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LAMINAR BURN RATES OF GUN PROPELLANTS MEASURED IN THE HIGH-PRESSURE STRAND BURNER

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ABSTRACT

The pressure dependence of the laminar burn rate of gun propellants plays a role in the design and behavior of high-performance guns. We have begun a program to investigate the effects of processing variables on the laminar burn rates, using our high-pressure strand burner to measure these rates at pressures exceeding 700 MPa. We have burned JA2 and M43 propellant samples, provided by Dr. Arpad Juhasz, ARL, from propellant lots previously used in round-robin tests. Our results at room temperature are in accord with other measurements. In addition, we present results measured for propellant that has been preheated to 50 °C before burning.

We used our thermochemical equilibrium code, CHEETAH,¹ to help interpret the simultaneous pressure and temperature measurements taken during the testing, and show examples of its use. It has been modified to provide performance measures and equations of state for the products that are familiar to the gun-propellant community users of BLAKE.²

INTRODUCTION

Design of the interior ballistics cycle for advanced, high-performance guns relies on accurate knowledge of the laminar burn rate throughout the entire pressure range. To first order, the burn rate is correlated with the flame temperature, which, in turn, depends on the chemical formulation. It is well-known that the energetic material particle size has significant effects on that burn rate. Other effects, for example the dependence of the burn rate on the time of mixing, which alters the intimacy of mixing, are not so well understood. A step in achieving such understanding is the detailed measurement of the burning rate and correlation with quantified processing and particle size variations. The LLNL high-pressure strand burner permits accurate burning rate measurements over a pressure range that exceeds normal operating pressures for guns. We present the first phase of work in this program.

EXPERIMENTAL METHOD

APPARATUS

The LLNL high pressure strand burner, described in detail at this conference,³ combines the features of a traditional closed-bomb burner with those of a traditional strand burner. The LLNL high-pressure strand burner confines a burning sample in a small volume, high-pressure chamber. We measure pressure as it changes during the run, and the burn front time-of-arrival to get the laminar burn rate over a range of pressure in one experiment. In a standard closed-bomb burner, only the pressure in the combustion chamber is measured, so that calculating the burn rate requires accurate knowledge of the equation of state of the product gases and accurate treatment of heat losses. The standard strand burner provides direct measurement of the surface regression rate in a large volume at a constant, but relatively low, pressure.

Our strand burner has a volume of about 75 cm³, and is designed to reach pressures of 1 GPa (150,000 psi). The pressure vessel body is built from two concentric shells of high-strength steel with

Approved for public release, distribution is unlimited.

¹ This work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract number W-7405-Eng-48.
interference between them to put the inner shell in compression. The burn sample is a cylinder 65 mm long and 6.4 mm in diameter, made of nine cylindrical propellant pellets stacked on end. Silver burn wires (75 µm diameter) are inserted between each pair of pellets, in a groove in each pellet. After assembly, the curved surface of the sample is coated with epoxy (Epon 828 with Versamid 140 catalyst) to prevent burning. This limits the burn front to the end of the cylinder, resulting in a cigarette burn. The sample end is ignited by a thin pressed pellet (30 mg) of HNS, which is in turn ignited by 130 mg of boron potassium nitrate, triggered by a hot wire. To conduct a measurement, the burn sample is inserted into the pressure vessel. The sample mounts into a pre-wired base that carries the signal wires through high-pressure feed-throughs. The system is pressurized with argon to the desired starting pressure (up to 400 MPa or 60,000 psi), and then burned. We use a pressure transducer and a load cell to measure the pressure in the bomb, and detect the arrival of the burn front by the burn-through of thin wires embedded in the sample. High speed digital scopes capture the data for subsequent analyses.

SAMPLE PREPARATION

The propellant samples provided by Dr. A. Juhasz, ARL Aberdeen, were 6.5 mm diameter rods about 250 mm long. The JA2 samples could be cut to the desired pellet size with a razor knife. The significantly harder and more brittle M43 samples were cut to size with a diamond saw. The nominal density based on the mass and physical dimensions of each pellet was recorded. There was little variation in the density. For M43, the lowest density recorded was 95% of the theoretical maximum density (TMD), and most pellets were 97% or more. The JA2 samples showed similarly small variation, although a few samples were less than 95% dense.

RESULTS FOR JA2

We show the measured burn rate as a function of pressure in (Figure 1). There is noticeable scatter in the data at low pressure. The open circles are those velocities for pellets with density less than 1.54 (about 95% TMD). Some, but not all of the low-pressure scatter can be attributed to reduced density. There is no apparent density effect at pressures exceeding 30 MPa (4500 psi). The literature data were measured in a closed bomb using both small (7.8 cc) and large (200 cc) chambers. Our data are consistent with the closed bomb data excepting at the lowest and highest pressures. At the highest closed-bomb pressures, the laminar burn rate apparently rises rapidly with pressure. The burn rate is determined from the pressurization rate and the geometry of the originally seven-perf grains. At the end of the burn, the grains are almost completely consumed, the geometry is the remaining slivers. Small variations in that geometry could lead to large uncertainties in the laminar burn rate, so the turn-up of the closed bomb results should be ignored. At the lowest pressure for the small bomb, there is some irregularity that we tentatively ascribe to the start-up of a single grain. In the low pressure end, our data show considerable scatter.

We performed a few experiments with the propellant at an initial temperature of 50 °C. To conduct such a burn rate measurement, we preheated the pressure vessel body to this temperature. Then the burn sample was sealed into the pressure vessel and pressurized to the desired starting pressure. During pressurization (2-15 minutes elapsed time, depending on the pressure), the gas and sample in the vessel were warmed. The temperature of the gas in the pressure vessel stabilized at the bomb temperature within ten seconds of reaching the desired starting pressure. We held the system at the starting temperature and pressure for three-to-five minutes more, to allow the sample to come to a uniform temperature. Following this soak time, the sample was burned and data collected in the normal manner. The results (Figure 1) merge with the room-temperature results at high pressure. There are not enough data to definitely commit to a faster burn rate at higher temperature. Although the trend line of the high-temperature burn is above the trend line of the ambient data, the high-temperature data are within the spread of the ambient data.
RESULTS FOR M43

The results for the M43 samples, propellant lot HELP1-0988-131 processed in September 1988, all taken at room temperature, are shown in (Figure 2). There is notably more scatter in this data than was present in the JA2 data. The data from the burn wires are consistent with the pressure records, in that a relatively faster burn shows up as a relatively faster pressure rise. We have eliminated those data points for which the burn-wire signals were not consistent with the pressure rise caused by the burning of a single propellant pellet.

The closed-bomb data from Peters are for the same propellant lot and for a more recently produced lot. At low pressure, our results are consistent with the data for propellant grains made of the same lot of material. At higher pressure, we observe that our measured burn rates are erratic and consistently higher than the closed-bomb data.

We have observed a similar behavior for HMX-based explosive/binder systems. For large grain HMX and for low binder fraction, the high-pressure burn rates are erratic, higher than expected, and exhibit a pressure increase that is consistent with the arrival times measured by the burn wires. Those erratic and rapid burn rates were associated with damage to the explosive-binder composite. We observed that a pressurization with argon, followed by depressurization disrupts the bond between HMX and its binder. We have not examined the M43 propellant after pressurization. We did examine our M43 material before pressurization with a scanning electron microscope (Figure 3). The occasional large particle, evident there, is comparable to the size of our 75-μm burn wires.

There are differences in the temperature-pressure cycle of closed-bomb testing and of our testing. In the closed bomb, the pressure rises to the maximum value as the propellant sample is completely consumed. For such testing, pressurization is accompanied by reduction in cross section and increase in temperature, so the highest pressure is applied to the residual slivers. In contrast, our strand burner imposes the argon pre-pressurization over a few minutes time at the initial temperature and applies that pressure to the full-diameter piece. Neither of these test methods is an accurate simulation of the pressure-temperature cycle that occurs in a gun breech, nor was either intended to do that.

As part of this program, we will be testing similar, more recently produced propellants. This will serve to assess the role, if any, of the effect of age on the response to pressurization.

DISCUSSION AND ANALYSIS

In analyzing the data for the JA2 propellant, we noticed that the foil thermocouple, which replaced the silver burn wire between the 5th and 6th pellet down the stack, always reported 5 to 10 millisecond early. This resulted in a characteristic too-fast followed by too-slow twitch in the inferred velocity, which added to the apparent data scatter. We used TOPAZ to analyze the transient temperature rise of these probes in a sea of JA2 products. We tentatively assumed that the heating would take place rapidly enough that mixing with the argon pressurizing medium would not take place. We assumed the 75 μm wire to be an infinite cylinder. The material properties needed for the heat transfer calculation are the conductivity and specific heat. We used nominal values for silver. For the properties of the JA2 products, we turned to CHEETAH. We evaluated the specific heat at constant pressure over a temperature range that spans the flame temperature and room temperature, and did this for several pressures between 10 and 500 MPa. For the thermal diffusivity, κ, we used a correlation from the kinetic theory of gases that uses the temperature, T, and the molar concentration, c, also provided by CHEETAH. That correlation,

\[ \kappa = 5 \times 10^{-7} \sqrt{\frac{T}{c}} \text{ cm}^2/\text{sec} \]

agrees within a factor of two with handbook values for thermal conductivity where we could do cross-checks. We thought that it would be adequate for our needs. We show the temperature rise in the silver wire as a function of time in (Figure 4). The melting transition is evident there. We assume that the time to reach 1200K will be a characteristic time to report. Although there is a definite change in the time-to-report with pressure, and that high-pressure reports sooner than low pressure, the use of
uncorrected values of time has an insignificant effect on the inferred velocity. Initial pressurization to 100 MPa results in a typical final pressure of 300 MPa, which corresponds to a difference in reporting time of 2 millisecond faster for the last high pressure pellet. With 7.5 mm long pellets, and 300 mm/s burn velocity, the burn duration for a pellet is 25 milliseconds. The 10% correction in velocity is small compared with the intrinsic scatter. However, the foil thermocouple is only 5 μm thick. We performed similar heat transfer calculations in plane strain, to represent the heating of a thin foil of unlimited extent. At 200 MPa, the calculated time to report is 0.3 millisecond, compared with 7.5 millisecond for the wire. This is in quantitative agreement with the observed early reporting of the foil thermocouple.

With the JA2 runs, the burn wire at the bottom of the stack reported only rarely. Our observation that the time to report corresponds to a burn advance on the order of 1 to 2 mm, suggested that for the last wire to report, there needs to be enough material on the downstream side that its environment looks like the other wires. We used a thin disk of LX-04 explosive (85% HMX, 15% Viton-A binder) under the last pellet to provide that environment for the M43 series. Almost all of the bottom wires reported.

CONCLUSIONS

We have demonstrated that our measurements of the laminar burn rate of gun propellants with the high-pressure strand burner are consistent with closed-bomb measurements by comparison with the results for JA2. Our measurements of M43, a much harder and more brittle material, indicate a higher but erratic high-pressure burn rate in comparison to closed bomb measurements. Since both the pressure record and the burn-wires are consistent with rapidly burning pellets, we are reluctant to dismiss our results as noise. We speculated that the pressurization process produces damage in the propellant, as we had observed for HMX-based explosives. We intend to test this hypothesis.

We have used CHEETAH to examine not only the performance of gun propellants, but also to extract properties of the product gases that we have used for further analysis and improvement of the strand burner.

ACKNOWLEDGMENTS

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Figure 1. Laminar burn velocity for JA2 measured in the high-pressure strand burner, and compared with literature data.

Figure 2. Laminar burn velocity for M43 measured in the high-pressure strand burner and closed bomb data for this propellant lot and for a more recently produced propellant.
Figure 3. Photomicrograph of M43 propellant with large RDX particle in evidence. Most RDX particles are in the 5-15 µm range.

Figure 4. Calculated temperature rise in a 75 µm silver wire immersed in products of JA2 combustion at various pressures. The calculated melting transition is evident.
REFERENCES


