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Weapons and Materials Research Directorate, ARL

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14. ABSTRACT
The US Army Research Laboratory is currently exploring methods of manufacturing propellants whose performance is negligibly impacted by the wide range of operating temperatures demanded of a fielded propellant. The current approach is to coat the propellant with an inert material such that the amount of exposed base grain available to initially burn is controlled through the temperature-dependent mechanical properties of the coating. In effect the coating inhibits surface area initially available to burn at hot temperatures and exposes the greatest amount of base grain at cold temperatures. The end result is a propellant performance (i.e., burning rate) profile that is independent of initial temperature.

This report discusses the strand burner results of 3 chosen candidate coatings that were applied to an AFP-001 base grain propellant. Included will be the base grain's burning rate at a pressure of up to 10 MPa and the burning rates of the coated propellants, also up to 10 MPa.

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temperature compensation, coating, propellant, strand burner, burning rate

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1. Introduction

The US Army Research Laboratory (ARL) is currently investigating methods to control the burning rate of gun propellants such that they are not affected by temperature.[1,2] It is widely known, past studies of gun propellant performance has shown dependence on temperature.[3] At elevated temperatures propellants typically exhibit an increased burning rate, and conversely exhibit a lower burning rate at decreased temperatures. This is of importance due to the large span of temperatures fielded propellants are required to perform, –32 to 63 °C.[4] Given this extreme temperature range, gas pressure generation of a given propellant can suffer by as much as 45% when comparing cold to hot values. This in turn leads to a decreased muzzle velocity of up to 14%.[5] In addition to adversely affecting the muzzle velocity of a projectile, this muzzle velocity variation will lead to greater weapon dispersion. While these values vary between weapon systems, they illustrate a significant performance penalty when firing at cold as opposed to hot temperatures.

In an effort to eliminate this temperature dependence of the propellants performance the ARL in conjunction with the Armament Research, Development and Engineering Center (ARDEC) have developed a program in which a propellant is coated with an inert material to control the amount of propellant initially available to burn at the onset of ignition. This behavior is controlled through various mechanical properties of the coating material chosen, one of which is the coatings glass transition temperature. At extreme low temperatures the coating is designed to spall off the propellant grain (or "disrobe"), thus exposing a large area of the base grain for ignition. While at the extreme high temperatures the coating will adhere to the propellant grain and inhibit some of the initial burning of the propellant. Employing this fracture control mechanism properly could allow for propellant performance, which is independent of initial propellant temperature.

Ideally, being able to predict how coated propellants will perform is desired. Therefore, the ARL is developing a model to replicate the early ignition phenomenon of temperature-compensated propellants. Inputs for the model will include burning rate information on the coated propellants, ballistic simulator data, as well as chemical and morphological results obtained from postmortem analysis of interrupted burning experiments. The burning rate information via strand burner experiments will be reported here. While the goal is to incorporate these coatings for temperature compensation, the strand burner facility at ARL does not have the capability to perform experiments at temperatures other than ambient. Therefore, all experimental data within is at ambient temperature.

2. Experimental Methods

2.1 Test Article Fabrication

The base propellant chosen for these experiments was AFP-001, lot RDD14F-00183. The samples were furnished in 20-cm (8 inch) long strands with a diameter of approximately 0.76 cm (0.30 inches). Strands were cut to produce 4 samples of 5 cm (2 inches) each. Overall, there were 4 different configurations: baseline, a C-100 coated, an SC-11 coated, and a urethane acrylate (UA) coated. C-100 is a polyurea based coating, SC-11 is an epoxy-based coating, and UA is a urethane-acrylate-based coating. These coatings were chosen to target a specific strength–toughness property, which can relate to specific mechanical properties. An in-depth detail on coating selection and mechanical properties can be found in a report by Robinette et al.[6] When performing strand burner experiments it is sometimes required to coat the propellant grain to inhibit flame spread resulting from edge effects. Since this experiment was evaluating specific coatings it was necessary to leave the base grain uninhibited to acquire the best comparable data. As such, the base grain did not appear to exhibit any edge effects during the course of the experiment (Fig. 1).

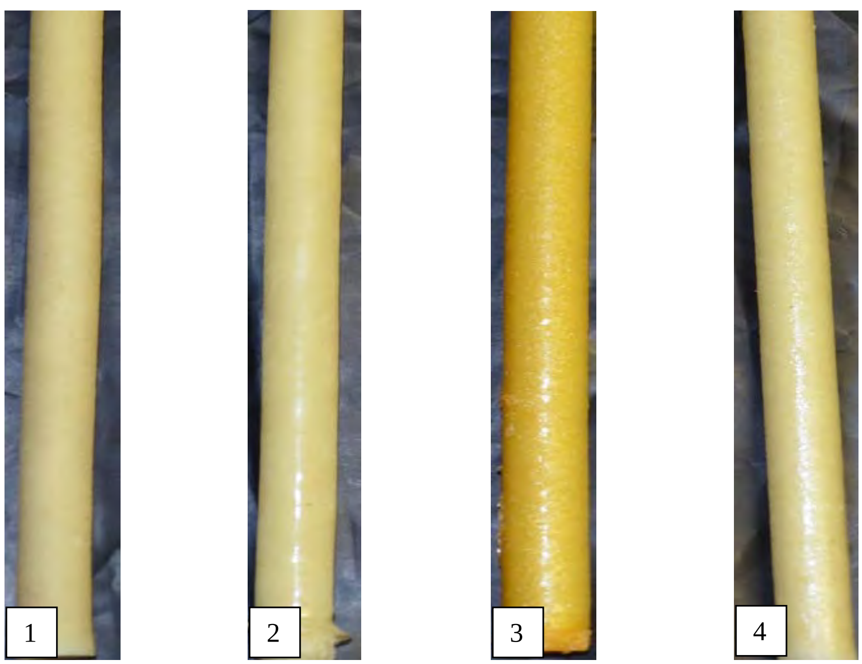

Fig. 1 Images of samples: 1) baseline AFP-001, 2) C-100, 3) SC-11, and 4) UA coated

2.2 Measurement Techniques

The prepared samples were all burned at a constant pressure ranging from 1.75–6.90 MPa (250–1,000 psi) in the ARL low-pressure strand burner,[7,8] as schematically shown Fig. 2. The apparatus includes a windowed chamber that is capable of being pressurized up to 10 MPa (1,450 psi, where atmospheric pressure is nominally 14.7 psi). In order to keep constant pressure the system includes a ballast tank that adds considerably to the system's overall volume, thus negating pressure increases due to propellant combustion. Nitrogen was employed as the pressurizing gas. Pressure was measured with both a Setra Systems pressure transducer and a Heise mechanical dial gauge. The desired chamber pressure for each experiment was established just prior to ignition. Ignition was achieved by running current through a nichrome wire placed on top of the sample. Events were recorded with a Phantom high-speed camera equipped with a fixed 50-mm Nikon lens and an aperture setting of f/8. Images were acquired at 60 frames per second (fps) with exposure ranging from 40–200 µs, depending on pressure regime. To prevent smoke and soot buildup from obscuring the camera's view, a slow, steady stream of nitrogen was flowed through the chamber during the course of each experiment. Gas flows from the inlet at the center of the chamber's base towards the exhaust port located at the center top of the chamber. In and out flow of gas is balanced such that the pressure remains constant in the chamber. Data from the event is processed with software provided by the camera manufacture to generate distance versus time plots, which are then given a linear fit to provide burning rate information.

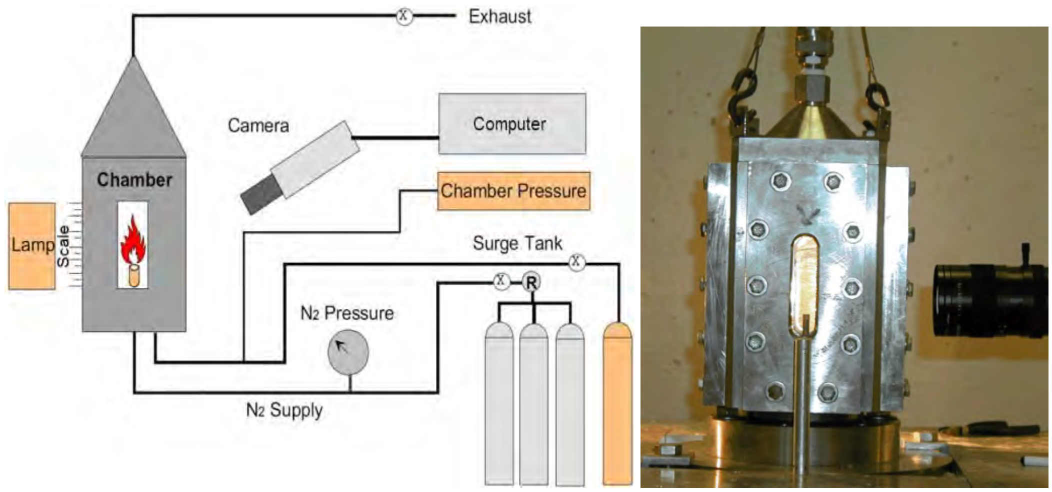

Fig. 2 Schematic of strand burner facility (left), windowed strand burner (middle), and control panel (right)

3. Results

3.1 Baseline

The baseline AFP-001 samples showed good end-burning behavior with data easily recorded. They burned in a flat, cigarette-like fashion as expected. However, it should be noted that at the lowest pressures (1.74 MPa) the samples exhibited a less than ideal burning profile, as if they were struggling to sustain a flame. Figure 3 illustrates the lack of flame development at low pressure versus higher pressure where the flame is fully developed. Furthermore, the samples would not ignite via the nichrome wire at atmospheric pressure (0.101 MPa).

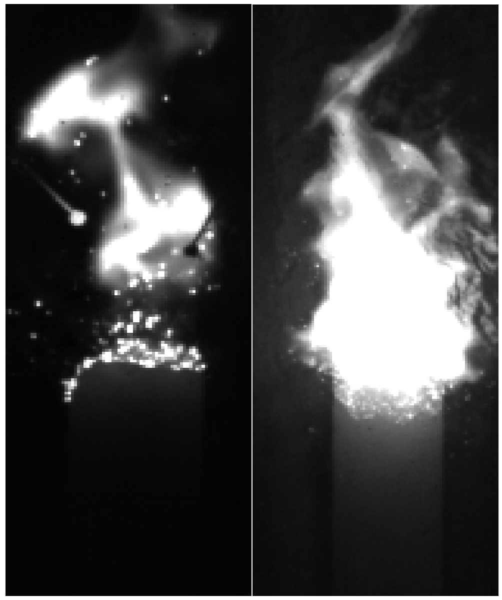

Fig. 3 Flame development at 1.74 MPa vs. 3.43 MPa

Measuring the burning rate at various pressures will allow the burning rate to be expressed by Vieille's Burning Law (Eq. 1), where BR is the burning rate, A is the burning rate coefficient, P is pressure, and n is the burning rate exponent.

$$BR = AP^n \tag{1}$$

For the baseline AFP-001 propellant the burning rate coefficient is 0.147 and the burning rate exponent is 1.144. Table 1 summarizes the burning rate data recorded from the baseline propellant. Plotted on a log-log scale of pressure versus burning rate and fitted with a power law trend line yields the plot in Fig. 4.

Table 1 Burning rate data for baseline AFP-001 grain

P (MPa)	BR (cm/s)	R^2
1.74	0.269	0.9964
1.72	0.253	0.9955
3.43	0.727	0.9988
5.15	1.027	0.9996
6.86	1.147	0.9991

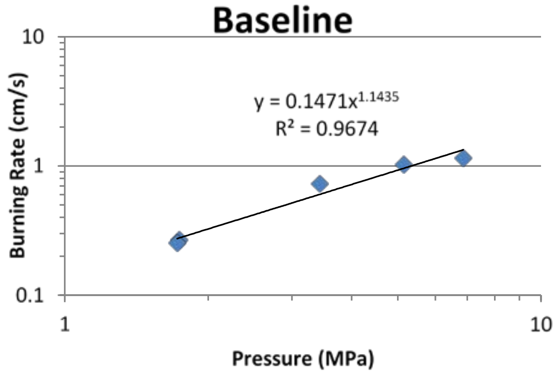

Fig. 4 BR of baseline AFP-001 propellant

3.2 Coated Propellants

Similarly, experiments were conducted on the coated AFP-001 samples and they too exhibited good, end-burning behavior. At pressures above 5.20 MPa the C-100 and UA coatings left a small amount of a gummy residue upon post-burning inspection. From the video images it appears the coating is melting away similar to a candle wax. At lower pressures the coating is consumed during the combustion event. The melting can be seen in Fig. 5 below where the dark spots inside the red circles appear to drip during the videos. From the videos it appears that the SC-11 coating produces the most soot, while the C-100 coating was the cleanest burning with respect to baseline AFP-001. The baseline was the least sooty of all samples.

Fig. 5 Image of C-100 coated propellant. Red circles indicate melting of the coating.

In general, the C-100 and UA coatings had minimal to no significant impact on the burning behavior of the AFP-001 propellant. Not surprisingly the baseline propellant exhibited the fastest burning rates, excluding the C-100 coatings burning at 1.72 MPa. At lower pressures there was a noticeable decrease in burning rate of the coated propellants, but as pressures approached 6.90 MPa there was less than a 4% reduction in burning rates between the baseline and C-100 or UA. The coating that appeared to exhibit the largest influence on the burning behavior was the SC-11. Its burning rate decreased 12% at the lowest pressure, 29% at the highest pressure, and up to 49% at the middle pressures. In general the coatings had less of an impact on burning rate differences as the pressure increased. The discrepancies at the lowest pressure may be attributed to the base grain's apparent difficulty in sustaining a consistent burning at that pressure. Tables 2–4 summarize the experimental results of the various coatings. Figure 6 illustrates their respective plots.

Table 2 Burning rate data for C-100 coated AFP-001 propellant

P (MPa)	BR (cm/s)	R^2	% Decrease of baseline
1.72	0.328	0.9993	12.1
3.46	0.646	0.9996	49.0
5.16	0.931	0.9992	40.8
6.92	1.102	0.9990	29.2

Table 3 Burning rate data for SC-11 coated AFP-001 propellant

P (MPa)	BR (cm/s)	R^2	% Decrease of baseline
1.75	0.236	0.9995	–22.2
3.43	0.370	0.9998	11.1
5.20	0.608	0.9998	9.4
6.70	0.812	0.9999	3.9

Table 4 Burning rate data for UA coated AFP-001 propellant

P (MPa)	BR (cm/s)	R^2	% Decrease of baseline
1.74	0.281	0.9986	–4.4
3.45	0.455	0.9984	37.4
5.18	0.907	0.9994	11.7
6.89	1.107	0.9988	3.5

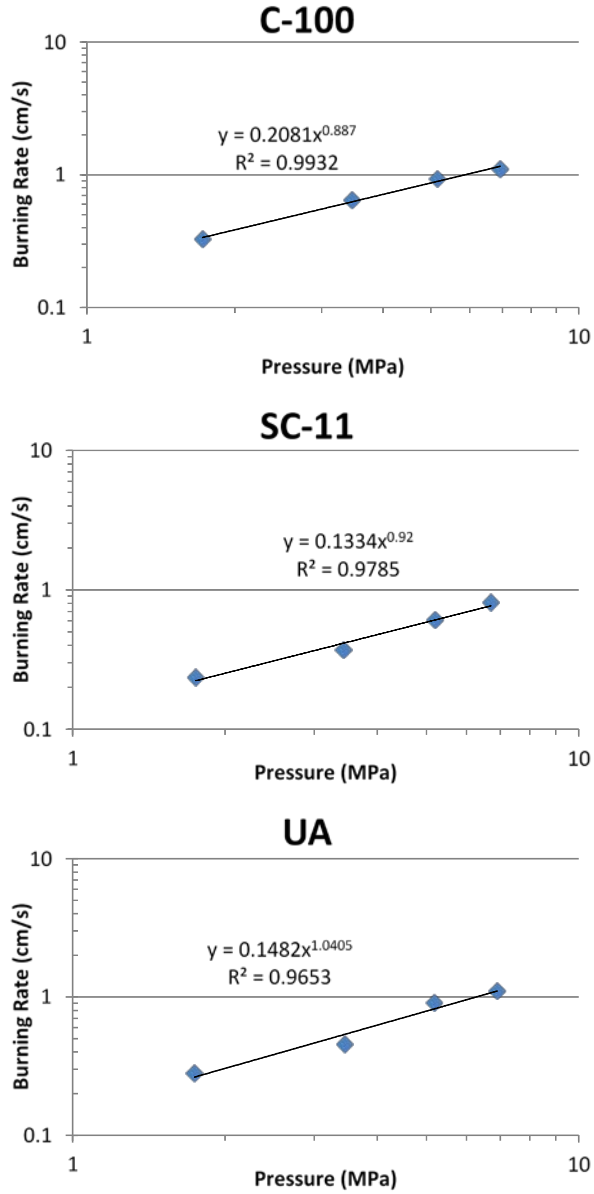

Fig. 6 Burning rate plots for AFP-001 coated propellants

4. Summary and Conclusions

The ARL windowed strand burner was employed to visualize the burning phenomena associated with coated AFP-001 propellant. Three different coating polymers were chosen for the experiments: an epoxy (SC-11), polyurea (C-100), and UA. The coatings were chosen for their various mechanical properties with the goal of eliminating temperature effects on a base propellant grain. The strand burner was employed to determine what effects, if any, the coatings would have on the base grain at an ambient temperature of up to 6.90 MPa.

The results indicate that the C-100 and UA coatings have a modest impact on the burning rate of the base grain at lower pressures, but at the maximum experimented pressure of 6.90 MPa the impact was trivial. However, the SC-11, epoxy-based coating, exhibited a much larger impact on burning rate performance; qualitatively, it also seems to have generated the greatest level of soot. The epoxy decreased the baseline propellant burning rate between 10%–50% depending on operating pressure. In general the coatings appear to have the greatest influence at the low end of the pressure range with a decreasing impact on performance as pressure is increased. This result is favorable for temperature compensation.

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List of Symbols, Abbreviations, and Acronyms

ARDEC	Armament Research, Development and Engineering Center
ARL	US Army Research Laboratory
BR	Burning Rate
cm	centimeter
cm/s	centimeter per second
fps	frames per second
FREEDM	Future Requirements of Enhanced Energetics for Decisive Munitions
JIMTP	Joint Insensitive Munitions Technology Program
P	Pressure
psi	pounds per square inch
MPa	Megapascal
mm	millimeter
R^2	coefficient of determination
UA	urethane acrylate
μs	microsecond

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