CONF-9004147--5
UCRL- 102578
PREPRINT

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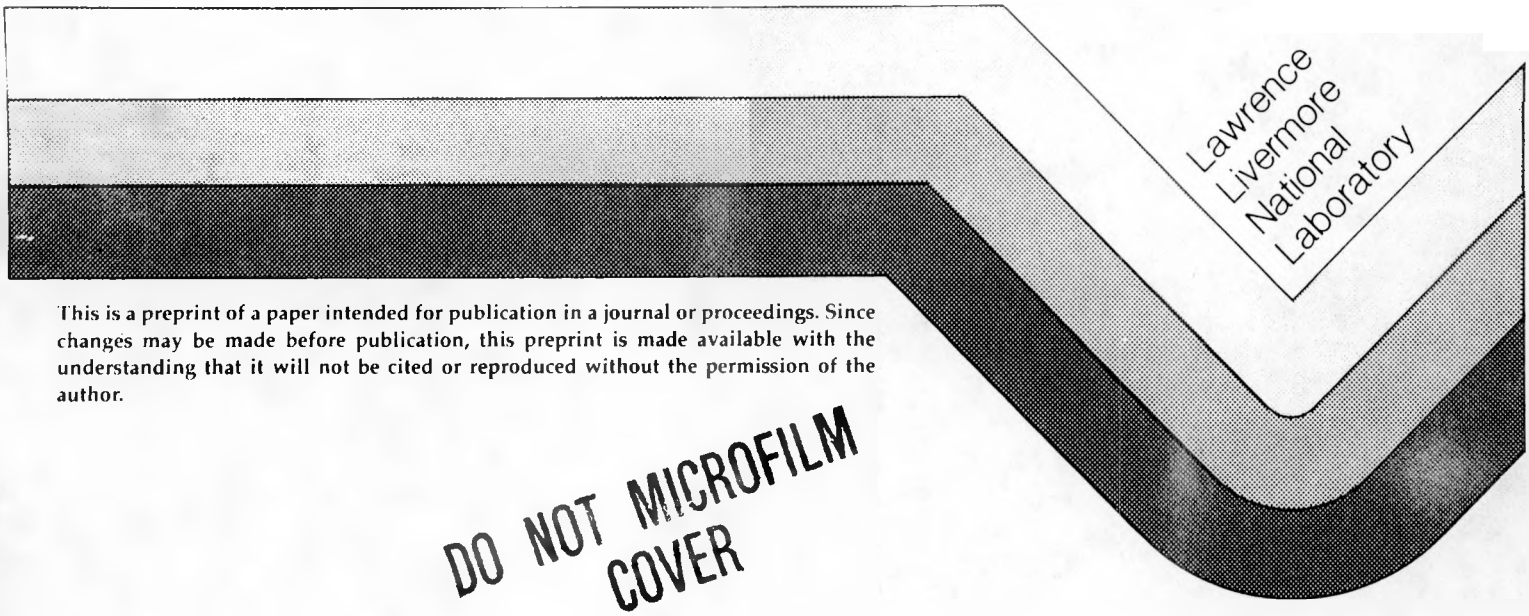
This paper was prepared for presentation at
and publication in the proceedings of
the 1990 JANNAF Propulsion Systems Hazards Subcommittee
Meeting at Johns Hopkins University
Applied Physics Laboratory, Laurel MD
April 3-5 1990

April 1990



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BURNING MECHANISM AND REGRESSION RATE OF RX-35-AU AND RX-35-AV AS A FUNCTION OF HMX PARTICLE SIZE MEASURED BY THE HYBRID CLOSED BOMB-STRAND BURNER.

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ABSTRACT

In this study, the average surface regression rate of two HMX-based cast explosives, RX-35-AU and RX-35-AV, is measured to pressures above 750 MPa using a hybrid closed bomb-strand burner. The hybrid design allows the simultaneous measurement of pressure and regression rate over a large range of pressures in each experiment. Nitroglycerin/Triacetin (75/25) and polyethylene glycol (PEG) are used as the energetic plasticizer and polymeric binder, respectively, in both formulations. The HMX solids loading in each formulation is 50 wt%, consisting of a narrow particle size distribution of 6 - 8 μm for RX-35-AU and 150 - 177 μm for RX-35-AV. Of special interest are the regression rate and burning mechanism as a function of the initial particle size distribution and the mechanical properties of the cast explosives. In general, the regression rate for the larger particle size formulation, RX-35-AV, is two to three times faster compared to that for RX-35-AU. Up to 750 MPa and independent of the initial confinement pressure, RX-35-AU exhibits a planar burning mechanism with the regression rate obeying the classical aP^n formalism. Comparison of the pressure-time and wire reporting-time curves indicates that there is no significant entrainment of still-burning condensed phase in the region behind the flame front. For RX-35-AV, however, the burning behavior is erratic for samples ignited at 200 MPa confinement pressure. At confinement pressures above 400 MPa, the regression exhibits more of a planar burning mechanism. The unstable combustion behavior for RX-35-AV at lower confinement pressures is related to several mechanisms: 1) an abrupt increase in surface area due to particle fracture and subsequent translation and rotation, resulting in debonding and creating porosity, 2) "thixotropic" separation of the binder and nitramine, causing the significantly greater fracture damage to the nitramine during the loading cycle, 3) microscopic damage to the nitramine crystals that increase its intrinsic burning rate.

INTRODUCTION

In the hazards assessment of propellants and energetic materials subjected to both thermal and shock stimuli, the ability to predict the burning mechanism and behavior is of prime importance. Unlike disciplines concerning with the design of high performance rocket motors[1-3] and the study of interior ballistic cycles of guns,[4,5] in which perturbations in the combustion rate due to crossflow and pressure transients result mainly in degradation of system performance, the design of ordnance involving the use of detonable propellants is much less tolerant with abnormalities in the combustion behavior. An abrupt increase in pressure, from a shift of the burning rate and regression surface, can easily trigger a deflagration-to-detonation transition resulting in sympathetic detonation. Even with systems filled with "insensitive" high explosives, it is virtually impossible to safeguard the munition from all possible threat scenarios and to maintain the original invulnerability and survivability standards.

The burning mechanism and regression rate of condensed energetic materials depend on a number of factors such as the combustion pressure, initial temperature of the material, chemical composition of the fuel and oxidizer, particle size, presence of energetic or inert binders, and the morphology of the composite mixture. Since most applications involve burning at the relatively low pressures of rocket motors (10 MPa), or the somewhat higher pressures found in guns (400 MPa), efforts to understand the conversion of a condensed propellant or explosive to gaseous products have been limited to these pressure ranges. For explosives applications, we are interested in learning about the physics and chemistry of burning at high pressures

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.
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(>500 MPa). Currently, we require something better in the computer models for hot spot ignition and growth in condensed explosives, such as those developed by Tarver,[6] than the extrapolation of mass regression laws found at pressures an order of magnitude lower than the application pressure. Their model incorporates a familiar aP^n mass regression factor in the ignition and growth terms. In practice, the quantities a and n are held constant at values found experimentally at low pressures, or are used as fitting parameters. Furthermore, we need to extend our fundamental understanding of the complex interactions between components (fuel, oxidizers, binder) in a composite formulation, especially the mechanical and thermal response of the composite within a weapon system while under static and dynamic loading. Deviation from a normal planar regression mechanism leading to deflagration-to-detonation transition is usually traced to abrupt changes in the amount of burning surface. Efforts in characterizing the sensitivity of damaged energetic materials have dealt mainly with correlating shock sensitivity of materials with internal porosity induced by poor processing techniques; voids produced by insufficient vacuum during the casting procedure or excess water reacting with the isocyanate during the curing step. Information concerning the changes in sensitivity from particle breakup, and the debonding of the binder and plasticizer due to dynamic loading from external fragment impact and internal stress loading are essential if we wish to develop tests and diagnostics that can readily screen energetic materials for hazards and vulnerability.

At the Lawrence Livermore National Laboratory, we are conducting technical-base research on the fundamentals of vulnerability of energetic materials. This multi-disciplinary program involves the formulation of a well defined series of energetic materials with different mechanical properties, the characterization of the material response under both shock and thermal loading, and the incorporation of the experimental results into a general model that can predict the vulnerability of future formulations. In conjunction with our efforts, Bob Frey at the Ballistic Research Laboratory will be performing large scale vulnerability and sensitivity tests with the same formulation. The large-scale test results serve to validate the model, which deals mainly with mechanistic details, and to help identify the important parameters in our test matrix. We recognized, in trying to develop a suitable formulation series for testing, the importance of adhering to a practical and realistic formulation, preferably one that is currently under evaluation for munition application. Toward this end, we have chosen the Low Vulnerability Explosive (LOVEX) formulation as a baseline, and have successfully produced variations of the baseline formulation that incorporate different particle size distributions, an energetic versus an inert binder system, and a brittle versus a compliant polymer matrix. The thermal characterization involves measuring high pressure combustion behavior, while the shock loading deals with complex-multiple dynamic stimuli. The interested reader is referred to the authors for a detailed description of the program.

In this paper, we investigate the combustion behavior and the surface regression rate of two LOVEX type formulations, RX-35-AU and RX-35-AV, to pressures above 750 MPa. The approach we have selected uses a hybrid closed bomb-strand burner, which allows the simultaneous measurements of regression rate and pressure, thereby generating information over a large pressure range in one experiment. Both formulations have a similar HMX loading in a relatively compliant binder matrix, and differ only in the particle size distribution. Of specific interest is the burning behavior of these explosive formulations under different initial pressure confinement. Previous investigation of a brittle, pressed formulation with a similar particle size loading and distribution (LX-14) indicated large-scale break up of the LX-14 strand resulting in abnormal rapid combustion and premature ignition through the sample. Tao and Costantino[7] found that the regression rate of an HMX-loaded extrusion cast explosive, with similar mechanical properties compared to RX-35-AU and RX-35-AV, exhibited an order of magnitude increase in its burn rate upon cycling to high pressures, unloading, and re-pressurizing.

EXPERIMENTAL APPROACH

MATERIAL PREPARATION

The RX-35-AU and RX-35-AV formulations are cast-cured high explosives loaded with 50 wt% HMX. Table I summarizes the composition of the two formulations. The baseline LOVEX series employ nitroglycerin/triacetin as an energetic liquid plasticizer and polyethylene glycol as the polymeric binder. In our formulations we added polycapralactone as a co-binder to prevent weeping of the triacetin after curing. We found that we cannot increase the HMX loading past 55 wt% without increasing the viscosity of the formulation and decreasing its processibility. The components are combined in a high-speed shear mixer at elevated temperatures, deaerated, and casted into break apart molds under vacuum. Upon complete

curing, which usually takes 24 hours, the material can be readily cut into different shapes for experiments. For the combustion experiments, the samples are a rubbery strand measuring 7.5 cm in length with an approximately circular cross-section at 100% TMD.

Table I. Composition of RX-35-AU and RX-35-AV formulations.

Components	RX-35-AU Weight percent	RX-35-AV Weight percent
Polyethylene glycol (PEG)	8.135	8.135
Polycapralactone (PCL)	6.845	6.845
Nitroglycerin/triacetin	33.255	33.255
MNA	0.10	0.10
CosCat 83	0.01	0.01
N-100	1.66	1.66
HMX	50.0 (6-8 microns)	50.0 (150-177 microns)

HYBRID CLOSED BOMB - STRAND BURNER

At high pressures, both the traditional closed bomb and strand burner methods of measuring the surface regression rate have significant disadvantages. While the strand burner provides a direct measurement of the regression rate, within assumptions about the burning surface to volume relation and the value of the sample density at pressure, the experiment must be carried out isobarically. This means that in a typical experiment, you get only one data point on the P vs r curve and that the buffering volume used to minimize the pressure rise owing to the product gases must be very large. The closed bomb method is used widely as a quantitative diagnostic method and, within fairly serious assumptions, to calculate burning rate law coefficients. The method is attractive because the pressure vessel is small and a large pressure range is available during a single experiment by adjusting the starting pressure and the loading density. However, there are no direct measurements of the surface regression rate, which must be calculated using assumptions about the shape of the burning surface and the thermochemistry.

Since our intent is to develop diagnostics that can be used to screen propellants and energetic materials for combustion abnormalities, we required a system with a fast turn around time and a maximum data acquisition efficiency. This led to the design and construction of a hybrid strand burner-closed bomb experiment, in which a strand burns isochorically in a relatively small volume, causing an increase in pressure owing to the product gases, with the surface regression measured directly using strand-burner-type probes. Figure 1 is an illustration of the apparatus, described in detail in references (7 & 8). In this work, we use a pressure vessel with a 3.05 cm diameter bore with 18 electrical feedthroughs in one sealing plug. A photograph of the sample assembly is in Fig. 2. The surface of the sample is inhibited with a thin layer of 60% Epon 828/40% Ancamide 350A epoxy. The electrical feed through across the pressure seal is effected with a stainless steel ball-stem arrangement manufactured by numerical-controlled machining. Electrical insulation between the ball and the pressure vessel is accomplished with 75 μm of mylar and 75 μm of kapton. Thirteen of the leads are used for twelve signal probes, each consists of 75 μm copper wire, and one common return line. Another two leads are used to carry an ignition current across a nichrome heater of about 8 amps at 7.5 volts. All of the leads are terminated inside the vessel in a male plug that permits easy installation of the shot assembly.

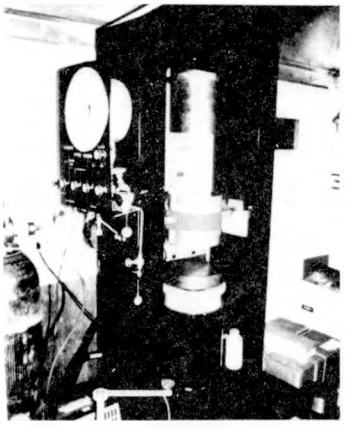

Figure 1. Hybrid Closed Bomb - Strand Burner. Illustrated are the load frame and the 2.5 GPa pressure vessel.

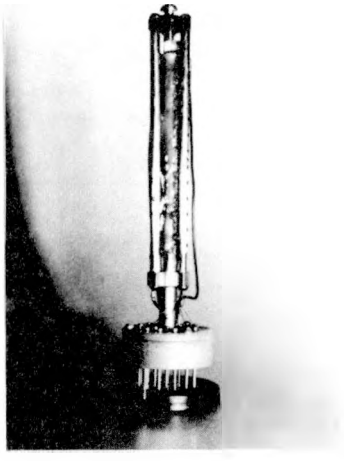

Figure 2. Sample assembly with copper breakwires.

The portable pressure generation system, shown in Fig. 3, uses a chemically-clean diaphragm pump in combination with a 1.2 GPa intensifier. The vessel is pressurized slowly with argon to the desired starting pressure, either 200 MPa or 400 MPa, and "frozen argon" valves are closed by immersing a length of high pressure tubing into liquid nitrogen. These valves are leak-free and are reliable to the bursting pressure of the tubing. We measure the pressure using a 1.3 MN load cell on top of the upper plug. At these burning rates (0.1-1.5 m/s), the pressure vessel-load frame is in mechanical equilibrium. Furthermore, the copper breakwires melt in a much shorter time frame compared to the time associated with the passage of the flame zone, and therefore can be treated as an instantaneous switch.

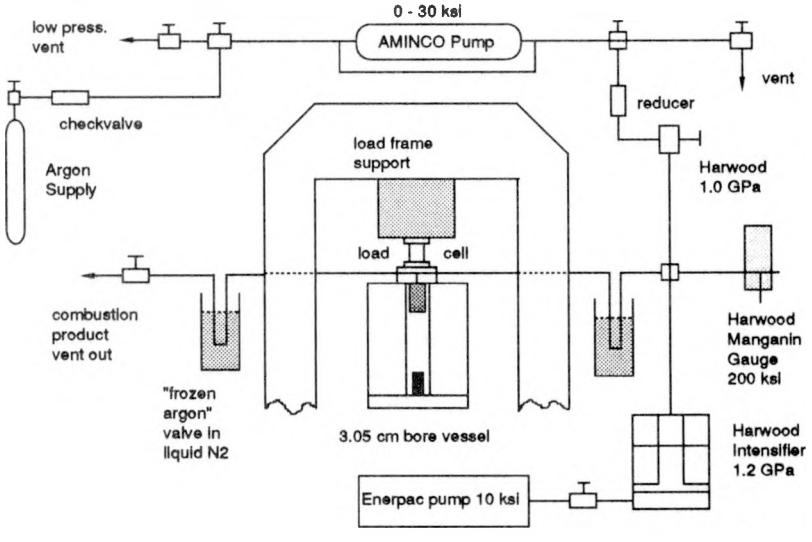

Figure 3. Portable pressure generation system. The "frozen argon" valves are an unique method for sealing high pressure.

DATA REDUCTION

Since the probes are located at discrete intervals along the strand, and the burning rate varies with the pressure as the flame moves between the probes, only an average burning rate between two probes can be calculated. Data for each shot consist of a pressure-time (P-t) curve and the times at which the signal wires reported, correlated by a common trigger. We fitted the entire P-t curve with a fourth order polynomial and used the fitted form to calculate dP/dt and to find the pressures at the times the switches reported. We then find the average surface regression rate between two switches using

$$r = (x_n - x_{n-1}) / (t_n - t_{n-1}) \ ,$$

where x_n is the distance of the nth switch from the ignition surface and t_n is the time the nth switch reported, at the average pressure $(P(t_n) + P(t_{n-1}))/2$. Note that we do not correct for the change in density owing to the hydrostatic compression. This introduces an error of about 5% in the calculated speeds.[9]

EXPERIMENTAL RESULTS

Figure 4 illustrates the P-t curve for a typical shot, in this case, a RX-35-AU (6 μm HMX) sample ignited at a pre-confinement pressure of 400 MPa. The slope, dP/dt, increases slowly as a function of pressure, suggesting that the regression rate is increasing monotonically. This is better illustrated in Fig. 5 in which the amount of material (linear strand distance) consumed is plotted against the time. In general, the pressure increase due to the combustion products is approximately 350 MPa. Superimposed on the P-t curve in Fig. 4 (square symbols) are the times and corresponding pressures at which the copper breakwires reported. It is important to note that the last breakwire reported essentially at the end of the burn signified by the peaking of the pressure. This observation, along with the absence of abrupt changes in dP/dt or slope-breaks, suggest that this sample regressed in a uniform planar fashion without significant deconsolidation. For the 150 μm loaded RX-35-AV, wires frequently would break during the initial pressurization or during the pressure rise from burning. Since the diameter of a wire is about half the diameter of the 150 μm particle fraction, we believe the breakage is a result of the relative motion of the nitramine particles as they move in the plastic binder. Nevertheless, there were adequate distance-time data in each shot not only to calculate burning rates, but to detect any significant excursions from non-uniform burning down the length of the sample.

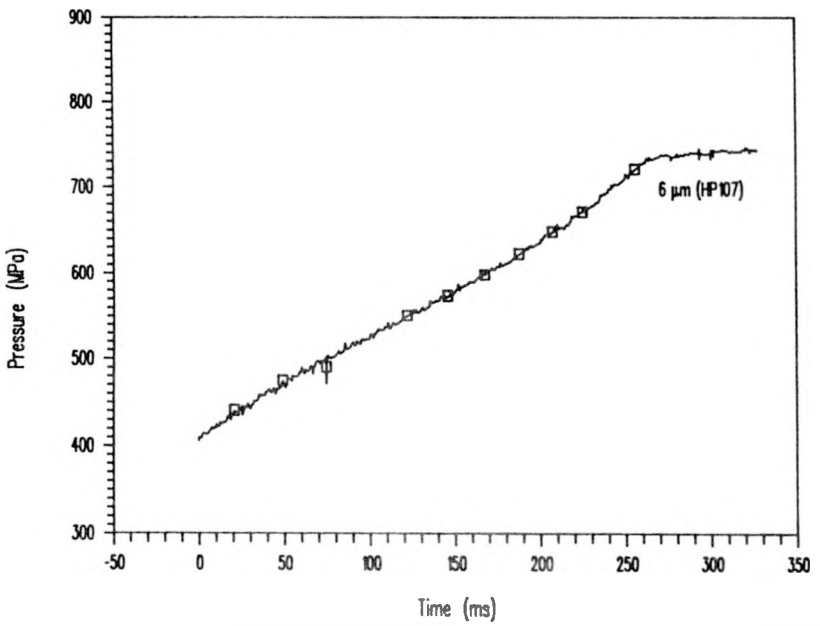

Figure 4. Typical pressure versus time profile of a sample ignited at a pre-confinement pressure of 400 MPa. The square symbols are the times and corresponding pressures when the copper breakwires reported.

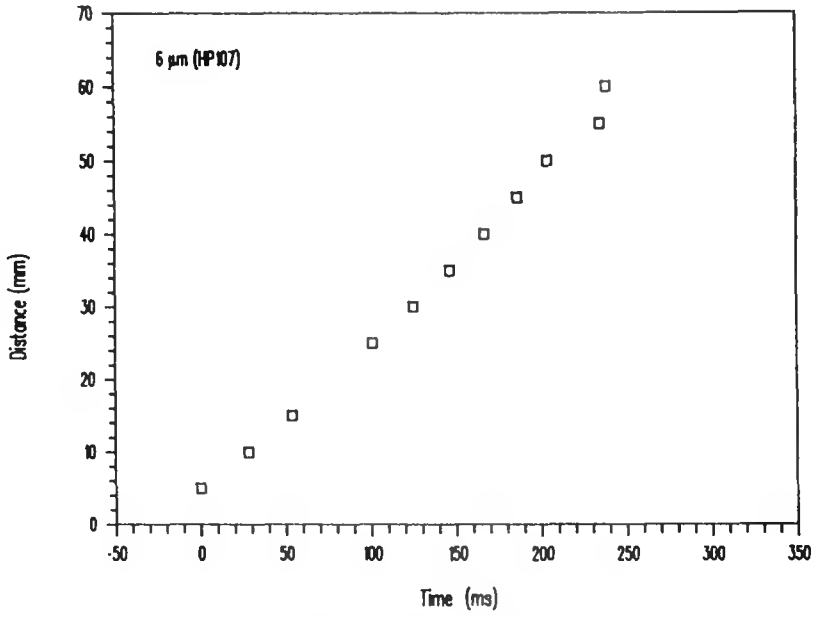

Figure 5. The amount of material, linear strand distance, consumed as a function of time.

Pressure-time curves for RX-35-AU (HP101 and HP103) and RX-35-AV (HP99 and HP100) shots fired at a starting pressure of 200 MPa are shown in Fig. 6. The RX-35-AU samples exhibit a uniform increase in pressure and the P-t curves are quite reproducible from sample to sample. For the larger particle size distribution samples, RX-35-AV, we find the burning behavior to be erratic and cannot be replicated. In fact, HP100 appears to have a regression rate an order of magnitude faster compared to HP101 and HP103. Shot HP99 starts out with a lower dP/dt compared to HP100 but abruptly approaches that of HP100 after 400 MPa. This abnormal pressure-time curve can result from an increase in the macroscopic burning area when the inhibitor fails and the sides of the sample ahead of the planar burning front ignite or when the sample breaks into large pieces. However, the wire-reporting data for this shot indicated that the burning front appears to move uniformly along the length of the sample, and that the abrupt change in pressure is probably due to an increase in the surface regression rate.

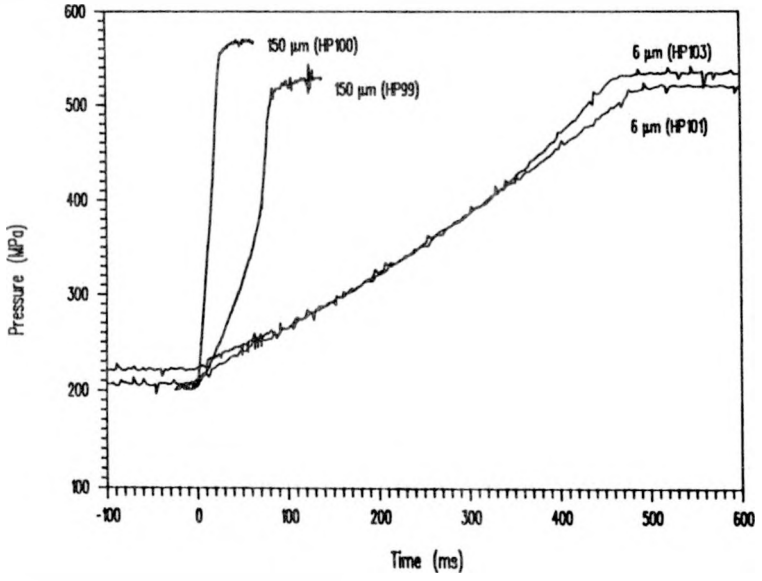

Figure 6. Pressure versus time profiles for RX-35-AU (HP101 and HP103) and RX-35-AV (HP99 and HP100) ignited at 200 MPa starting pressure. Note the unstable combustion behavior of the 150 µm samples.

Similar pressure-time curves for RX-35-AU (HP105 and HP107) and RX-35-AV (HP106 and HP111) samples ignited at a 400 MPa starting pressure are shown in Fig. 7. Again, the burning behavior for samples with the 6 μm HMX particle size distribution is normal, and the smooth P-t profile is reproducible. At an initial pre-confinement of 400 MPa, the RX-35-AV samples with the 150-177 μm HMX particle size distribution also exhibit a normal burning behavior that can be easily replicated. Furthermore, the regression rate for RX-35-AV samples ignited at starting pressures above 400 MPa is only two to three times faster than that for RX-35-AU, in contrast to the difference in regression rates illustrated in Fig. 6 with shot HP100 having a regression rate an order of magnitude greater than shots HP101 and HP103. The pressure vessel and seals for shots HP106 and HP107 leaked during the combustion at 740 MPa and 540 MPa, respectively. As illustrated in Fig. 7, the P-t profiles for both runs are normal until the pressure at which leakage occurred.

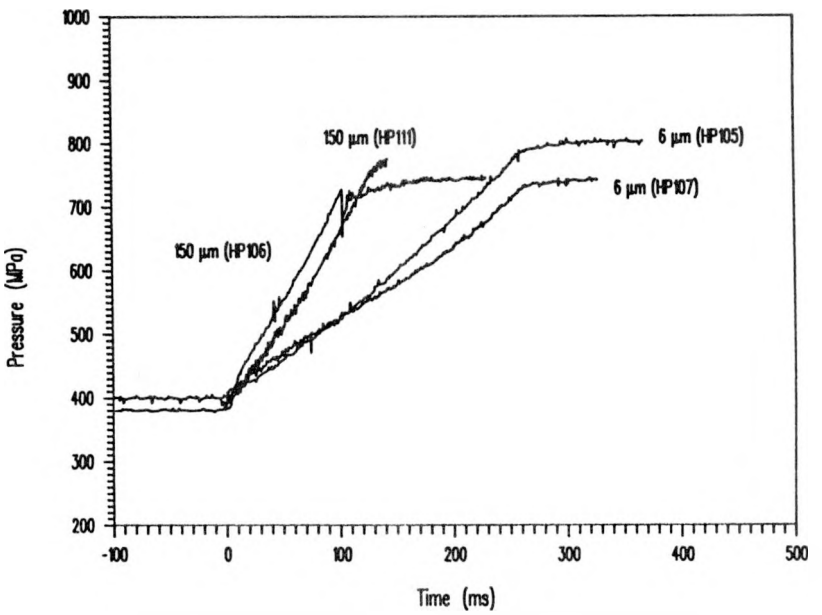

Figure 7. Pressure versus time profiles for RX-35-AU (HP105 and HP107) and RX-35-AV (HP106 and HP111) ignited at 400 MPa starting pressure. At this confinement pressure, the P-t curves for the 150 μm samples are reproducible.

During several experiments with the larger particle size RX-35-AV samples, a few of the copper breakwires will report during the pre-confinement pressurization. Instead of igniting these samples, we unloaded the pressure and examined the area where the broken wires were located. In each case, we found that the portion of the copper wire imbedded within the strand had broken, and a small amount of the sample had exuded out of the surface through the epoxy inhibitor coating. This did not occur for the RX-35-AU samples.

DISCUSSION

Previous studies, over the past several years, to measure the burning rate of HMX and fast burning propellants have seldom correlated the influence on the burning behavior from a systematic variation of the components within a baseline formulation. Fifer and Cole[10] investigated the regression rate of HMX strands separately filled with small (<44 micron) and large (300 micron) particles having densities from 60% (loose powder) to 99% TMD. Their results suggested that the strands do not burn with a uniform, planar flame, but rather with a "deconsolidation" mechanism, in which hot gases flow through the porosity ahead of the apparent flame front, loosening, heating and igniting the HMX particles. On the other hand, Boggs et. al.,[11] using HMX compacts pressed to 99% TMD, showed a smooth burn, with no transition to a very fast burning rate. In our study, we vary only the initial monomodal particle size of the HMX while maintaining the same HMX solids loading, binder/

plasticizer type and content, and method of formulation. The cast-cure method was chosen over other processing methods such as pressing or extrusion loading in order to minimize any damage to the material matrix due to processing. We can safely assume that we have a near 100% TMD formulation with the solids homogeneously dispersed in a uniform polymeric binder matrix. An uncontrolled variable in the formulation is the "wetting" efficiency between the binder and the two different HMX particle size distributions. We can only assume that, by staying with an easily processable formulation with only 50 wt% HMX solids loading and by processing with a high speed shear mixer, the degree of wetting between the binder and solids in the final RX-35-AU and RX-35-AV formulations is similar.

INTRINSIC VERSUS SURFACE REGRESSION RATES

The rate at which the condensed energetic phase is converted to gaseous products is a function of the density of the condensed phase, the area of burning surface, and the surface regression rate. A difficult issue in the interpretation of closed bomb, strand, or hybrid experiments is knowing what surface is actually burning. This is especially important when we are attempting to attribute abnormal burning behavior to abrupt changes in the surface area available for burning. In order to improve the formulation, we must identify the weaklinks between the different components. The simple assumption that the thickness of the zone containing both unreacted condensed phase and products is small compared to the spatial resolution of the diagnostic used to detect the motion of the burning front does not apply in most cases. An additional complication arises when, in experiments such as ours, the condensed phase is a mixture of nitramine component having a particular particle size distribution and a binder. In these situations, the product mass generation rate, dm/dt, requires not only a measurement of the surface regression rate, r, but also a knowledge of the particle morphology, size, and intrinsic burning rate.

For multi-component explosives, it is easy to see that the surface regression rate depends in detail on the connectivity and intrinsic burning rates of the components. For example, the surface regression rate of a formulation with a low loading density of nitramine in a binder having a low intrinsic burning rate will be close to the intrinsic burning rate of the binder. On the other hand, that for a formulation having a loading density of nitramine high enough so that the nitramine particle network is connected will have a surface regression rate nearer to the intrinsic nitramine rate, as the flame is propagated from particle to particle. Similarly, the component with the slower burning rate will continue to burn after the flame front passes. Although the RX-35-AU and RX-35-AV formulations only have 50 wt% HMX solids loading, we can safely assume, by keeping the other components in the formulation the same, that we are measuring the effects of HMX particle size on the surface regression rate. It is of interest, in a future study, to investigate the intrinsic burning rate of the individual 6 μm, 150-177 μm, and NG/TA/PEG energetic plasticizer/binder components dispersed in a non-reactive matrix, and to correlate the results with the measured regression rate of the RX-35-AU and RX-35-AV formulations.

ABRUPT CHANGES IN THE SURFACE REGRESSION RATE

As mentioned earlier, the abrupt increase in the regression rate is ultimately related to changes in the amount of surface area available for combustion. Intuitively, we would have expected the 6 μm RX-35-AU, which has a much higher HMX particle surface area compared to that of RX-35-AV, to regress much faster. We observe, however, that the regression rate of RX-35-AV can be up to an order of magnitude faster, as shown in Fig. 6, than that for RX-35-AU. The fact that the burning behavior of RX-35-AV is erratic lends further support to our suspicion that the surface area available for burning is changing.

The change in the combustion surface area can be due to several mechanisms. Additional damage in the form of internal porosity can be introduced through mechanical deformation during processing, decomposition of the energetic material due to exposure to adverse thermal and moisture environments, poor processing conditions in the casting, and chemical incompatibility between the components in the formulation. Since our formulations have similar components and processing techniques, we can safely rule out the contribution from these mechanisms to changes in the combustion surface area in our RX-35-AU and RX-35-AV formulations. For porous explosives, the transition from conductive to convective burning is due to the penetration of the hot gases into the pores ahead of the flame front. Fifer and Cole[10] have proposed, for laterally confined low density charges with HMX, that a subsonic pressure wave crushes and deconsolidates the sample ahead of the flame. For unconfined charges, they observed a "progressive deconsolidation" mechanism in which the enhanced burning surface does not exist in the interior of the charge, but rather primarily in the two phase (gas-particle) zone extending a considerable distance from the sample. The extended flame zone is not related to gas phase chemistry, but rather is determined by the particle burnout distance, which in turn is dependent on the particle size and the intrinsic burning rate. Even if our assumption

of a non-porous formulation is invalid, the preceding arguments would suggest a slower regression rate for the larger HMX particle size formulation accompanied by a non-planar burning behavior. We observe, however, a faster regression rate for RX-35-AV exhibiting a planar burning behavior.

A third mechanism that changes the amount of burning surface is the shear fracture of the nitramine particles, creating a new particle distribution. This occurs if the details of the macroscopic applied stress, the as-formulated particle size distribution, and the amount and nature of the binder result in shear stresses at particle-particle contacts greater than the failure strength of the nitramine. Costantino and Tao[12] investigated the change in particle size distribution of a nonconsolidated bed of HMX subjected to hydrostatic compression to 500 MPa. For a well-characterized 150 - 200 μm distribution of Class C HMX, analysis with scanning electron micrograph and Coulter counter after pressure unloading shows a substantial shift to smaller particle sizes and multi-modal distribution. It is reasonable to attribute the increase in the regression rate for RX-35-AV compared to that for RX-35-AU, at both 200 and 400 MPa confinement pressure, to fracture of the HMX grains embedded in the compliant binder. As the pressure increases, the volume of the highly compressible NG/TA/PEG binder decreases, permitting the relatively stiff nitramine particles to contact each other. At some point, the nitramine network carries a significant fraction of the applied load, and the particle-particle stresses are in excess of the failure surface, resulting in shear fracture. Thus the original particle size distribution changes to one having a larger surface to volume ratio resulting in a higher regression rate during combustion.

By fracturing the HMX grains in the binder matrix, we have inadvertently introduced porosity into the RX-35-AV formulation. The observation that RX-35-AV samples ignited at a confinement pressure of 200 MPa yielded erratic and non-reproducible P-t profiles while samples ignited at a confinement pressure of 400 MPa resulted in replicable runs, suggests that the final HMX particle size distribution at 200 MPa is a random one with different amount of surface area for each sample. At a confinement pressure of 400 MPa, the final particle size distribution approaches a more statistically uniform distribution with a similar amount of surface area between samples. This qualitative argument supports the experimental observation that the regression rate for RX-35-AV samples ignited at 400 MPa is uniform and replicable. If the binder matrix is compliant enough such that it wets the newly exposed surfaces, thereby "annealing" the damage, we should observe no difference between the regression rate of the two formulations; the intrinsic regression rate for the HMX/NG/TA/PEG formulation is independent of particle size if the solids loading and the ratio between energetic and inert components have not changed. The fact that we observe a shift of the P-t curves for RX-35-AV samples ignited at 400 MPa toward that of RX-35-AU lends support to this hypothesis. Clearly, the RX-35-AV samples at 400 MPa are still porous.

Comparison of the pressure-time and wire reporting-time curves indicates that there is no significant entrainment of still-burning condensed phase in the region behind the flame front for either formulations. Additionally, the slopes of the pressure-time curves are almost constant at the end of the burn. This means that the slope of the switch - time curve is an "intrinsic" regression rate for the nitramine-binder mixture. Figure 8 illustrates the calculated surface regression rate as a function of pressure for both RX-35-AU and RX-35-AV. The regression rate - pressure data can be fitted adequately with a power law of the form $r = aP^n$. Table II presents a summary of the fitting constants for RX-35-AU and RX-35-AV over the range 200 to 800 MPa.

Table II. Summary of the parameters of the regression rate power law, aP^n.

	RX-35-AU	RX-35-AV
n	0.939	1.004
a	4.48 (10-4)	8.93 (10-4)

SUMMARY

We have measured the surface regression rates of two highly compliant explosives using a hybrid closed bomb - strand burner apparatus to pressures greater than 750 MPa. These formulations are carefully chosen so as to study only the effects of HMX particle size on the burning behavior. The data indicate that the surface regression rate can be directly related to the

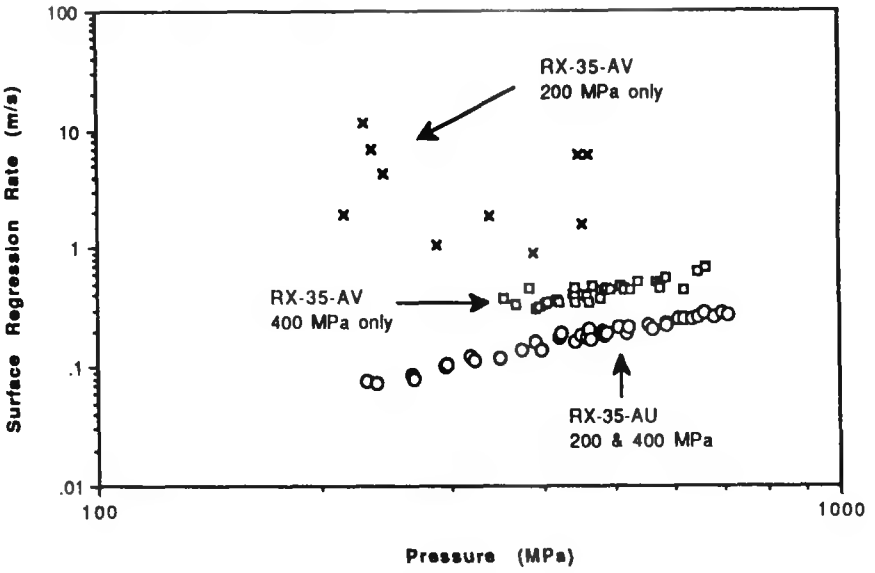

Figure 8. Calculated surface regression rate as a function of pressure.

intrinsic burning rate of the nitramine-binder mixture. The burning rates obey an aP^n law over the pressure range using a single set of parameters. We attribute the increase in regression rate for the larger HMX particle size RX-35-AV formulation compared to that of RX-35-AU to fracturing of the nitramine solids during static pressure loading. In future studies, we will characterize the new particle size distribution after static loading by dissolving away the binder and examining the HMX solids with a Scanning Electron Microscope. We will also vary the mechanical properties of the binder by altering the ratio of the plasticizer and polymeric binder.

This work is a continuation of an on-going program to study the fundamentals of vulnerability in energetic materials subjected to different stimuli. We believe that this is necessary not only to provide empirical date for the functional form and the parameters for the mass regression for use in explosive performance codes, but also to understand the effect of the stress history in vulnerability and hazards scenarios. Finally, we can easily imagine using the intrinsic mechanical properties of the components of the explosive, such as their failure strength, compressibility, etc., to tailor the mixture so that it has different properties under different stress fields. For example, using a large, mono-modal particle size distribution for the nitramine in the as-formulated explosive may result in a slow-burning, relatively safe explosive under normal stresses encountered in storage and handling but, after exposure to a stress adequate to fracture the particles, may have a desirably high burning rate in the application environment.

We continue to demonstrate the use of a hybrid strand burner-closed bomb apparatus to measure the surface regression rate of energetic materials. We expect that peak pressures in excess of 2 GPa are possible. The method combines the relative simplicity of the strand burner in obtaining regression rates with the very high pressure capability of the closed bomb. Our intent is to measure regression rates at pressures well beyond those found in gun and rocket propellant studies. These empirical relations are required to deal with the problem found in deflagration to detonation transition, ignition and growth of reaction owing to particle impact, and abnormal burning in the interior ballistic cycle.

ACKNOWLEDGEMENT

The authors would like to acknowledge Mr. Jack Bullock for his support of the experimental facility, and Mr. Ted Jessop for his help in preparing the samples. Also, the time spent by Mr. LeRoy Green on technical discussion is greatly appreciated.

REFERENCES

1. Kubota, N., "Survey of Rocket Propellants and Their Combustion Characteristics", in Fundamentals of Solid-Propellant Combustion, edited by K. Kuo and M. Summerfield, American Institute of Aeronautics and Astronautics, New York, New York, 1984, Vol. 90.

2. Serao, P., and Pierce, J., "Sensitivity of Ballistic Performance to Propellant Combustion Properties", in Interior Ballistics of Guns, edited by H. Krier and M. Summerfield, American Institute of Aeronautics and Astronautics, New York, New York, 1979, Vol.66.

3. Kumar, M., and Kuo, K., "Flame Spreading and Overall Ignition Transient", in Fundamentals of Solid-Propellant Combustion, edited by K. Kuo and M. Summerfield, American Institute of Aeronautics and Astronautics, New York, New York, 1984, Vol. 90.

4. Price, C. F., and Boggs, T. L., "Modeling the Deflagration to Detonation Transition in Porous Beds of Propellant", Proceedings of the Eighth Symposium (International) on Detonation, NSWC, Albuquerque, New Mexico, 1985, p.934.

5. Kim, K., and Sohn, C. H., "Modeling of Reaction Buildup Processes in Shocked Porous Explosives", Proceedings of the Eighth Symposium (International) on Detonation, NSWC, Albuquerque, New Mexico, 1985, p.926.

6. Tarver, C. M., Hallquist, J. O., and Erickson, L. M., "Modeling Short Pulse Duration Shock Initiation of Solid Explosives", Proceedings of the Eighth Symposium (International) on Detonation, NSWC, Albuquerque, New Mexico, 1985, p.951.

7. Tao, W., Costantino, M., and Ornellas, D., "Burning Rates of Two Cast Nitramine Explosives Using a Hybrid Closed Bomb-Strand Burner", Proceedings of the Ninth Symposium (International) on Detonation, NSWC, Portland, Oregon, 1989.

8. Costantino, M., and Ornellas, D., "A Hybrid Closed Bomb-Strand Burner for Very High Pressure Burning Rate Measurements", Proceedings of the 23rd JANNAF Combustion Meeting, CPIA Publication 329.

9. Costantino, M., Tao, W., Ornellas, D., and Clements, R., "Compression of Two Extrusion-Cast Explosives to 500 MPa", UCRL - 53827 Report, Lawrence Livermore National Lab, Livermore, 1987.

10. Fifer, R. A., and Cole, J. E., "Transitions from Laminar Burning for Porous Crystalline Explosives", Proceedings of the Seventh Symposium (International) on Detonation, U. S. Naval Academy, Annapolis, Maryland, 1981, p. 164.

11. Boggs, T. L., Price, C. F., Atwood, A. I., Zurn, D. E., and Eisel, J. L., "The Combustion of HMX", Proceedings of the 17th JANNAF Combustion Meeting, CPIA Publication 329, Vol. II, p. 431.

12. Costantino, M., and Tao, W., "Compaction of Non-Consolidated HMX Beds", Proceedings of the JANNAF Propulsion Systems Hazards Meeting, Marshall Space Flight Center, Huntsville, Alabama, 1987.

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