Flame Propagation into the Crack of Solid-Propellant Grain

T. Godai*
National Aerospace Laboratory, Tokyo, Japan

The combustion of solid propellant having a slit or a hole which simulates a fault, such as crack, void, or an unbonded area in a solid rocket motor is investigated experimentally. The results indicate that there exist critical values for the width of the gap which are the threshold of propagation and nonpropagation of flame into it. Test specimens with a slit or a hole orientated perpendicular to the burning surface are prepared, using ammonium perchlorate based composite propellants. The combustion parameters are conditioning temperature of propellant, pressure, binder type, size and content of oxidizer and metal fuel, amount of carbon black and burning rate modifier, and an existence of an end wall. The threshold crack gap is fundamentally a function of the burning rate. A simple thermal model qualitatively exhibits the features of flame propagation in a crack for a nonaluminized composite propellant. However, it can not explain the behavior of flame propagation for a highly aluminized composite propellant.

Introduction

SOMETIMES cracks or voids occur in a solid-propellant grain and a breakdown of the interfacial bond or an unbonded area appears in the adhering layer between solid propellant and liner material. These faults are due to unsuitable grain design, low viscoelastic strength and elongation of propellant, some imperfection in the manufacturing process, and accumulative stress during storage, handling, and transportation. Currently, nondestructive testing of solid-propellant grains and motors, x-ray, gamma ray, and ultrasonic wave techniques are in general use. The extent to which the size of the faults might be harmful to the motor performance has not been studied and should be investigated through nondestructive inspection. Sometimes, in the development phase of a specified motor, a few firing tests were tried for studying the effect of artificial cracks and voids in the grain on the motor performance. However, any systematic and fundamental investigation concerning combustion dynamics in the small cavity of the solid propellant has not been reported. It is currently believed that the exposed surfaces in the faults add excessive burning area to the expected burning surface, and that, because of the combustion inside the faults, the chamber pressure will increase beyond what is expected. If the faults are sufficiently large, combustion will obviously take place on the inside surface of the faults. However, it is not clear whether flame will propagate in the faults and the inside surface of the faults will burn, even if their size were sufficiently small.

This paper presents the experimental investigation of flame propagation in the narrow slit and fine hole of solid-propellant grain.[1] It is expected that further work will give a useful measure to the setting of standards of nondestructive inspection for solid-propellant grains and motors.

Test Specimens and Procedure

The propellant used in this study was an ammonium perchlorate based composite propellant, and two kinds of resins, i.e., polyester and polybutadiene, were used as fuel binders. Although polybutadiene and ammonium perchlorate combination was used in the current rocket motors, the polyester and ammonium perchlorate combination was mostly employed in the study as it was easy to prepare precise specimens. As shown in Fig. 1, three kinds of specimens simulating the faults of propellant were used in order to study the flame propagation inside the surface of faults. A test specimen (A), referred to as "crack" specimen, had a slit orientated perpendicular to the original burning surface. Two 5-mm square propellants were assembled with a tiny space between them to obtain a slit equivalent to a crack. The sticks of propellant were held with an adhesive between plexiglas panels to maintain the slit spacing. By using front and rear panels the influence of flow into and out of the slit could be avoided. The slit was open at the ignition end and closed at the other end. The propellant was milled to make a fresh and flat plane and the slit opening was measured by thickness gages and a projector. These procedures were carried out on the day of firing test. The propellant was ignited by a heated nichrome wire tacked onto the surface of propellant to be ignited. Using propellant with the same composition, test specimens were made differing only in the width of the slits (ranging from 0.05 to 0.5 mm) and 10–40 specimens were tested. When the burning surface moves only perpendicularly to the crack and the inside of crack does not ignite so that it burns just as if there were no crack, we refer to this as "nonpropagation of flame into a crack." In contrast, when the flame moves parallel with the original ignition surface, and the inside surface of crack ignites and burns shortly after the initial movement of flame, we refer to it as "propagation of flame into a crack." When flame propagates into a crack, it is possible to observe a running flame front through a transparent panel. Moreover, flame propagation is accompanied by a fierce burning sound so that it is generally easy to determine propagation or nonpropagation. The optical measurement was carried out to observe the propagation phenomena. Typical examples of nonpropagation and propagation into cracks are shown in Figs. 2 and 3, respectively.

A test specimen (B), referred to as a "single hole" specimen, had a fine hole orientated perpendicular to the original burning surface in a 6-mm square stick of propellant. It was prepared to study the shape effect of a cavity on flame propagation. The hole drilled was open at both ends. In the same manner as in the case of specimen (A), test specimens using a propellant with the same composition were made to differ only in the diameter of holes (range from 0.5 to 2 mm) and firing tests were performed under the same condition. The phenomena were similar to those on specimens with slits.

A test specimen (C), referred to as a "multihole" specimen, had eight holes oriented parallel to the initial burning

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* Chief, Solid Rocket Section.

Table 1 Propellant composition[a]

Propellant code	Binder (parts & type)	Oxidizer (parts & type)	Additives (parts) CB	CC	AL
PEA	25 PE	75 B1	...	...	...
PEB-1	25 PE	75 F	0.13	...	...
PEB-3	25 PE	75 C	0.13	...	...
PEB-4	25 PE	75 F/M	0.13	...	...
PEB-7	20 PE	80 F	0.13	...	...
PEB-8	20 PE	80 M	0.13	...	...
PEB-9	20 PE	80 C	0.13	...	...
PEB-11	25 PE	75 M	0.03	...	...
PEB-13	25 PE	75 F	...	...	...
PBA-1	25 PB	75 B2	...	...	...
PBA-2	25 PB	75 B2	...	...	10
PBA-3	25 PB	75 B2	...	...	20
PBA-4	25 PB	75 B2	...	...	30
PBA-6	20 PB	80 B2	...	...	...
PBA-7	20 PB	80 B2	...	...	10
PBA-8	20 PB	80 B2	...	...	20
PBA-9	20 PB	80 B2	...	...	30
PBA-10	20 PB	80 B2	...	3.0	10
PBC-2	25 PB	75 B3	...	...	10
PBC-9	25 PB	75 B3	...	0.5	10
PBC-10	25 PB	75 B3	...	1.0	10
PBC-11	25 PB	75 B3	...	2.0	10

[a] PE: polyester, PB: polybutadiene, AL: aluminium, CB: carbon black, CC: copper chromite, F: fine (range 5–50, average 24 μ), M: medium (range 60–250, average 160 μ), C: coarse (range 200–800, average 480 μ), B1, B2, and B3: blended.

plane and simulated bubbles in the propellant grain. When a burning surface moving with a constant burning rate reaches a hole, flame does not propagate inside it and the inside surface of hole does not ignite so that the strand specimen burns with the unchangeable burning rate as if there were no hole, we refer to this as "nonpropagation of flame into a hole." On the contrary, when a burning surface reaches a hole, flame spreads inside the hole and its inside surface ignites and burns so that the specimen burns with an increased burning rate, we refer to this as "propagation of flame into a hole." Distortion of burning surface from its initial shape during flame propagation in a hole was observed using 16-mm motion picture film (approximately 32 frames/sec).

The experimental parameters included in the study were as follows: 1) conditioning temperature, 2) pressure, 3) propellant formulation, and 4) existence or absence of an end wall. Although most of specimens were tested in the open atmosphere and at ambient temperature, for examining the effect of temperature on flame propagation, some tests were performed at conditioning temperature of $-25°$, 0° and 25°C.

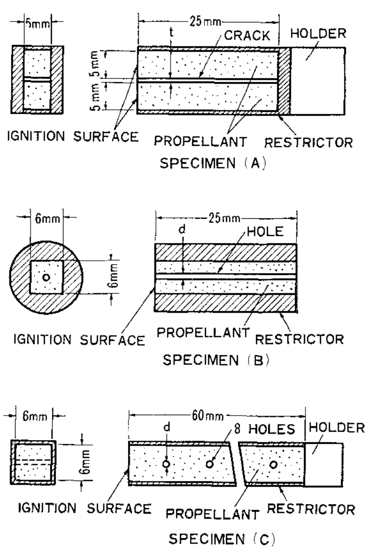

Fig. 1 Test specimens.

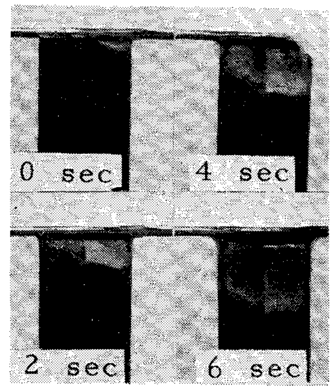

Fig. 2 Sequence of photographs showing the nonpropagation of flame into a crack. Polybutadiene based composite propellant (CTPB 25 parts, AP 75 parts, AL 10 parts), 1 atm, room temperature, open end, width of crack; t = 0.22 mm.

The propagation phenomena under the pressurized condition were observed under a controlled pressure of air (1–4 atm) in Crawford bomb with windows. A nonaluminized propellant containing 75 parts oxidizer (average 80–100 μ) and 25 parts polyester resin was tested for studying the effect of temperature and pressure on flame propagation. The formulation variables include particle size distribution of ammonium perchlorate, fuel-oxidizer ratio and addition of carbon black for polyester based composite propellant, and fuel-oxidizer ratio and differing amounts of copper chromite catalyst and aluminium for polybutadiene based composite propellant. All propellants were supplied by commercial propellant manufacturers. Oxidizer used in polyester based composite propellant was blended from fine, medium and coarse particles. Compositional data on the propellants used in the study are given in Table 1.

Experimental Results

Results of Crack Experiments

Effect of temperature

The effect of conditioning temperature on flame propagation of nonaluminized polyester based composite propellant is shown in Fig. 4. A threshold crack gap t^* was determined by bracketing successively narrower limits in a series of trials. It was observed that flame propagated into cracks if the width of crack was 0.25 mm or greater, whereas flame did not propagate into cracks if the width of crack was 0.20 mm or less. Although the experimental data scattered somewhat, at the higher temperature there was a tendency to decrease the threshold crack gap ($t^* = 0.24$ mm at $-25°$C and $t^* =$ 0.22 mm at 25°C). The linear burning rate varied from 0.77 mm/sec at $-25°$C to 0.88 mm/sec at 25°C.

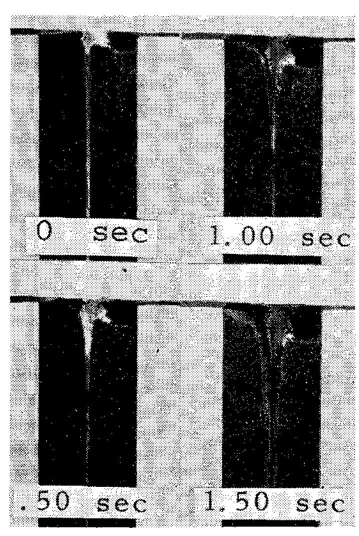

Fig. 3 Sequence of photographs showing the propagation of flame into a crack. Polybutadiene based composite propellant (CTPB 20 parts, AP 80 parts, AL 30 parts), 1 atm, room temperature, open end, width of crack; t = 0.60 mm.

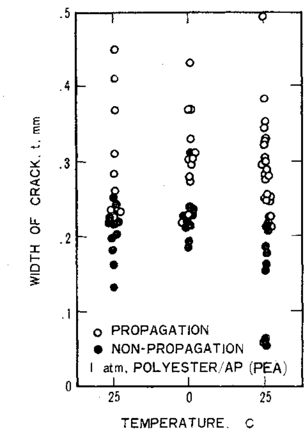

Fig. 4 Effect of temperature on flame propagation in crack.

Effect of pressure

In order to examine the effect of pressure on flame propagation into crack, the modified specimen (A), which had a slit closed at both ends, was used. According to the result of preliminary tests, the property of environmental gas had no or negligible effect on t^*. Experiments conducted in nitrogen gave the same t^* as in air and a slight difference between t^* in air and t^* in helium may have been due to a great difference in transport properties.[2] Figure 5 is a presentation of data relating pressure to threshold crack gap for a nonaluminized polyester and ammonium perchlorate composite propellant. It is evident from the curve that threshold crack gap decreased with increasing pressure. The threshold crack gap under the pressure of 4 atm or greater could not be obtained, since the specimen with a slit opening of 0.4 mm or less could not be prepared. Probably the threshold crack gap at higher pressure above some 10 atm becomes as thin as a hair crack.

Effect of propellant formulation variables

Figure 6 shows a plot of threshold crack gap t^* as a function of oxidizer particle size and fuel-oxidizer ratio for nonaluminized polyester based composite propellants. The threshold crack gaps for propellants including 80 parts oxidizer were found to be lower than those for propellants containing 75 parts oxidizer over the whole range of oxidizer particle size. Threshold crack gap increased with increasing mean diameter of oxidizer particles. From the fact that the polyester based composite propellant with 0.13 parts of carbon black (emissivity 0.95) had the same threshold crack gap as the propellant without carbon black (emissivity 0.45), it was shown that the radiation had a negligible effect on flame propagation into crack for nonaluminized propellants. The effect of fuel binder composition on flame propagation could not strictly be examined, since propellants differing only in the fuel binder composition were not prepared in this study. Although the particle size distributions of these propellants were different from each other, the threshold crack gap of polybutadiene based composite propellant was one-third or less of that of polyester based composite propellant, whereas the burning rate of the former was one and a half times of that of the latter. Results of further study supported the fact that the use of polybutadiene as fuel binder reduced the threshold crack gap for flame propagation.

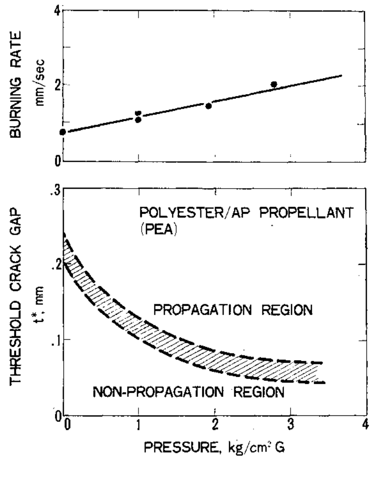

Fig. 5 Correlation of threshold crack gap with pressure.

Effect of existence or absence of an end wall

Tests were performed to determine whether an end wall of a slit influenced flame propagation into a crack of polyester based composite propellant (PEA). The threshold crack gap t^* ranged from 0.20 to 0.26 mm in slit with a closed end, and from 0.18 to 0.23 mm in slit open at end. The experimental data scattered to some extent, however, it may be argued that an absence of an end wall in a crack decreased t^*. It was also observed that an absence of an end wall accelerated the flame propagation velocity. Between a burned or reactive gas within the upstream portion of a slit and the air enclosed in a cavity of the slit there is a pressure difference. Therefore the gas pushes the air which was prevented by the side wall of propellant from flowing. If the downstream end of slit is open, the expansion of gas would be unrestricted and a flame front could expand out of the open end. When the downstream end of slit is closed, the burned gas, acting like a piston, would compress the air in the slit and the expansion of gas would be restricted.

The flame propagation velocity in a crack with a closed end under ambient pressure and room temperature was of an order of several to dozens of centimeters per sec in the first phase of propagation for a nonaluminized polyester and ammonium perchlorate composite propellant.

Results of Single Hole Experiment

Effect of propellant formulation variables

The threshold diameters of flame propagation into a fine hole open at an end for nonaluminized polyester based composite propellants are shown in Fig. 7, as a function of oxidizer particle size and fuel-oxidizer ratio. This study was made for the purpose of comparing data for hole with those for crack obtained previously in Fig. 6. Again, there existed the threshold diameter d^*, which distinguished propagation and nonpropagation regions. It was interesting to note that the threshold diameter for propellants containing 75 and 80

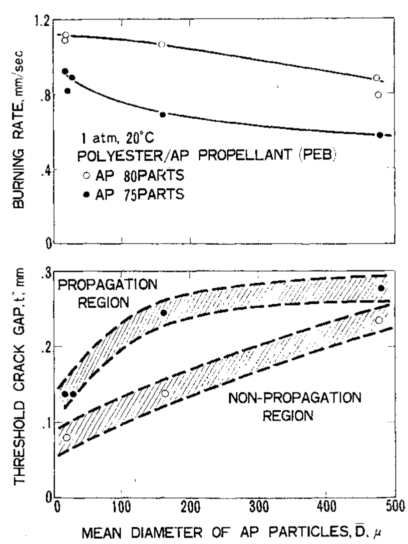

Fig. 6 Effect of fuel-oxidizer ratio and AP particle size on flame propagation in crack.

parts oxidizer had the same value, though there was a large difference between their burning rates.

Effect of aluminium

Test specimens used for studying the effect of aluminium added to propellant on flame propagation into a hole open at an end were made of polybutadiene and ammonium perchlorate composite propellants with varied amount of aluminium. The flame propagation data obtained under atmospheric pressure and room temperature were graphed in the form of threshold diameter and burning rate vs amount of aluminium, as shown in Fig. 8. Though the burning rate remained relatively constant, the threshold diameter increased considerably with increasing amount of aluminium powder. The threshold diameter for propellants including 75 parts oxidizer were found to be larger than those for propellants containing 80 parts oxidizer over the entire range of oxidizer particle size. For non- or less-aluminized propellants, it was very easy to distinguish regions of go and no go of flame propagation and determine the exact threshold diameter.

For highly aluminized propellants, a local surface zone in the vicinity of the upper edge of the propellant stick receded, deformed like a crater. In this local zone the flame did not propagate into the hole. With increasing diameter of the hole, the cratered effect tended to grow. Such an irregular flame propagation in combustion of highly aluminized propellant had not been observed in combustion of nonmetallized propellants.

Effect of burning rate modifier

Propellants in which small percentages of copper chromite powder had been added were tested for flame propagation into a hole open at an end. Copper chromite is a catalyst for the thermal decomposition of ammonium perchlorate and is used for increasing burning rate. A small amount of catalyst was added to the propellant, which consisted of 75 parts oxidizer, 25 parts polybutadiene binder, and 10 parts aluminium. As shown in Fig. 9, the threshold diameter decreased and the burning rate increased with increasing amount of copper chromite catalyst. Another polybutadiene based composite propellant including 3 parts copper chromite was supplied from another propellant manufacturer and tested for flame propagation into a hole at atmospheric and reduced pressure (200 torr). Flame of this propellant had a strong tendency to propagate into the finest hole of 0.4 mm even under the reduced pressure, and the threshold diameter could not be determined.

Effect of existence or absence of an end wall

As mentioned earlier, an existence or absence of an end wall in a crack influenced the threshold crack gap for polyester based composite propellant. Tests were performed whether flame propagation into a hole would also be affected by an existence of an end wall. The interesting thing is that

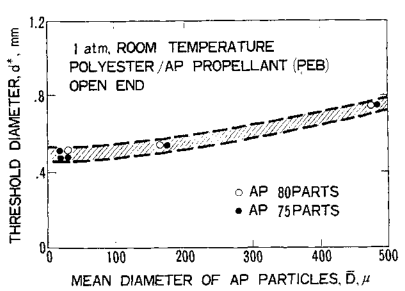

Fig. 7 Effect of fuel-oxidizer ratio and AP particle size on flame propagation in hole.

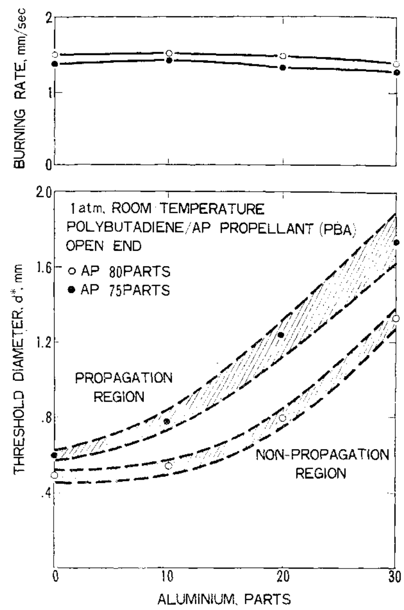

Fig. 8 Effect of aluminium on flame propagation in hole.

in the holes closed at the downstream ends flame could not propagate at all for any kind of propellant. Even in 10 mm-diam hole drilled on a propellant block, the flame could not propagate and the inside surface of hole did not ignite and burn. The reason that the threshold crack gap t^* existed and that the threshold diameter d^* could not be determined in cavities closed at ends may be because of the three-dimensional effect of flow in cavities. In the slit of specimen (A), an internal reverse flow of air against a propagating flame front is generated along the plexiglas panels and the air enclosed in the downstream cavity, compressed by the burned gas, flows out of the slit. The existence of an internal reverse flow was proven by the optical observation of incandescent gas circulating in the test specimen which had a slit 25 mm high, 25 mm wide, and 0.5 mm deep. The local ignition caused the internal air flow in the slit and hence the propagation of flame into it, while the uniform ignition over the propellant surface suppressed the growth of reverse flow in the slit and the flame could not propagate. In a hole closed at an end, however, such a venting flow can not generate. The fact that flame can propagate into an end-closed hole when it has a finer vent hole, shows the effect of the existence of an internal flow on flame propagation. The vent hole acts as a flow channel of the air enclosed in the cavity.

Results of Multihole Experiments

Since a trial to make propellant containing bubbles with a given diameter failed, firing tests were performed with specimen (C) in order to simulate flame propagation into bubbles of propellant grain. A plot of average burning rate of strand specimen (C) as a function of diameter of holes drilled indicated that the burning rate kept the same value as that of the propellant itself when the diameter of hole was 1.0 mm or less and the burning rate increased linearly as a function of the diameter drilled in the range of 1.0 mm or greater. It was concluded that the threshold diameter d^* for flame propagation into a horizontally drilled hole existed and that for a nonaluminized polyester based composite propellant the threshold diameter was 1.0 mm. When the burning front reaches a hole with a diameter greater than d^*, the flame expands inside the hole because of the presence of pressure difference and the inside surface ignites and burns with some ignition time lag. Figure 10 shows a 16-mm motion picture record of examples of successive positions of the burning surface moving in the vicinity of a hole. Because the plexiglas through which pictures were recorded interfered with combustion of propellant, it was difficult to obtain the exact pro-

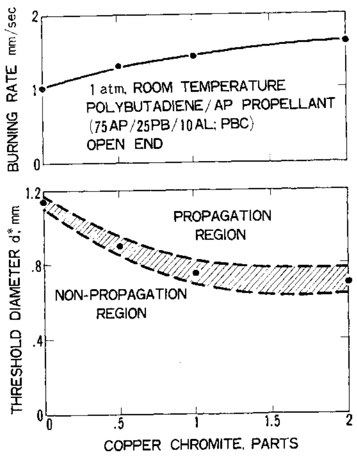

Fig. 9 Effect of burning rate modifier on flame propagation in hole.

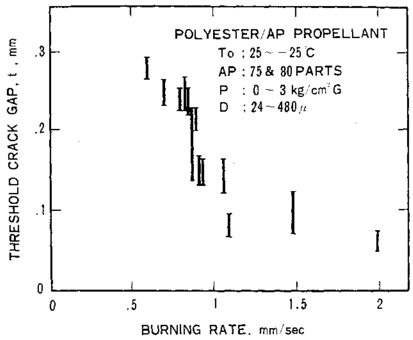

Fig. 11 Correlation of threshold crack gap with burning rate for nonaluminized polyester/AP propellants.

file of burning surface. However, the aforementioned phenomena of flame propagation was indicated. In the case of 1.2- and 2.5-mm-diam holes, the equivalent burning rate which was the distance of diameter divided by the time of traverse of the flame increased by about 10% and 35%, respectively, in comparison to the net burning rate of propellant.

Discussion of Results

Temperature, pressure, fuel-oxidizer ratio, and oxidizer particle size distribution are the principal variables that can affect the burning rate of a specified type of propellant. As mentioned earlier, these factors also affected the threshold crack gap and diameter for flame propagation into cavities. Figure 11 is a plot of the threshold crack gaps as a function of burning rate for nonaluminized polyester based composite propellants. Data plotted in the figure include those obtained over the range of temperature (25° to −25°C), fuel-oxidizer ratio (75 and 80 parts oxidizer), pressure (1–4 atm) and mean diameter of oxidizer particles (24–480 μ). The threshold crack gap varies inversely with the increase of burning rate, whereas measurements are considerably scattered. However, from the fact that, for instance, t^* for a propellant with 75 parts fine oxidizer is approximately double t^* for that with 80 parts coarse oxidizer (both propellants having the same burning rate), it is evident that the threshold crack gap is not determined entirely by the burning rate. Inverse proportion relationship between the threshold diameter and the burning rate also exists in the case of flame propagation in a hole for a nonaluminized polybutadiene based composite propellant. The same relationship appears for propellant with 10 parts aluminium and varied amount of copper chromite catalyst measurements of which are shown in Fig. 9. In an attempt to account qualitatively for the aforementioned features of flame propagation which is similar to quenching of a gaseous flame,[2–6] a simple model is developed and the detailed analytical description is forthcoming. The appearance of an incandescent gas between the upper rims of slit was observed when flame did not propagate in the slit and a specimen burned at a steady state burning rate as strand burning. It was sometimes observed that flame following an incandescent gas propagated in a slit when the width of slit was greater than t^*. Behavior of flame propagation in a slit is schematically presented in Fig. 12. Vapors of fuel binder and oxidizer are issued from propellant surface by solid phase decomposition. Diffusion of vapors and gas phase exothermic reaction occurred in a thermal layer to establish flame. Since the specific volume of incandescent gas is greater than that of air, the gas pushes the air in the slit and expands in the slit. However, the side walls will interfere with the temperature increase of the reactive vapors. Heat loss is mainly caused by heat conduction from the heated vapors to cool propellant walls, as the gas is in a quasi-stationary condition. Temperature of vapor gas is too low to react in the thermal layer and form flame front and, consequently, flame does not exist and propagate in a slit. A simple model for flame propagation in a crack on a thermal basis ignoring radiation is qualitatively postulated as follows.

The rate of heat generation in a crack would be proportional to the product of burning area, mass flow rate per unit area and liberated heat, $2Lr\gamma_p Q_s$. The rate of heat loss to the wall would be roughly proportional to the product of area, thermal conductivity and temperature gradient, $2LK(T_f - T_p)/t/2$. Using t as the threshold crack gap t^* this may be represented by equating the two heat rates. This yields

$$t^* \propto K(T_f - T_p)/r\gamma_p Q_s$$

where Q_s is the over-all heat liberated at the surface per unit mass, r is the burning rate, K is the thermal conductivity of gas, γ_p is the density of propellant, T_f is the flame temperature, and T_p is the propellant surface temperature.

Effect of conditioning temperature, pressure, oxidizer particle size distribution, and addition of copper chromite catalyst on the threshold crack gap may be explained by this simple equation. For instance, an addition of a small amount of copper chromite catalyst has negligible influence on values of K, and γ_p and slightly decreases values of Q_s, T_f and depresses T_p, while it greatly increases r. By putting together these factors in the equation, the effect of copper chromite catalyst may be correlated.

The features of flame propagation for highly aluminized propellants are quite different from those of flame propagation expressed by the equation. Heat conduction is a major mechanism of energy feed back and radiation is a minor mode of energy transfer in combustion of nonaluminized propellant

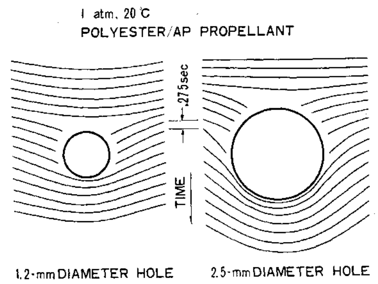

Fig. 10 Movement of burning surface in the vicinity of a hole.

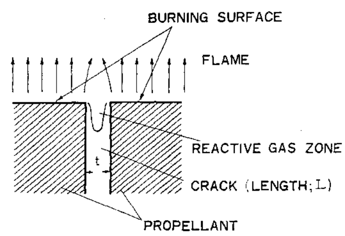

Fig. 12 Simplified model for flame propagation in crack.

since flame emissivity is 0.1 or less.[7] In combustion of highly aluminized propellant a cloud of radiating condensed particles which are gray bodies of emissivity of close to unity exists. High emissivity and temperature make radiant energy transfer consideration more important. Heat flux is proportional to the concentration of radiating particles, consequently, the threshold crack gap and diameter would be a function of content of aluminium in propellant.

Summary

Present analysis for flame propagation in small cavities of solid-propellant grain can be summarized as follows. 1) There exists a threshold crack gap, where flame will propagate in a crack if the width of crack is greater, and where flame will not propagate in a crack if the width of crack is less than this value. 2) Threshold diameter also exists for flame propagation in a fine hole of solid-propellant grain. 3) Threshold crack gap and diameter are represented fundamentally as a function of burning rate and decreases with increasing the burning rate, although they are functions of conditioning temperature, pressure and propellant formulation variables. 4) Flame can not propagate in a fine hole closed at an end. 5) A simple thermal model exhibits the features of flame propagation in a crack for nonaluminized composite propellant. 6) Behavior of flame propagation for highly aluminized composite propellant is quite different from flame propagation of non-aluminized composite propellant. Threshold diameter increases with increasing the content of aluminium.

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