Propellant Burning Rate Uniformity Identified by Ultrasonic Acoustic Emissions

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The objectives of the study were to develop a methodology for measuring solid propellant burning rates and burning rate nonuniformities at high pressures. Burning rate variations of nitrocellulose-based propellants (M1 and M26), burning at pressures between 10,000 and 40,000 psi, are recognized by examining the level of the combustion-generated acoustic emissions. Multiperforated propellant grains are burned lengthwise (1 to 1.5 cm) and the rms levels of ultrahigh-frequency acoustic emissions are recorded. The burning rate variations of single-base propellants are attributed to incomplete dispersion of fibrous nitrocellulose. The double-base propellants produced neither irregularities in their acoustic emissions nor unusual variations in burning rate. These uniformities are attributed to the nitroglycerin, which acts to disperse the nitrocellulose and to enhance burning rate.

Introduction

A TECHNIQUE has been demonstrated for recognizing localized and intermittent variations in burning rate, i.e., burning rate variations occurring in regions as small as 0.5 mm and over time intervals of a few milliseconds. The diagnostic technique described in this paper is capable of recognizing burning rate variations that occur in individual grains of nitrocellulose-based propellants. Average burning rate variations traditionally are recognized from r vs p data obtained by burning long strands or from detailed analysis of closed-chamber p vs t records. However, these methods seldom give clues as to why the burning rate deviates from a standard. Furthermore, it is not uncommon to experience increases in the standard deviations of burning rate, operating pressures, and other types of performance parameters which cannot be related easily to any particular average burning rate measurement.

The value of this type of nonuniform burning determination is immediate. For example, the results show that propellants with short, localized burning rate variations have proportionally larger average burning rate standard deviations; these larger deviations (which would be masked in long strand data) may be symptomatic of unacceptably large deviations in ballistic performance. As another example, the technique has utility as a process control tool which enables the process engineer to locate the source of burning variations; short, localized burning rate variations may be symptomatic of problems such as incomplete mixing, porosity, and irreproducible flow alignment during extrusion or casting. The technique is being evaluated for use as part of the on-line quality control of propellants manufactured by continuous processes. In that application, the propellants are tested immediately after the grain extrusion step; thus, process corrections can be made within a relatively short time interval.

Apparatus

An apparatus was developed in which the primary observables are: 1) ultrahigh-frequency acoustic emission (UHFAE) generated by the combustion process;[1-3] and 2) very small pressure fluctuations, which are a direct consequence of burning propellants in a hydraulic medium with a very small free gas volume. This study employs the apparatus to focus on the combustion of nitrocellulose-based solid propellants in the form of multiperforated grains and conventional strands. Individual components of the high-pressure (up to 50,000 psi) apparatus include an air-actuated high-pressure hydraulic pump, a liquid-filled (usually water) combustor cell, the UHFAE data acquisition system (Dunegan/Endevco AE 4001 amplifier, 802P-A preamplifier, and 731 transducer), and a 100 kHz piezoelectric pressure transducer (Kistler 607A).

The combustion-generated UHFAE sensed by an acoustic transducer is processed as shown in Fig. 1. The transducer output is filtered and frequency components above 100 kHz are preamplified 1000 times (60 dB) and then conditioned in a frequency-to-voltage (FTV) converter which was set to produce a 1- to 10-V signal when rapid changes in acoustic emission frequency occurred. The burn duration is determined directly as the period of this latter signal. This acoustic burning rate measurement technique eliminates the drilling of holes for breakwires and precludes propellant contact with anything but the burn medium.

The UHFAE signals are stored in a digital waveform recorder capable of sampling the conditioned data at rates as fast as 0.01 msec. These data are accompanied by the pressure history of the combustor (i.e., total pressure rises are typically 1 to 4%) and the output of a time-mark generator used as a time reference to determine accurately the burning interval.

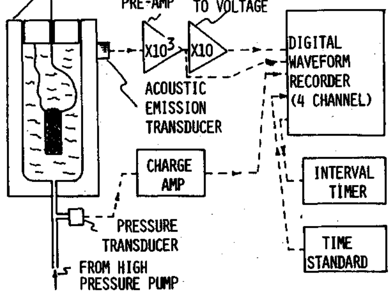

Fig. 1 Instrumentation used to measure burning time interval and acoustic emissions.

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One of the goals of this study was to make direct determinations of the burning rates of as-manufactured propellants, which in this case were propellant grains with seven perforations and outside diameters ranging from 0.6 to 1.2 cm and lengths ranging from 1.0 to 1.5 cm. Accordingly, the grains were burned lengthwise as strands. To prepare the test specimens, individual grains were trimmed square and measured to within ±0.005 cm. Then, a flattened nichrome-wire igniter in zig-zag form was mounted on one end of the strand with a smear of acetone-based cement. Finally, to promote uniform flame spreading across the surface, a thin (0.05 cm) cardboard disk was held lightly against the nichrome wire.

The strand and its mount assembly were installed in the combustor which had been prefilled with tap water of controlled temperature and the system was pressurized to the desired pressure. To avoid questions concerning the immersion time, ignition was programmed to occur three minutes after the propellant first was immersed.

In most cases, the liquid medium effectively prevented flame spreading along the side of the propellant strands. However, in the experiments discussed here, the grains were inhibited to eliminate all questions concerning flame spreading into the perforations.

Previous studies[2,4] have demonstrated that when the experiment is properly designed, burning in a liquid medium does not affect burning rate. High-speed photographs reveal that the combustion gases issuing from the burning surface form a gaseous atmosphere above the burning strand which prevents the surrounding liquid from coming into contact with the burning surface. However, if either the pressure is sufficiently low or the cross-sectional dimensions of the strand are sufficiently small, the momentum of the gases issuing from the burning surface will be too low to exclude the surrounding liquid.

Results

The burning rate properties of the propellants listed in Table 1 were studied. Nitrocellulose (NC) is the primary ingredient in all of the propellants. The Lot U M1 propellant has a higher K_2SO_4 and entrained water content than the Lot P M1 propellant.

The fibrous NC used in the M1 propellants becomes tangled and causes discontinuities (with dimensions on the order of 1 mm). Those regions in which the tangles of fibrous NC have not been dispersed have relatively small concentrations of the other propellant ingredients, all of which act to suppress burning rate and energy level. It is well known that increasing the energy of NC-based propellants also increases their burning rates. Accordingly, it is reasonable to expect the discontinuous regions containing higher NC concentrations to have higher burning rates. The nitroglycerin which is added to increase energy also acts as a plasticizer and, thereby, tends to distribute the fibrous NC to make the propellant more homogeneous. Accordingly, M26 propellants appear to be much more uniform in composition than the M1 propellants.

The burning rates of the propellant grains burned as end-burners are shown in Figs. 2 and 3. The range, number, and mean value at each test pressure are indicated on the figures. The variations in the M26 burning rates are less than those for M1. As shown in Fig. 3, the burning rate variations of propellant M1 Lot P are greater than those of propellant M1 Lot U.

The frequency-to-voltage (FTV) signal resulting from the acoustic emissions, the AC components of the acoustic emission signal, and the pressure rise records for representative tests are shown in Figs. 4–6. The results for an irregularly burning propellant specimen (Fig. 4) should be compared with those of a uniformly burning propellant specimen (Fig. 5). The history of propellant burning can be traced on Fig. 4. When the propellant ignites, a rapid onset of the acoustic emission signal occurs and the pressure in the chamber begins a uniform rise. When the propellant combustion and burning rate are uniform, the acoustic emission level (particularly the FTV signal) is reasonably constant (e.g., the upper trace on Fig. 5) compared to the six prominent spikes which appear on Fig. 4. Such spikes corresponding to enhanced UHFAE output are referred to as A.E. blasts. The peak pressure occurs at strand burnout. Note that a propellant

Table 1 Propellants used in experiments

	Single base M1		Double base
	Lot U	Lot P	M26
Nitrocellulose[a] (13.15% nitration)	84.73	84.74	67.25
Nitroglycerin	0	0	25.0
Dinitrotoluene	9.97	9.65	
Barium nitrate			0.75
Potassium nitrate			0.70
Ethyl centralite			0.30
Dibutylphthalate	5.30	5.61	
Diphenylamine	1.07[b]	1.10[b]	6.0
K_2SO_4	2.10[b]	0.62[b]	
Total volatiles	2.67	0.95	
Residual solvent	0.27	0.18	1.20
Water	2.40	0.77	0.3
Grain diameter, cm	0.60	0.60	
Lot	RAD-PE -441-U	RAD-PE -441-P	RAD-65116

[a]Wood sulfite cellulose. [b]Added to basic propellant.

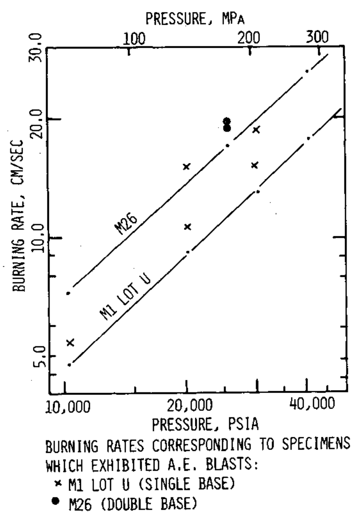

Fig. 2 Comparison of single-base and double-base burning-rate data. (Tests which exhibited A.E. blasts are not included in mean.)

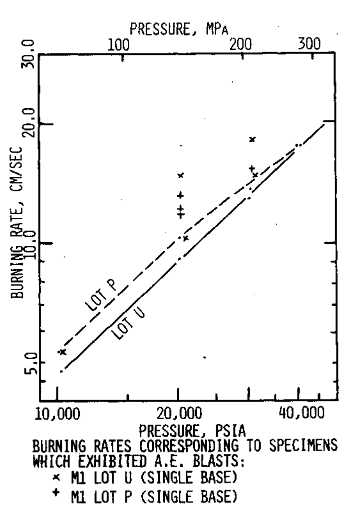

Fig. 3 Comparison of two lots of single-base propellant showing that the extremes of the burning-rate variabilities are similar. (Tests which exhibited A.E. blasts are not included in mean.)

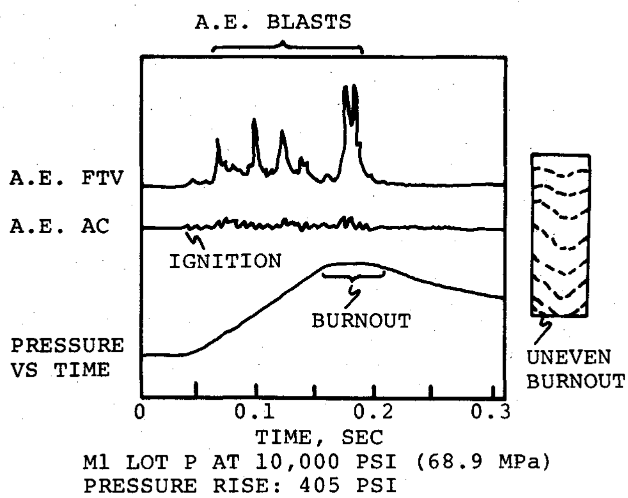

Fig. 4 Example of high level of acoustic irregularity and the corresponding uneven burnout as indicated by the lack of sharp pressure peak.

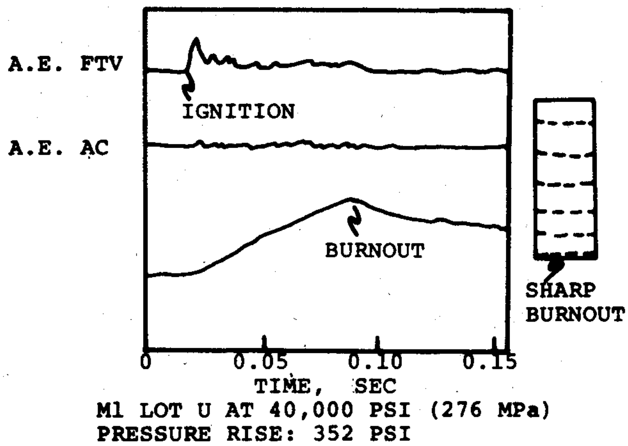

Fig. 5 Example of very regular acoustic emission and the corresponding sharp burnout.

grain with a regular burning rate has a well-defined pressure peak which corresponds to a relatively flat burning surface intersecting the base of the cylinder; whereas, the irregularly burning propellant grain has an ill-defined pressure peak (or a rather broad pressure plateau) corresponding to the irregular burning surface intersecting the base of the cylinder.

M1 and M26 grains that had burned about 4 or 5 mm were extinguished by rapid depressurization and the contours of the extinguished surfaces examined. The uniformly burning M26 propellant has surface irregularities which were generally 0.3 mm or less. The surface irregularities of the more uniformly burning M1 propellants were generally on the order of 1 mm and in cases of very irregularly burning specimens, pits as deep as 7 mm occurred. This is direct evidence that the A.E. blasts are associated with localized increases in burning rate.

The propellant specimens which produce the A.E. blasts and ill-defined pressure peaks also have appreciably shorter burning times. The A.E. blasts are believed to be produced during the combustion of local regions (with typical dimensions on the order of 1 mm) of significantly higher burning rate. Indicated on Figs. 2 and 3 are the burning rate points which were determined from grains which produced A.E. blasts. Note that in all cases those burning rates are high. A direct relationship was found between duration and severity of the A.E. blasts and the increase in burning rate above that of uniformly burning propellants. In Fig. 7, the rather large variations of burning rate of particular lots of M1 are plotted in terms of the duration of the A.E. blasts. A

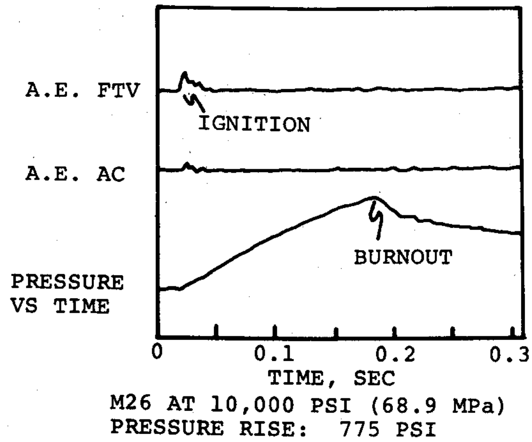

Fig. 6 Very low acoustic emissions from double-base propellant M26.

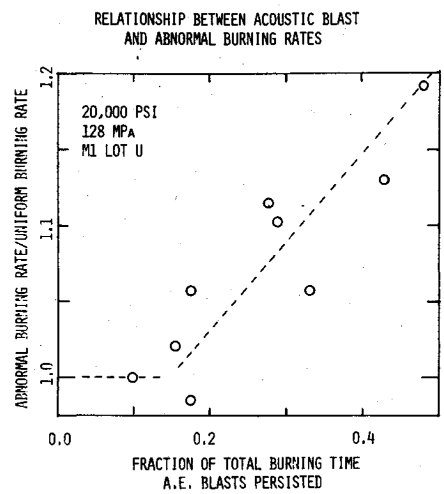

Fig. 7 Acoustic emission data indicate that burning rate increases abnormally during period of A.E. blasts.

refinement of this type of correlation has direct application in quality-control procedures.

Examination of the pressure rise on expanded time and pressure scales often reveals that, associated with the A.E. blasts there are small increases in the pressurization rate. This is further evidence that the A.E. blasts are associated with higher burning rates.

The acoustic emissions (following the ignition transient) from M26 propellant are barely perceivable using the same instrumentation and amplification as were used for the M1 propellants (compare the results of Figs. 5 and 6). Normally, the acoustic emission of the M26 was amplified by a factor of 10 higher than that in Fig. 6 in order to observe the signal.

The reason that the M26 propellant burns more uniformly is probably a result of the nitroglycerin acting as a plasticizer to disperse the fibrous nitrocellulose and the nitroglycerin acting to increase burning rate. Since the nitroglycerin dominates the burning-rate-controlling processes, its contributions overcome the discontinuities produced by incomplete dispersion of the fibrous nitrocellulose.

In summary, the foregoing discussion shows that three observations are consistent with abnormally short strand burning times: 1) intervals of increased acoustic emission, 2) gradual decrease in pressurization rate at strand burnout, and 3) extinguished burning surfaces which are irregular and pitted.

Conclusion

The detection of acoustic emission from burning propellants in addition to being used to time burning intervals also provides information relatable to the quality of burning and, thus, the quality of the propellant. Excessive variation in the acoustic emission level can be the basis for identifying a propellant lot that was improperly manufactured.

In the course of the study, burning rate irregularities of nitrocellulose propellants were related to the degree to which the fibrous nitrocellulose was dispersed. Energetic plasticizers which increase burning rate and improve mixing of ingredients are expected to improve burning rate uniformity.

Burning a propellant charge consisting of several hundred multiperforated NC grains tends to average the effects produced by the higher burning rates of individual grains. Nevertheless, propellant lots with higher populations of nonuniform burning grains will be manifested by higher overall burning rates (i.e., higher relative quickness[5] and less well-defined pressure vs time programs.

The technique described in this paper is relatively easy to implement and is applicable to all classes of propellants. Accordingly, it should be considered whenever propellant burning rate uniformity is in question (e.g., damage to propellants resulting from high strains, propellants in which dewetting of solid particles is a possibility, and propellants which contain networks of cracks or porous regions).

Acknowledgment

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