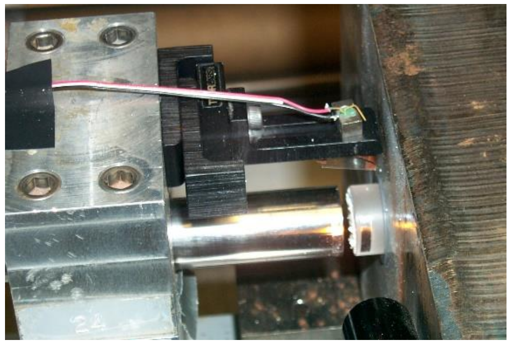

Fig.2. Sapphire window configuration for thermal imaging

To obtain temperature profiles as a function of time, a mid-wave band infrared imaging camera from CEDIP, model Silver 450 was used. This camera was selected considering the expected temperature range, framing rate and integration time. This thermal imager was used in synchronization with the side IR detector to obtain 3,600 frames per second on an 80x 64 pixel frame to locate hot spots. The framing rate on this camera could be increased to 28,000 frames per second on a reduced integration time and smaller window. However, reduction of integration time would degrade accuracy of measurements for low temperatures. Therefore the speed was restricted to 20,000 frames per second. These thermal profiles are extremely useful for calibration of models since they reflect the contribution of the friction and material properties just before the onset of ignition.

The expected temperature range in the pre-ignition regime was from room temperature at the lower end to about the cook-off temperature at the high end. Thus, initial camera calibration was selected to be between 10° C and 300° C. It was known that further calibration would be required before a reasonable estimate of temperature rise could be reliably obtained. Additionally, when the camera operates in the higher framing rate, the calibration ranges would be altered due to integration time available for specific acquisition rate. During the initial demonstration, actual temperature ranges for various integration times were identified for the specific camera model.

During initial thermal imaging trials, significant losses were observed through the sapphire window. To account for these losses, additional calibrations were performed using a mid-wave blackbody calibration source between 32°C and 215°C for camera placed 12" from source. An additional single point IR thermocouple (K220) was also connected to digital temperature reader. Readings were taken with and without the sapphire window between the source and the camera. The process was repeated for high and low integration times on a reduced area acquisition, and plotted to obtain a calibration curve. The image acquisition program on the IR camera was not setup for processing this secondary calibration from the raw data; hence the calculations were done manually.

Experimental

Cylindrical samples of PBXN-110 were characterized for their high strain rate mechanical behavior in a Split Hopkinson Pressure Bar followed by another series to obtain ignition threshold in the Hybrid Hopkinson Bar [9]. Experimental conditions for samples near threshold conditions and IR imaging on an identical material and sample size are given in Table 1. Only striker velocity is shown for samples tested on a sapphire window, since the load cell had to be substituted at the same location.

Table 1. Experimental Conditions

Shot#	Sample Dia inch	Sample Thickness inch	Striker Velocity m/s	Energy (J/mm^3)	Energy Rate (W/mm^3)
110-01F	0.250	0.138	9.06	1.28e+08	1.22e+12
110-02F	0.250	0.138	8.40	1.15e+08	1.11e+12
110-07F	0.187	0.134	8.06	1.20e+08	1.22e+12
110-IR1F	0.187	0.134	8.31	N/A	N/A
110-IR2S	0.187	0.134	6.19	N/A	N/A
110-IR3S	0.250	0.138	7.39	N/A	N/A
110-IR4S	0.250	0.138	7.38	N/A	N/A

Extra samples made for the previous test series were used for new experiments to obtain thermal images of near-ignition threshold conditions. This was done to obtain correct thermal excursions during compression on an identical input velocity basis. The energy-energy rate threshold plot, as computed from result are shown below.

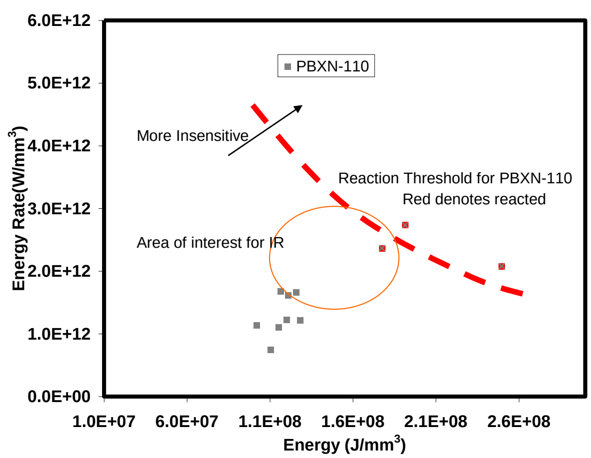

Fig.3. Threshold curve for PBXN-110, extracted from [9]

Results- IR Imaging

The real time IR images for samples during compression show temperature changes on the rear face of the sample, as a function of time. The non-ignited samples show increase of less than 70°C, but the ignited samples show rise of over 110°C. Since the sample is released from the compression state immediately after attaining minimum thickness (measured to be 0.010"-0.017", depending on initial velocity), the cooling process is fairly rapid. Temperature profiles as a function of time for IR1 and IR4 are shown below. The differences in the frame timings are due to changes in the viewing area, altering the framing rates.

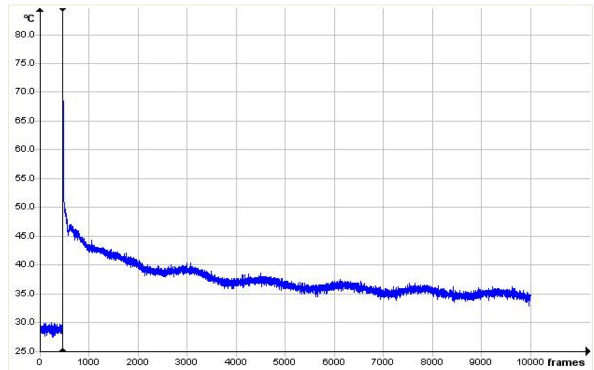

Fig.4. Temperature profile obtained in a non-ignited sample. Each frame is 50 µs apart.

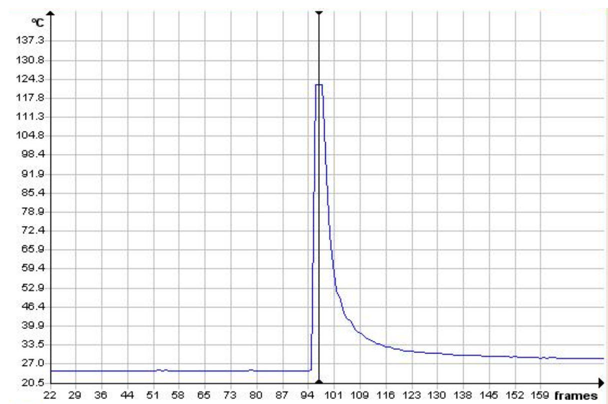

Fig.5. Temperature profile in an ignited sample. Each frame is 277 µs apart.

Modeling of Experiment

Simulations of high strain rate compression leading to ignition condition in the Hybrid Hopkinson Bar were conducted using CTH code. The input conditions for sample sizes and velocities were taken from the ignition threshold conditions from experiments. The material for the striker and the anvil was modeled as standard AISI 4340 steel and the initial velocity of striker bar was imposed on the striker, which had 64 nodes across the diameter in an axi-symmetry configuration. The material properties of PBXN-110 were obtained from another code library, similar to the ones used by Miller et al. [10]. A reactive burn (HVRB and the Lee-Tarver) model under CTH was used to identify the onset of ignition. The model scheme is shown below.

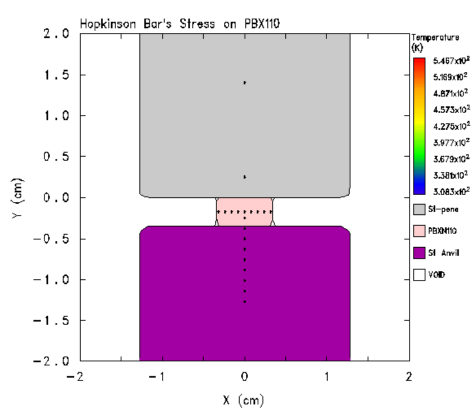

Fig.6. Hybrid bar simulation setup at the beginning of compression.

Results of Simulations

Calculations were run for sufficiently long time to completely compress the sample, similar to the actual experiments. Starting with an initial striker velocity of 8.31m/s the simulations was run up to end of compression cycle. The schematic of the simulation at the end of the cycle setup is shown in Figure 7. Stress, strain and temperatures from the simulations were compared to the experiment. The output files were plotted for temperature rise as a function of time starting at the compression cycle.

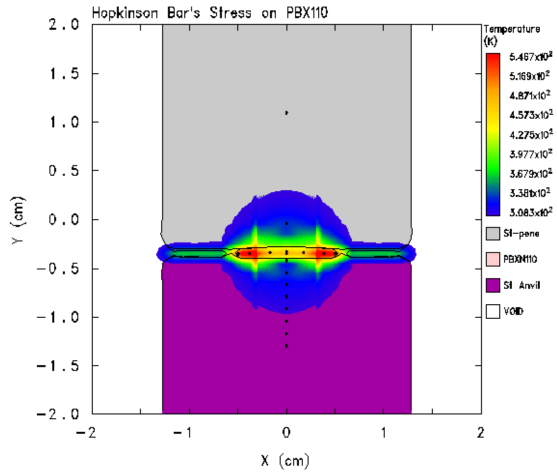

Fig.7. Simulation condition at the end of the compression cycle.

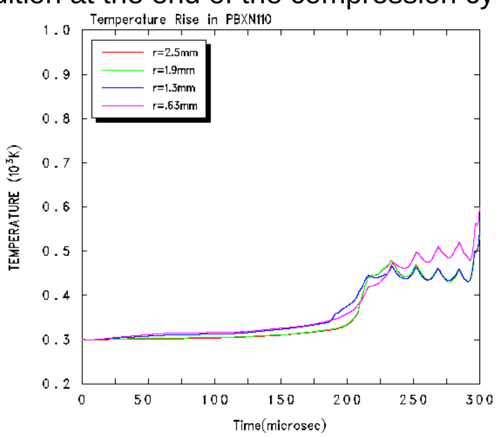

Fig.8. Simulation of temperature as a function of time at the various points of the sample.

The time step on the temperature profile on simulations plot is far shorter than the one obtained from the thermal imager. At 50 µs per point of the imager, the total rise time to the peak occurs within 5 images on figures 4 and 5, and as such the gradual rise is not acquired. For comparison of temperatures at the onset of ignition, final temperature of 121°C on Figure 5 corresponds to a calibrated temperature of 190°C is close to the simulation temperature of 210°C. The initial increase in the temperatures is slow due to higher compliance of the binder in the material. Once the binder is sufficiently compressed, the solid-solid interaction dominates, giving rise to steep increase in temperatures. Although the temperature profiles follow the actual experiments, temperatures in the interior of the sample cannot be seen by the camera, which is one of the limitations of the thermal imaging method. Therefore, temperature rise at the interface of the sample with sapphire window were reasonable comparisons.

Discussions

Although the temperature profiles obtained from modeling show close correlation in the current runs, revisiting previous efforts for mechanical property determination may be useful in reducing the differences between the experimental and the modeling values from current efforts. There may be some differences between interfaces during load cell testing and sapphire window testing, in terms of dynamic friction coefficients. Further efforts are planned to refine the calibration accuracy of the losses due to insufficient integration times for higher speed IR imaging, which is known to exist in these camera systems.

Conclusions

The Hybrid Drop Weight Hopkinson bar as a system is suited to measure the threshold of energy and power needed for ignition. With the addition of real time infrared temperature measurements and modeling fully realizes the potential of the apparatus. Temperature calibration from the high speed IR camera contributes to substantial gain in model verification.

Acknowledgements

This work was supported by the Internal Research Program of Naval Surface Warfare Center Indian Head EOD Technology Division, Indian Head, Maryland, USA. Support from Clint Richmond (modeling) is highly appreciated.

References

1. Gray, G. T. and Blumenthal, W.R., "Split Hopkinson Pressure Bar Testing of Soft Materials," ASM Handbook, 10th edition, 8, pp. 488-496 2000
2. Joshi, V.S., and Lee, R.J., “High Strain Rate Behavior of Explosives Containing Polymeric Binders,” in Fundamental Issues and Applications of Shock-Wave and High-Strain-Rate Phenomena, edited by K.P. Staudhammer et al. Elsevier Press, pp. 43-46, 2001
3. Joshi, V. S. and Lee, R. J., “Use of High Speed Photography to Augment Split Hopkinson Pressure Bar Measurements of Energetic Materials,” Proceedings of the Shock Compression of Condensed Matter, AIP Press, Furnish, Thadhani and Horie eds., pp 860-863, 2002.
4. Joshi, V. S. and Lee, R. J., “Use of Split Hopkin-son Pressure Bar for Measuring High Strain-Rate Behavior of Energetic Compositions,” Proceedings of JANNAF 18th Propulsion Systems Hazards Subcommittee (PSHS) Joint Meeting, Monterey, CA, November 13-17, 2000.
5. Lee, R. J. and, Joshi, V. S. “Resolving Mechanical Response of Plastic Bonded Explosives At High Strain-Rate Using Split Hopkinson Pressure Bar”, Proceedings of the Shock Compression of Condensed Matter, AIP Press, Furnish, Thadhani and Horie eds., pp 701-704, 2002.
6. Guirguis, R. H., "Role of Macroscopic Shear in Explosive Initiation - A Generalized Reaction Model," Proceedings of the 1996 JANNAF PSHS, vol. 2, pp. 87-106, CPIA, Columbia, MD, 1996.
7. Joshi, V.S., Budd, D.L., Cart, E, and Guirguis, R. H., “Measurement of Ignition Threshold of Explosives Using a Hybrid Hopkinson Bar-Drop Weight Test,” Proceedings of the 13th International Detonation Symposium, Norfolk, VA, July 23-28, 2006.
8. Joshi V.S., and R. H. Guirguis, “Development of a Hybrid Drop Weight Hopkinson Bar Test to Characterize Ignition and Mechanical Properties of Explosives And Propellants” in Proceedings of the 40th JANNAF PSHS meeting, North Charleston, SC, June 13-16, 2005.
9. Joshi, V.S., “Recent Developments in Shear Ignition of Explosives Using Hybrid Drop Weight-Hopkinson Bar Apparatus,” Shock Compression of Condensed Matter, edited by M. Elert, M. D. Furnish, R. Chau, N. Holmes, and J. Nguyen, CP955 pp 945-950, 2007.

10. Miller, P.J., Sutherland, “Reaction rate modeling of PBXN-110,” Shock Compression of Condensed Matter, Seattle, edited by S.C. Smith and W.C. Tao, CP370, pp 413-417, 1995.