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Determination of Pressure Dependence of Burning Rate in Solid Motors Using Ultrasonic Technique

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The instantaneous burning rate of an aluminized composite solid propellant in a ballistic evaluation motor was measured continuously using an ultrasonic pulse-echo technique. The motor was designed to operate over a range of pressure from 2.5 to 4.5 MPa during its burning period. Hence, the burning-rate data could be obtained at different pressures directly from a single motor firing itself, and the data were used to determine the pressure dependence of the burning rate. Thus, the technique is shown to overcome the need for carrying out several strand tests or ballistic evaluation motor tests, each at a different pressure, for characterizing a solid propellant burning rate.

Nomenclature

a = constant in burning-rate law
C = acoustic velocity
K = constant
n = burning-rate index
p = pressure
r = burning rate
T = temperature
t = time
V = voltage
x = thickness
Δt = time lapse

Subscripts
p = pressure
R = reference condition
T = temperature

Introduction

IN conventional methods of the burning-rate measurement of solid propellants, e.g., using a strand burner or a subscale motor, the burning rate is determined by monitoring the time taken for the burning of an initially known thickness of propellant. These methods give the burning rate of a propellant specimen or grain at the web-average pressure, but do not give the local burning rate inside the propellant. Because each test gives only one value of burning rate (at the test-average pressure), the determination of the burning-rate index (n in the power law, $r = ap^n$) necessitates conducting several tests, each of them at a different pressure. Alternatively, the burning rate at different instants can also be deduced from the measured pressure–time history, knowing the surface area evolution profile; but this method would be affected by uncertainties like surface area, throat area, characteristic velocity, etc. These drawbacks of conventional methods can be overcome by the use of a measurement technique wherein the instantaneous burning rate is determined directly at different pressures as the propellant web burns. The ultrasonic pulse-echo technique is one such technique used for the measurement of the burning rate of solid propellants and fuels.[1–5]

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In the present work, an ultrasonic pulse-echo technique was employed to measure the instantaneous burning rate of an aluminized composite solid propellant at different pressures in a ballistic evaluation motor test, and the parameters a and n in the burning rate law $r = ap^n$ were obtained from a single test. Although the ultrasonic pulse-echo technique has been used for burning rate measurement by several authors,[1–5] there is no report of its application for determining the pressure dependence of a burning rate from a single motor test. The current work addresses this aspect. Emphasis was given to develop measurement procedures and a posttest data-processing methodology for achieving an accuracy of ±1% in burning rate measurements.

Experimental Details

Ultrasonic Pulse-Echo Technique

The application of an ultrasonic pulse-echo technique to measure the instantaneous burning rate of the propellant involves transmitting an ultrasonic pulse through the grain web, and the reception of the reflected echo pulse from a burning surface-combustion gas interface by the same transducer (Fig. 1). If the acoustic velocity in the propellant is known, the time lapse between the emitted pulse and the received echo-pulse gives the instantaneous web thickness of the propellant with time, and thereby an instantaneous burning rate can be evaluated as

$$x = C\Delta t/2 \tag{1}$$

$$r = -\frac{dx}{dt} \tag{2}$$

The ultrasonic equipment called the pulse-echo interface measurement system (PIM system) used for this work was developed by Prins Maurits Laboratory–TNO, The Netherlands.[4] The system uses a transducer operating at 2.25 MHz. It can emit and receive (echo) the pulses through the transducer at an adjustable rate of 0.5–5 kHz (in this work the pulse rate used was 2 kHz). The output of the equipment is the voltage corresponding to the time lapse between the emitted pulse and the user-selected pulse, e.g., echo pulse.

To reduce near-field effects and to ensure operation of the technique down to zero propellant thickness, an intermediary coupling material is used between the propellant and the transducer. This will also insulate the ultrasonic transducer from the severe pressure and temperature conditions in the motor. A proper selection of the transducer characteristics, coupling ma-

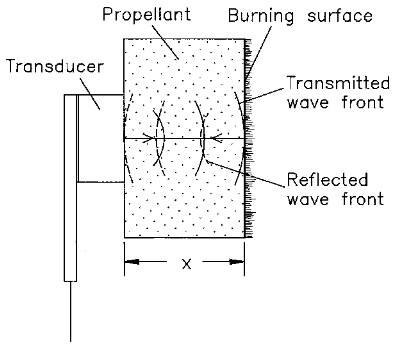

Fig. 1 Principle of ultrasonic pulse-echo technique.

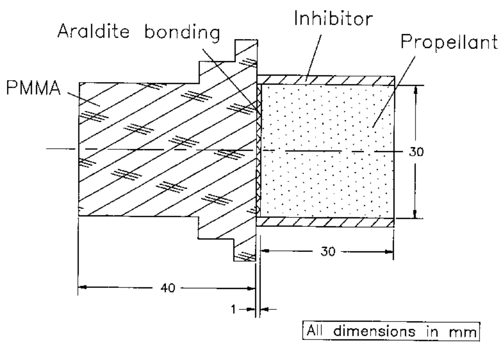

Fig. 2 Propellant specimen.

terial, its thickness, and proper bonding of coupling material with the propellant are important factors for the successful application of the technique.[1] Also, it is required to have a smooth and flat surface of the coupling material in touch with the ultrasonic transducer for better contact.

Preparation of Propellant Specimen

In the present work the burning rate of ammonium perchlorate–hydroxyl terminated polybutadiene–aluminum propellant (18% metal and 86% solid loading) was studied. Polymethyl methacrylate (PMMA) was used as the coupling material. A cylindrical piece of propellant (diameter-30 mm, length-30 mm) from the same batch mix of propellant as the motor, was bonded to the PMMA adaptor using Araldite (Fig. 2). The composition of resin (CY 230) and hardener (HY 951) in Araldite was controlled and all bubbles in the mix were removed by evacuation. The thickness of the Araldite layer used for bonding was maintained constant (~1 mm).

Measurement of Acoustic Velocity in Propellant

The measurement of the propellant burning rate by an ultrasonic technique requires prior knowledge of acoustic velocity in the propellant. The acoustic velocity in a material is obtained by measuring the time lapse between the emitted pulse and received echo-pulse (using the PIM system) for the known thickness of that material. Its dependence on pressure and temperature can be represented as[1]

$$C/C_R = [1 + K_T(T - T_R)][1 + K_p(p - p_R)] \tag{3}$$

where K_T and K_p are constants.

To evaluate K_T, the acoustic velocity in the propellant specimen was measured at different temperatures at the same ambient pressure. The propellant specimen mounted with an ultrasonic transducer (on the PMMA surface) was kept in a constant-temperature bath (temperature variation less than ±0.2°C) for 3–4 h. The specimen's temperature uniformity

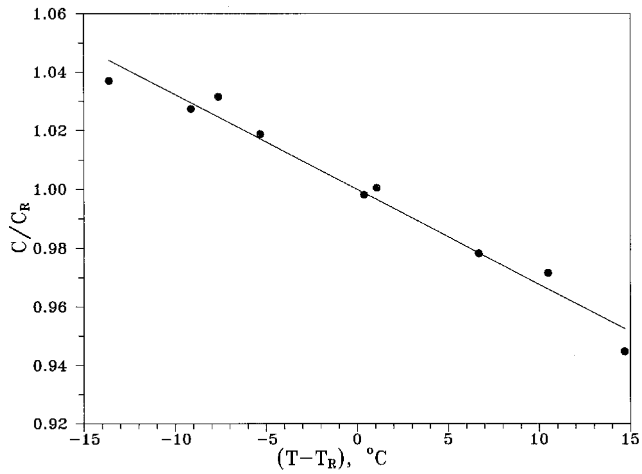

Fig. 3 Variation of acoustic velocity with temperature in propellant.

was monitored by chromel–alumel thermocouples cemented on the specimen at four different locations. These experiments were carried out for the temperature range of 20–60°C. A decrease of acoustic velocity in the propellant with an increase in temperature was observed. Variation of C/C_R with $(T - T_R)$ is shown in Fig. 3. From the slope of this curve, the K_T for the propellant was found to be -3.23×10^{-3}/°C.

To evaluate K_p, the acoustic velocity in propellant at the same ambient temperature but at different pressures was measured in the laboratory setup shown in Fig. 4. The laboratory setup consists of a combustion chamber (70 mm diameter and 150 mm length) connected to a nitrogen gas reservoir (0.1 m^3) through a flow line. The propellant specimen was mounted on the end flange of the combustion chamber and the ultrasonic transducer was fixed on the PMMA face of the specimen. The setup was pressurized by nitrogen gas at different pressures. An increase of acoustic velocity with an increase in pressure was obtained. The variation of C/C_R with $(p - p_R)$ is shown in Fig. 5. K_p obtained from the slope of this curve was 3.32×10^{-3}/MPa.

Tests for Establishing Accuracy and Repeatability of Measurements

Before using the ultrasonic technique for the burning-rate measurement in motors, it was first applied on end-burning propellant specimens. These specimens were cast from the same batch mix of propellant and tested at a nearly constant pressure. The same test setup (Fig. 4) described earlier was used. The entire test setup was pressurized to about 2 MPa by nitrogen gas supplied from gas bottles. Propellant ignition was achieved by the pyrotechnic charge fixed on the propellant surface. The ultrasonic transducer was connected to the PIM system to obtain instantaneous propellant web thickness during burning. The outputs of the PIM system and pressure transducer were recorded at the rate of 500 data/s for the entire burning time of a propellant specimen (~6 s), using a personal-computer-based data-acquisition system.

Output of the PIM system and pressure in a typical test are given in Fig. 6. PIM output was converted to time lapse by using the calibration constant of the equipment. From this, the instantaneous burning rate was obtained using Eqs. (1) and (2). To compare the burning rates during the test, the measured values were normalized to a reference pressure of 3.24 MPa (33 kgf/cm^2). A typical burning-rate result from the test is shown in Fig. 7. In Table 1, the results of normalized burning rates from several tests are given. The normalized burning rates in the four tests were 4.92, 4.94, 4.96, and 4.95 mm/s. These results show that the measured burning-rate values are consistent and are within ±1%. For the propellant of this

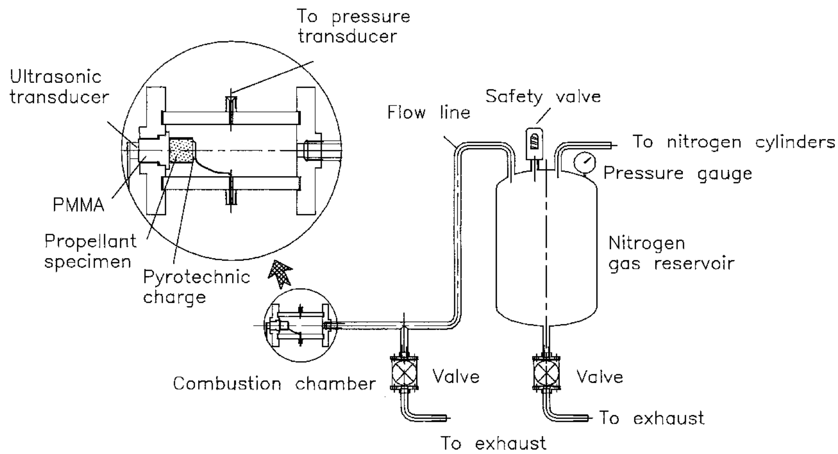

Fig. 4 Laboratory setup for burning rate measurement of end-burning propellant specimen.

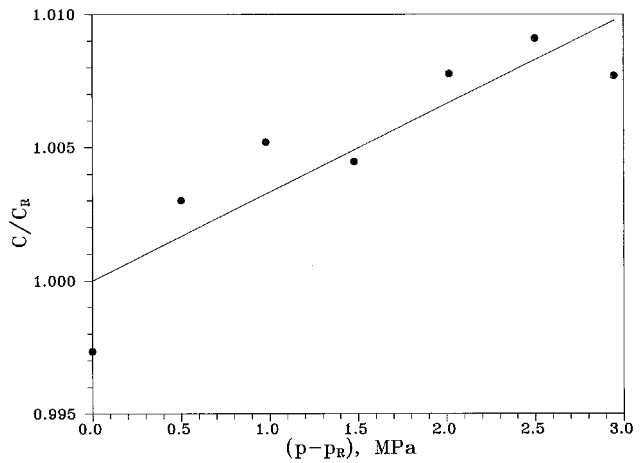

Fig. 5 Variation of acoustic velocity with pressure in propellant.

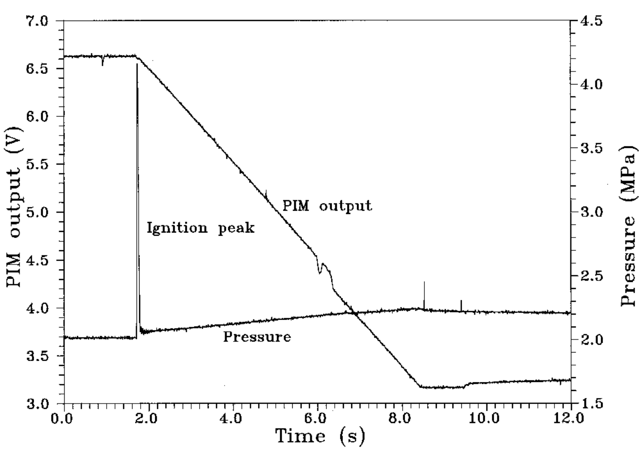

Fig. 6 PIM output from a typical end-burning propellant test.

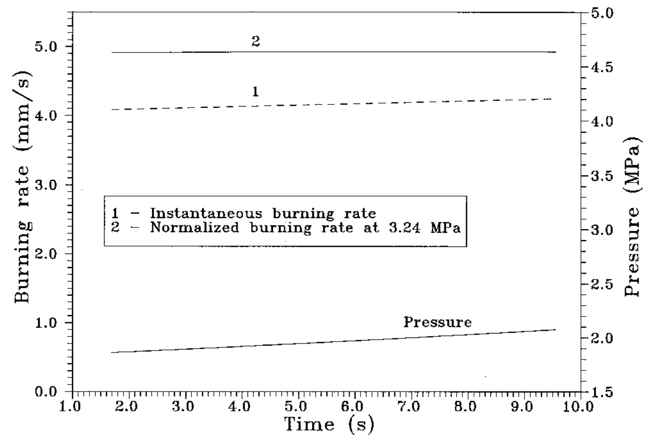

Fig. 7 Instantaneous burning rates in an end-burning propellant specimen.

batch, the burning rate evaluated using the conventional method in two static tests was 4.96 and 4.97 mm/s. This further confirmed the results obtained by ultrasonic technique.

Instantaneous Burning Rate Measurement in Motor

Following the preceding tests at the specimen level, the ultrasonic measurement technique was applied to motors with cylindrical perforated grains. The objective being the determination of the propellant burning-rate law in a single test, the following aspects were considered in grain design: 1) progressive burning profile providing a moderately wide range of motor pressure variation in a test, and 2) a simple cylindrical grain geometry to monitor web thickness accurately during burning.

The ballistic evaluation motor that was 200 mm in diameter and with a cylindrical perforated grain of 1000 mm in length was designed to give a variation of chamber pressure from 2.5 to 4.5 MPa during the motor burning time of ~6 s. Details of the motor are given in Fig. 8 and also as follows: Grain dimensions (in millimeters)—length = 967.6, head-end o.d. = 198.6, head-end i.d. = 120.8, nozzle end o.d. = 198.4, and nozzle end i.d. = 134.0. Weight of the grain = 31.15 kg. Nozzle throat dimensions (in millimeters)—before the test = 52.5 and after the test = 52.7. A cutout in the motor chamber was provided at the head end for the burning-rate measurement. In this cutout, a premachined PMMA adaptor (coupling material) was fixed. The hardware was insulated except at the location of PMMA adaptor. To measure the instantaneous burning rate using the PIM system, an ultrasonic transducer was fixed on the PMMA adaptor. Pressure at the head end of the motor was measured by a pressure transducer. The motor ignition was achieved by a pyrotechnic igniter at the head end. The outputs of the PIM system and the pressure transducer were recorded at the rate of 500 data/s using the personal-computer-based data-acquisition system.

The results of the static test of this motor and the measured burning-rate values are presented and discussed in the next section.

Results and Discussion

PIM output and motor pressure from a static test of the ballistic evaluation motor are shown in Fig. 9. Data were usable for almost the entire (~90%) motor burn time. Data from

Table 1 Results of burning rate measurement of propellant specimens using ultrasonic technique[a]

Test no.	Normalized burning rate at 3.24 MPa (mm/s)	Maximum variation during a test, %
1	4.92	0.04
2	4.94	0.90
3	4.96	1.06
4	4.95	0.66

[a]For this batch mix of propellant, burning rate values obtained by the conventional method at 3.24 MPa are 4.96 mm/s (in motor no. 1), and 4.97 mm/s (in motor no. 2).

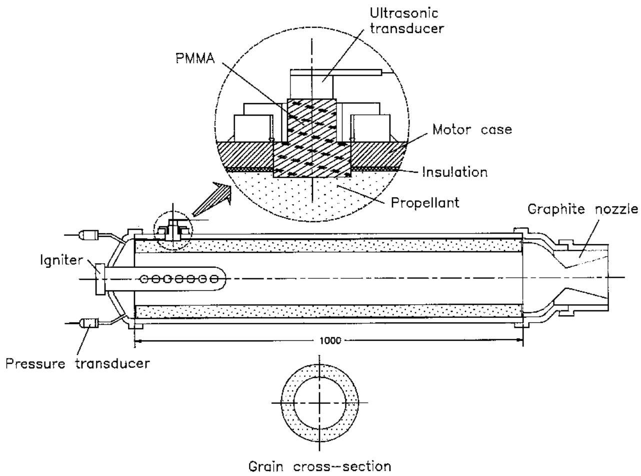

Fig. 8 Ballistic evaluation motor for burning rate measurement by ultrasonic technique.

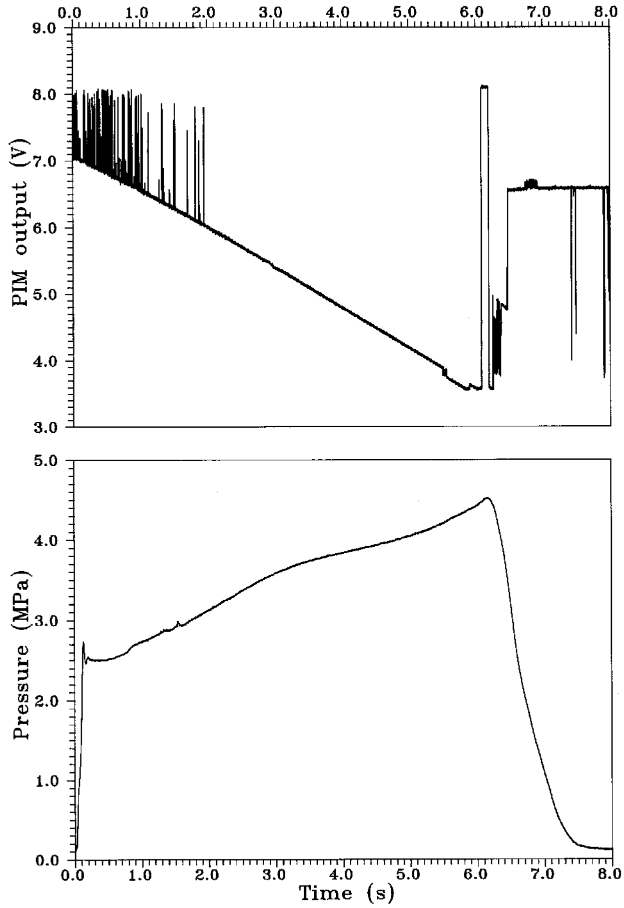

Fig. 9 PIM output and chamber pressure of the ballistic evaluation motor.

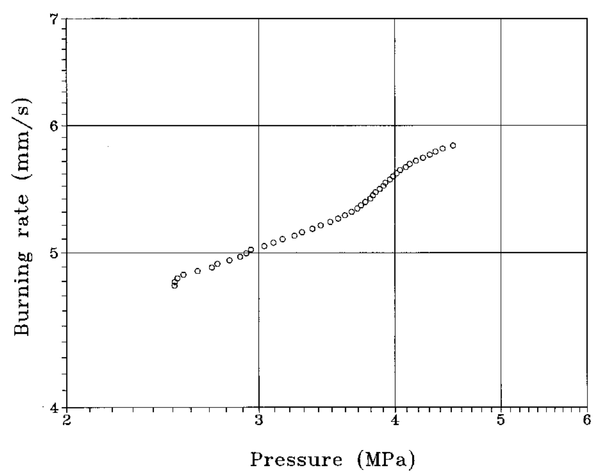

Fig. 10 Variation of burning rate with pressure.

the end of burning were not usable. This is because of the inherent incapability of the PIM system to detect return-echo-pulse from the burning surface very close to the propellant coupling material interface caused by signal interference. The output of PIM (voltage) was converted into time lapse by using the calibration constant of the equipment. From this, the instantaneous web thickness of propellant with time was obtained from Eq. (1). Finally, the instantaneous burning rate was evaluated from the slope of web thickness vs time curve. Figure 10 shows the measured burning rate at different motor pressures. From Fig. 10, the best fit for burning rate in the form $r = ap^n$ is obtained as

$$r = 3.48p^{0.34} \tag{4}$$

where p is pressure in MPa, and r is the burning rate in mm/s. The resulting burning-rate index is 0.34. This is very close to the value of 0.33 derived from the conventional method of several static test firings of this propellant, each test being at a different pressure.

Comparison of Measured and Simulated *p-t* Curves

The accuracy of measured burning rates was also checked by comparing the pressure history calculated using the derived burning-rate law, with the measured pressure trace. In the computations, the measured throat erosion value was used, and uniform throat erosion was assumed. The *p-t* curve thus predicted has been compared with measured motor pressure (Fig. 11). It shows an excellent match in burn time, thereby indicating the correctness of the burning rate law. The measured pressure trace exhibits the midweb anomaly, i.e., higher pressure than predicted in the midweb region. This has been widely reported in the literature[6,7] for solid motors with center perforated grains. In calculating the pressure–time history, if the measured local burning rates are used instead of the burning-rate law $r = ap^n$, the measured pressure trace is very well simulated.

Comparison with Burning Rate from Conventional Method

The average burning rate in the previous test was also computed from the conventional method using the measured web thickness and burn time. The burning rate was 5.3 mm/s at the test web-average pressure of 3.47 MPa. On the other hand, the burning rate as per the burning-rate law [Eq. (4)] using an ultrasonic technique is 5.29 mm/s (at the same pressure). Thus, the burning rate obtained by an ultrasonic technique matches very well with that using a conventional method.

The close matching of measured and predicted parameters (burning rate, pressure, burn time, and burning-rate index) validated the instantaneous burning-rate measurement and the burning-rate law determined by an ultrasonic technique.

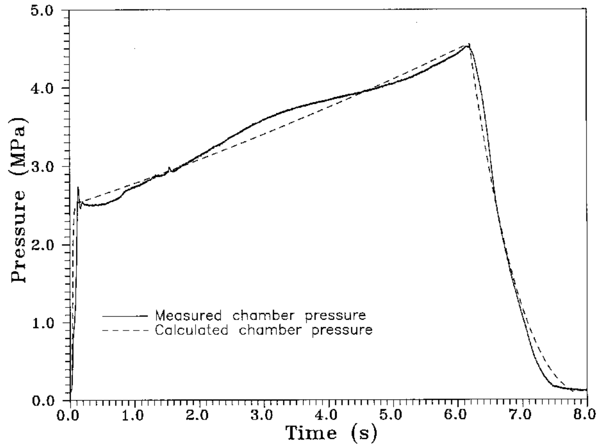

Fig. 11 Measured and calculated pressure–time curves.

Conclusions

The instantaneous burning rate of an aluminized composite solid propellant has been measured by the nonintrusive ultrasonic technique in a ballistic evaluation motor test. The accuracy and repeatability of burning-rate measurements have been established. The technique is found to be extremely useful to obtain the burning-rate law of the propellant from a single motor test. It can substantially reduce the number of tests required to determine burning-rate law.

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