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FLAMESPREADING MEASUREMENTS AND MECHANISMS IN PERFORATED LOVA GUN PROPELLANTS

MARTIN S. MILLER

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Flamespreading rates in simple linear arrays of individual grains have been measured for two lots of LOVA gun propellant. Differences were sought which might explain the pressure behavior exhibited in ballistic tests. Although no significant differences were found, an abrupt pressure threshold for rapid flamespreading involving convective burning in the perforations was found. Further experiments with parallel solid strands separated by a variable gap width revealed a second mode for rapid flamespreading. Both modes are likely to be important during the ignition transient in guns and may present opportunities for control over ignition delays and reliability through grain geometry design.

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I. INTRODUCTION

The present work was motivated by the observation during gun firings of a higher maximum pressure for one of two nominally identical lots of LOVA propellant. The two lots, A2-201 and A2-202, are unimodal RDX/CAB/ATEC/NC formulations. Due to a change in processing sequence, A2-201 was known to contain higher agglomerations of RDX particles and was the lot which resulted in higher maximum pressures in the ballistic tests. Closed bomb tests (see Figure 1) indicated that the two lots had the same burning rates above 28 MPa, but over the range 13-28 MPa the A2-201 lot appeared to burn about 30% faster. In a strand burner, burning rates under constant pressure conditions were measured for individual grains and found to be the same for the two lots over the range 1-4 MPa. Note that the closed bomb data extends down to about 13.5 MPa though data below about 34 MPa is often considered unreliable due to effects associated with ignition of the charge. Each of these data points, however, are averages of three separate runs so that the differences in apparent burning rate are reproducible even if not necessarily the actual linear burning rate. The hypothesis was advanced that the difference in apparent burning rates between the two curves in Figure 1 may reflect differences in flamespreading rates between the two lots.

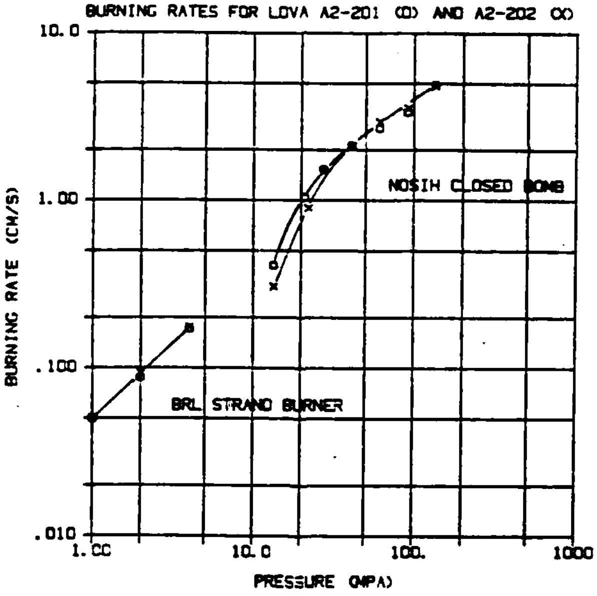

Figure 1. Comparison of Burning Rates Measured in the Closed Bomb and Strand Burner

The goal of this study was to develop a simple but controlled laboratory flamespreading test for use as a comparative analysis tool in propellant development. Although the objective has not yet been achieved, a number of interesting features of the phenomena have been revealed and progress has been made toward breaking the process down into its component parts. This kind of understanding is needed in order to insure that the lab test being developed will reflect all of the mechanisms relevant to interior ballistic effects.

II. GENERAL EXPERIMENTAL PROCEDURES

All of the work reported here was performed with a low pressure strand burner operated at approximately constant pressure. This apparatus consists of a steel vessel with four acrylic windows. In normal operation a mechanical pressure regulator is used to maintain a constant pressure by regulating the flow of nitrogen into the chamber. Nitrogen enters the chamber at its bottom and forms an axial shroud about the sample. The exhaust flow, consisting of nitrogen and combustion gases, exits at the top of the vessel and is constricted by a removable sapphire orifice, the diameter of which is selected to provide the desired flow rate through the chamber. In all of the present measurements the orifice diameter was 0.44 mm resulting in flow rates between 17 and 68 slpm over the pressure range 1-4 MPa. All measurements were made at ambient temperatures (21-25°C). Ignition of the LOVA grains (whose dimensions were about 0.8 cm diameter x 0.8 cm long) was in all cases effected by means of an M30 pellet (1.7 mm thick x 6.4 mm dia.) glued to the top of the grain. The thickness of the pellet, which determines the vigor of ignition, was controlled by a micrometer-drive wafering saw and therefore should be the cause of negligible variation in ignition stimulus. The M30 pellet was ignited by a hot wire.

The combustion events are recorded by a 30 Hz, shuttered video camera/recorder to which a 10 microsecond strobe is synchronized. A time code generator superimposes the elapsed time on each video frame. Motion analysis is permitted by an on-screen X-Y coordinate digitizer.

III. LINEAR BURNING RATES

Measurements of the linear burning rate were first performed on individual grains. The ends of each grain were first cut normal to the axis of the grain, then glued to a plastic mount. The perforations were thus blocked at one end. Previous experience with perforated LOVA grains had indicated that inhibition of the perforation walls was not necessary at the pressures used here. Reproducibility in the burning rates was good despite the shortness of the grain. Results are given in Table 1 and shown in Figure 1.

Table 1. Measured Linear Burning Rates for Three Lots of LOVA Propellant

Lot	Pressure (MPa)	Rate (mm/s)
A2-201	1.0	0.501 ± 0.017
A2-201	2.0	0.883 ± 0.020
A2-201	4.0	1.73 ± 0.136
A2-202	1.0	0.507 ± 0.027
A2-202	2.0	0.937 ± 0.019
A2-202	4.0	1.78 ± 0.044
A1-0585-113	2.0	0.81
A1-0585-113	2.5	1.11
A1-0585-113	3.0	1.39
A1-0585-113	4.0	1.70

IV. FLAMESPREADING OBSERVATIONS AND RATES

Figure 2 shows the arrangement for the first set of tests. A linear, vertical array of six grains is ignited at the top and the flame observed to spread downward. The grains were affixed to a pair of alumina rods using cyanoacrylate adhesive allowing about a 1/16 in. (1.6 mm) gap between end faces of adjacent grains. An attempt was made to align the perforations of the grains but, because of the small perf size (0.38 mm) and large number of perfs (19), this goal could only approximately be met.

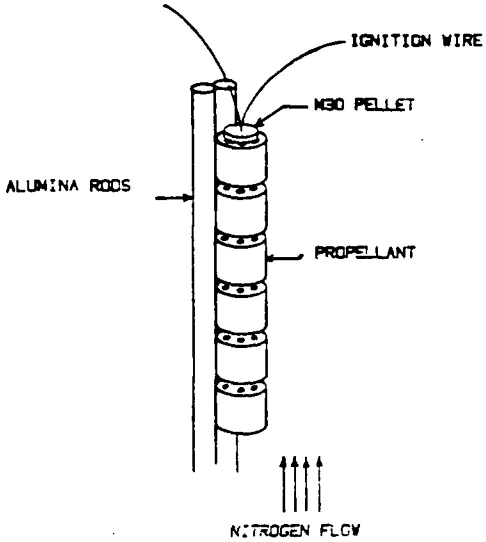

Figure 2. Experimental Arrangement for Observing Flamespreading by the In-Perf Mode

The test was conducted at 1, 2, 3, and 4 MPa. Below 4 MPa the grains in the array burned one by one at the same rate measured above. At 4 MPa flame penetrated the perforations quickly and plumed out of the gap between the first and second grains before much change in the side dimension could occur. This process was repeated in subsequent grains of the array. In some cases this cascade of flame occured quickly enough that the last (bottom) grain was ignited before the first grain was consumed. The thickness and vigor of the flame emerging at each gap suggested that small changes in gap width would not influence the result although this was not checked experimentally. Chamber pressure during these events was monitored by a Heise (bourdon type) gauge and observed to rise by about 30%. However, since the gauge was connected to the chamber by several meters of small gauge tubing, the actual chamber pressure rise would have been higher. This lack of constancy in pressure leads to some variability in the quantitative flamespread measurements. If we define the flamespreading rate as the length of the grain divided by the difference in times between first light in successive gaps, the rate at 4 MPa is 3.7 ± 1.1 cm/s for A2-201. For a given run this rate is computed only over the interior 4 grains to eliminate end grain effects. The measurements for each of these grains is then averaged. The averages for each of 7 runs are averaged to give the above rate. Because very little propellant was available from the A2-202 lot, only 2 runs were made giving 4.4 ± 0.8 cm/s.

In relation to the experimental precision of these measurements (about 30%), there is no discernible difference in flamespreading rate between the two lots. Although the outer surfaces of the grains were not chemically inhibited, flamespreading on the outer surfaces played no role in these experiments. The orderly axial arrangement and perforation alignment of the array is also such that we are probably measuring the maximum rate of flamespread. Nevertheless, it seems likely that other arrangements would give proportional results.

On the other hand, the above experiments reveal interesting phenomena relevant to an understanding of interior ballistic processes. At 3 MPa there is no perforation involvement and the flamespread rate (for this grain arrangement) is the same as the linear burning rate, i.e., slow (0.17 cm/s). With just a 30% increase in pressure, the flame spreads (again, for this arrangement) at some 20 times the linear burning rate. Such an abrupt and dramatic change in behavior could have important implications for early flamespreading rates in guns.

V. CONDITIONS FOR FLASH-DOWN

In order to define the circumstances under which the flame flashes down through the perforations, experiments were conducted on single grains mounted as in Figure 2. The center perforation was drilled out to larger diameters and ignited at different pressures to determine a go/no-go map for flash-down as a function of these variables. The results are shown in Figure 3. It is clear that flash-down occurs at lower pressures when the perf diameter is increased. This observation is consistent with that of Margolin and Chuiko[3] who described the go/no-go boundary as a constant product of pore diameter and burning rate. Similarly, Belyaev, et. al.,[4] described the boundary as a constant product of diameter and pressure. These relations suggest that, in addition to its classical function in gun performance, the perforation size may play an important role in determining the length and character of ignition delays in guns (at least with LOVA propellants). Ballistic simulator tests[1,2] with LOVA propellant have established that relatively long delays occur at about 2 MPa during the ignition transient. It may be possible to shorten this delay by either increasing the chamber pressure caused by the primer or increasing the perforation diameter.

VI. INTERSTITIAL FLAMESPREADING

As pointed out above, the linear array tests did not allow an examination of flamespreading along the lateral surfaces of the grains. From the single grain tests of Section V, it was found that the flame does not propagate along the outer surfaces at a rate faster than the linear burning rate; however, one could imagine that cooperative burning between adjacent surfaces might enhance the rate of flamespread. This mode of propagation might be termed interstitial flamespreading. In order to test this possibility, two solid strands of LOVA propellant (A1-0585-113), with compositions nominally identical to A2-201 and A2-202 except for a bimodal distribution of RDX particle sizes in the A1, were positioned parallel to one another with a given gap size between them, as shown in Figure 4. The twin strands (each 0.38 cm in diameter by 3-5 cm long) were oriented vertically and ignited at the top with a bridge of M30 pellets.

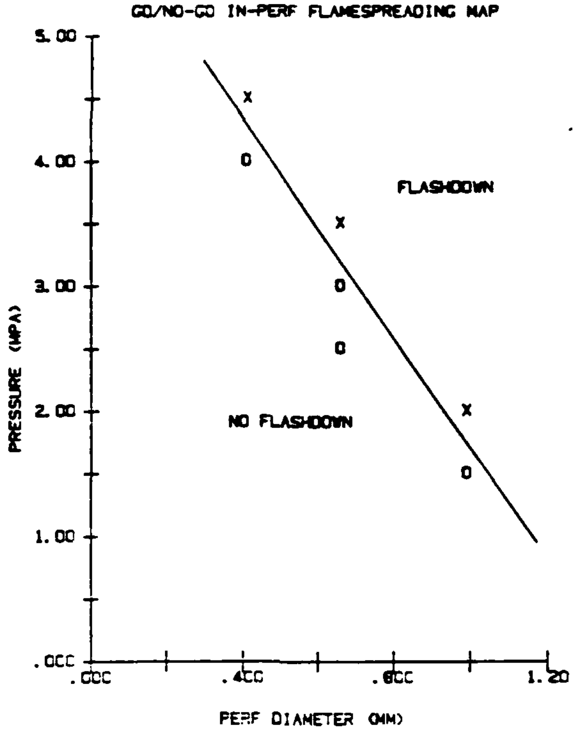

Figure 3. Map Summarizing Conditions for Rapid Flamespreading by the In-Perf Mode

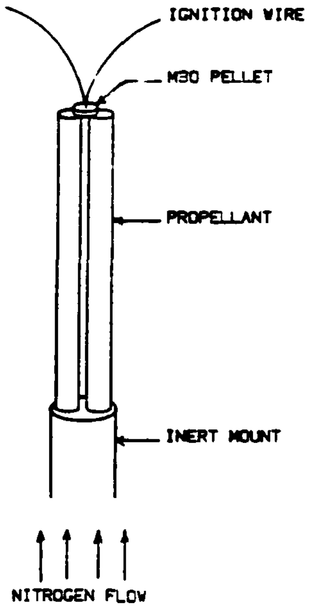

Figure 4. Experimental Arrangement for Observing the Interstitial Mode of Flamespreading

The result of this test was that for sufficiently small gaps and high pressures the flame propagated rapidly (20 times the linear burning rate at one set of conditions) down between the two strands. This was surprising as there was no confinement, such as in a perforation, to sustain local pressure increases and no convective flow in the downward direction ahead of the flame front. The purge flow, in fact, was counter to the direction of flamespread. The observations are summarized in Figure 5. The go/no-go boundary (dashed line) is only suggestive in view of the incompleteness of the data; however, it is consistent with the observations and is arguably plausible. The existence of a maximum gap width beyond which flashdown cannot occur for any pressure is certainly reasonable. The low pressure portion of the boundary is related to the existence of a pressure threshold for the appearance of the visible flame. This threshold is observed to be about 2 MPa for this propellant. The points in Figure 5 at the 2 mm gap are assigned from a single run. At the beginning of the run, ignition of the M30 pellet caused about a 10% increase in test chamber pressure and cooperative burning occurred between the two strands. (Transient chamber pressure measurements were made in this set of experiments.) As the pressure (controlled by a mechanical regulator) stabilized to 2.0 MPa, the strands began to burn independently of each other. At 2 MPa and a 0.8 mm gap, cooperative burning occurred over the entire length of the strands although the flamespreading rate was only a few times the linear burning rate, this point is therefore probably close to the boundary. The flame bridging the gap in this case was much brighter than that for an isolated strand at this pressure (which is barely visible). Thus, the visible flame appears to be an important factor in the flashdown phenomenon.

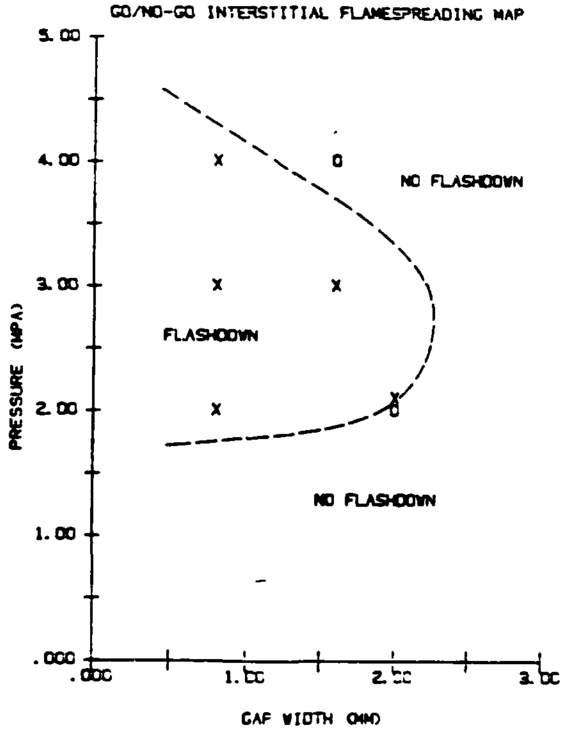

Figure 5. Map Summarizing Conditions for Rapid Flamespreading in the Interstitial Mode

The behavior in the high pressure part of the boundary would seem to be due to the interplay of two factors: radiation and convective heating. At a given pressure, radiative heating of one strand by the other should diminish with increasing gap, in agreement with Figure 5. However, at a fixed gap, radiative heating should increase with pressure as the flame burns more brightly, in contradiction to Figure 5. The other factor, convective heating of one strand by the visible flame of the other, seems to be in complete accord with the high pressure leg of the flashdown map. At a given pressure, increasing the gap eventually removes the heating effects. Since the flame standoff distance decreases with increasing pressure, at a given gap the increase of pressure may eventually decrease the overlap and interaction between the flame zones of the two strands. This may be the explanation of the observed behavior at 3 and 4 MPa for the 1.6 mm gap.

The linear burning rates for A1-0585-113 (See Table 1) were measured for a few strands and found to be in good agreement with the values for the granular material. At 4 MPa the flame speed in the gap (0.8 mm) was clocked at 2.5 ± 1.8 cm/s. At 3 MPa flame speeds were 2.7 ± 1.3 cm/s in the 0.8 mm gap and 1.6 ± 0.5 cm/s in the 1.6 mm gap.

To further investigate the plausibility of the flame zone convective heating effect, the flame standoff distances (surface to beginning of visible flame) as a function of pressure were measured. Results are given in Figure 6. At 3 MPa the standoff distance is 1.1 mm and flashdown is observed at gap widths of 0.8 and 1.6 mm. Thus, if flashdown can occur when the gap is less than, say, two standoff distances, an extrapolated standoff distance at 4 MPa of 0.4 mm allows flashdown in the 0.8 mm gap but not in the 1.6 mm gap, in agreement with observation. These arguments, while plausible, are rather speculative in view of such scanty data; however, they do give direction to follow-up work.

VII. CONCLUSIONS

Differences in the interior ballistics of nominally identical lots of LOVA propellant prompted the design of controlled laboratory experiments designed to detect differences in flamespreading rates between the two lots. The tests showed no significant differences but led to further study of the flamespreading process and conditions under which it was distinguishable from linear surface regression.

Flamespreading rates in excess of 20 times the linear burn rate were measured in simple linear arrays of LOVA propellant grains at pressures near 4 MPa. This phenomena is therefore likely to play a critical role in the ignition of propelling charges in guns. Two significant modes of rapid flame propagation have been identified in this work: in-perforation and interstitial flamespreading. The in-perf mechanism onsets abruptly when the pressure exceeds a threshold value which increases with decreasing perf diameter. The interstitial mechanism appears to have more complex criteria but can occur for gaps smaller than some threshold value which decreases with pressure in some cases. This behavior is consistent with convective heat transfer from the flame zone of one burning surface to an adjacent one. Though the data is rather incomplete, the trend is still clear that interstitial flamespreading is a potentially important mode of flamespreading in both granular and stick propelling charges and is governed by different criteria than the in-perf mode. An understanding of these two modes may lead to constraints on grain geometry (perf diameter and external shape) which minimize ignition delays and maximize ignition reliability in addition to the classical function of grain design.

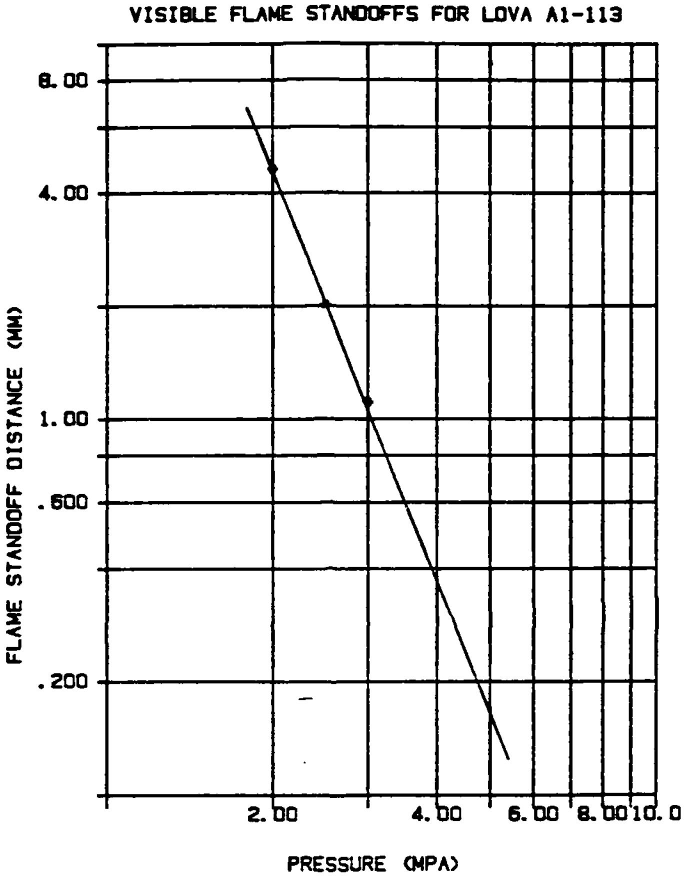

Figure 6. Flame Standoff Distances (Surface to Luminosity) for LOVA Lot A1-0585-113

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