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Combustion Behaviour of Advanced Solid Propellants*

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ABSTRACT

The study reports the effect of incorporation of *Al* and ammonium perchlorate (AP) individually and in combination with each other on combustion pattern and specific impulse (*Isp*) of minimum signature propellants. Incorporation of *Al* obviates the combustion instability problems; however, it has marginal effect on burning rates. The composition containing AP and zirconium silicate combination gives superior performance; however, its *Isp* is considerably lower than the composition incorporating 9 per cent AP. A combination of 6 per cent AP and 3 per cent *Al* gave 20 per cent enhancement in burning rate and 12 s increase in *Isp* as compared to purely nitramine-based composition, cal-val results also reveal increase in energy output on incorporating AP and *Al*. Hot stage microscopic and propellant combustion studies indicate occurrence of intense decomposition reaction in case of AP-based compositions.

1. INTRODUCTION

Nitramine-based solid propellants have an important role in the military as well as the space applications, because of their superior performance and minimum signature[1]. Minor quantities of AP and *Al* need to be incorporated in these compositions to achieve desired ballistics. *Al* is reported to overcome the combustion instability problems[2]. However, its influence on ballistics is not clearly defined. Some of the researchers suggest that the inclusion of *Al* reduces the burning rate while the others claim that it results in increase in burning rate[3]. AP is reported to ballistically modify nitramine-based compositions by reducing the pressure exponent (n) and increasing the burning rate[4]. Assessment of the effect of incorporation of AP on combustion instability phenomenon will also be of great interest. Further, in view of the primary smoke problems associated with *Al* and secondary smoke problems attributable to AP, it is necessary to arrive at optimum quantities of these ingredients to achieve desirable ballistic performance for nitramine-based minimum signature compositions.

To get useful information on these aspects and to provide supporting evidence for various prevailing theories[3-8], nitramine-based double-base (DB) compositions with varying quantities of AP and *Al* were prepared and evaluated. A unique feature of this study was determination of ballistics including *Isp* by statically evaluating the grains in a small rocket motor while other researchers have reported strand and burner results and theoretical *Isp* for nitramine and AP based CMDB[9].

2. EXPERIMENTAL

All the compositions were prepared by the slurry cast technique[10]. For ballistic measurements, the compositions containing two parts of ballistic modifiers were used. To determine ballistic behaviour, the propellant charges of 110 mm outer diameter, 76 mm inner diameter and 190 mm length were evaluated. Thrust and pressure-time profiles were recorded by using strain gauges and load cells in conjunction with a data acquisition system.

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Flame structure was determined in air by recording combustion phenomenon with high speed video camera. Differential thermal analysis (DTA) was carried out using indigenously assembled apparatus with *Pt-Rh* (13 per cent) thermocouple. Hot stage microscopic studies were undertaken on GmBH Weltzler polarising microscope. The decomposition phenomenon was recorded with Leitz camera.

3. RESULTS AND DISCUSSION

In the static evaluation of rocket motor, purely nitramine-based composition recorded combustion instability (Fig. 1). Incorporation of 3 per cent *Al* obviated the combustion instability problem. At 50 ksc, aluminised composition gave 7 per cent increase in burning rate; *n* values in 50-70 ksc region remained almost unaffected (0.6). Inclusion of 6 per cent AP in combination with 2 per cent zirconium silicate was also effective in arresting combustion instability, leading to smooth pressure time (*p-t*) profile (Fig. 2). The composition recorded 14 per cent increase in burning rate. At 6 per cent level, AP alone was ineffective in overcoming the combustion instability problem. However, addition of 9 per cent AP led to 20 per cent rise in burning rate with eradication of the problem of unstable combustion associated with purely nitramine-based composition. The pressure exponent (*n*) for this composition was 0.5. A combination of 6 per cent AP and 3 per cent *Al* gave burning rate of the same order with lower *n* value (0.42).

As regards to *Isp*, at 50 ksc it was 209 s for purely nitramine-based composition and increased to 211 and 219 s in case of compositions containing 6 per cent AP with 2 per cent zirconium silicate and 9 per cent AP, respectively. The composition with 6 per cent AP and 3 per cent *Al* gave the *Isp* of 221 s which corresponds to *Isp* of 230 s at 70 ksc.

Incorporation of nitramine leads to lower burning rate because it tends to melt in condensed phase and undergoes combustion, away from the surface in luminous zone of double-base flame. Thus, there is no significant heat feedback to condensed phase, therefore cyclotrimethylene trinitramine (RDX) acts as a diluent. The present results bring out that *Al* as reported by

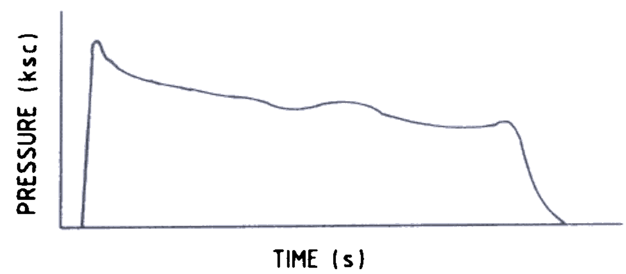

Figure 1. Ballistic output of nitramine-based composition.

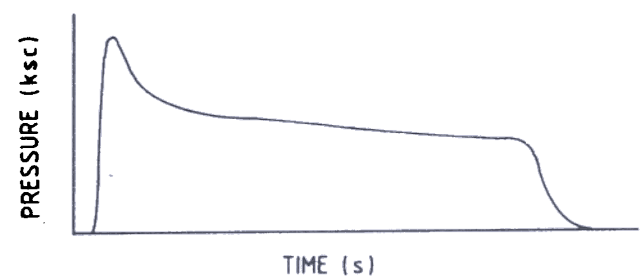

Figure 2. Ballistic output of composition with stable combustion.

Table 1 : Static evaluation results

Basic matrix DB: ballistic modifiers 2 parts

Compositions	Burning rate at chamber pressure (mm/s)			*n*	*Isp* at 50 ksc
	50 ksc	60 ksc	70 ksc	50-70 ksc	(s)
12% RDX nitramine (control)	8.6	9.7	10.6	0.63	209
12% RDX, 3% *Al*	9.2	10.0	10.7	0.61	212
12% RDX, 6% AP, 2% zirconium silicate	9.8	10.7	11.5	0.46	211
12% RDX, 9% AP	10.4	10.7	11.7	0.50	
12% RDX, 6% AP, 3% *Al*	10.4	11.7	12.5	0.40	211

various researchers stabilises the combustion and has marginal effect on burning rate. It's effectiveness in stabilising combustion may be due to its melting leading to the formation of a thin layer of molten metal protected with alumina (Al_2O_3) on regressing propellant surface which through thermal inertia reduces the thermal response at the burning surface of propellant. As *Al* combustion takes place subsequent to the breaking of oxide layer at about 2500 K in high temperature zone it does not contribute to burning rate appreciably. A minor increase in burning rate observed during present study may be due to increased thermal conductivity and enhanced heat transfer by radiations resulting from high luminosity of *Al* combustion.

Incorporation of AP results in increase in burning rate to remarkable extent which may be attributed to the fact that AP introduces the flames in fizz and dark zone resulting from interaction between oxidizer rich AP decomposition products, and fuel rich DB matrix decomposition products, leading to increase in reaction rate in fizz zone contributing to elevation of condensed phase temperature.

Higher *Isp* of the composition containing 6 per cent AP and 3 per cent *Al* than that of the formulation based on 9 per cent AP may be explained on the basis of highly exothermic combustion of *Al* to Al_2O_3. AP is expected to provide oxygen for such reactions to occur efficiently.

These findings and those of various researchers[2-8] were supported by recording flame structure of compositions in air atmosphere. Nitramine-based composition revealed flame structure similar to that of DBP compositions, comprising foam, fizz, dark, and luminous zones. AP-incorporated compositions gave intense flame with reduction in dark zone. *Al* did not have much effect however, AP and *Al* in combination gave highly intense flame (Fig. 3).

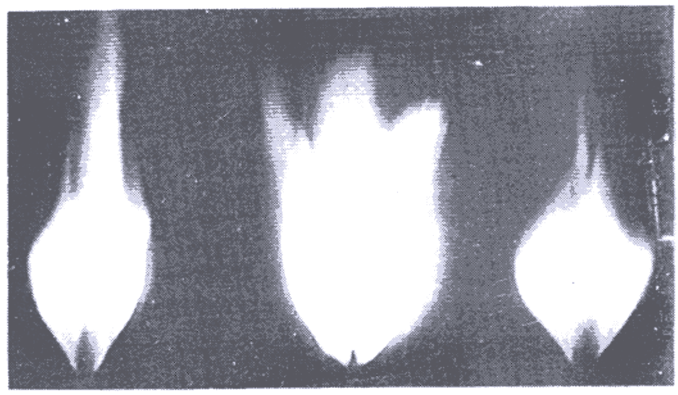

Figure 3. Flame structure of minimum signature compositions (a) RDX, (b) RDX+AP, and (c) RDX+*Al*.

The cal-val of these compositions reveal that incorporation of AP and *Al* in nitramine-based composition leads to an increase in heat output. AP and *Al*-based composition gave the highest thermal output (Table 2).

DTA results (Table 3) revealed lowering of *Tm* by about 11-12 °C from 204 °C on addition of AP and *Al* individually. Incorporation of AP and *Al* in combination brought the *Tm* further down to 190 °C.

In order to provide further supporting evidences, compositions were subjected to hot stage microscopic

Table 2. Density, cal-val and mechanical properties of minimum signature compositions

Basic matrix DB: ballistic modifier 2 parts

Compositions	Density (g/cc)	Cal-val (cal/g)	Mechanical properties TS (ksc)	Elongation (%)
12% RDX nitramine (control)	1.66	996	32	13
12% RDX, 3% *Al*	1.67	1070	33	11
12% RDX, 6% AP, 2% zirconium silicate	1.63	1072	20	25
12% RDX, 9% AP	1.67	1104	19	20
12% RDX, 6% AP, 3% *Al*	1.64	1144	20	25

Table 3. DTA results of compositions

Basic matrix : DB

Composition	Decomposition temperature		
	Ti	*Tm*	*Tf*
		(°C)	
12% RDX	189	204	237
3% *Al*	184	193	232
6% AP	187	192	226
12% RDX, 3% *Al*, 6% AP	189	190	232

Table 4 . Observations of hot s.age microscopic studies

Basic matrix : DB

Composition	Temperature (°C)	Observations
!% RDX	200	Crystals in matrix started melting
	220	Charring occurs
3% *Al*	220	Brown colour developed and branched network with greenish tinge observed
6% AP	180	Profused evolution of gases
12% RDX, 3% *Al*, 6% AP	200	Melting of crystals accompanied with evolution of gases observed. Network structure fully developed

studies. In case of nitramine-based compositions melting was observed at 200 °C. Aluminised composition reflected needle like particulate and globbules which may be due to the undecomposed *Al* at the propellant surface. In case of AP based compositions intense reaction was observed at 180 °C which resulted in the formation of ridges on the surface (Table 4). Density and mechanical properties of these samples are also reported in Table 2.

4. CONCLUSION

Combustion instability problems associated with nitramine-based minimum signature composition may be overcome by incorporating small quantities of *Al* or AP-zirconium silicate combination. Inclusion of 9 per cent AP not only results into smooth pressure-time profile but also leads to superior performance. A combination of 6 per cent AP and 3 per cent *Al* gave best results.

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