Aluminized Solid Propellants Burning in a Rocket Motor Flowfield

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Combustion and agglomeration processes of aluminum particles emitted from the surface of an aluminized double-base propellant (NC/TMETN) were studied under rocket motor, crossflow conditions. High-speed color photographs (~2000 frames/s) were taken of burning Al/Al_2O_3 agglomerates forming on the surface, moving along the surface, and entering the flowfield. As an example, a propellant containing 6-μm Al burning at 7 MPa and 6 m/s crossflow produced a mean agglomerate size of about 250 μm. Analysis of size distributions of the agglomerates leaving the surface revealed that the following parameters decrease with increasing pressure: collision frequency on the surface, the agglomerate stay time on the surface, and mean agglomerate size. Increasing the crossflow velocity decreased the mean agglomerate size. The propellants which contained the large aluminum particles (50 μm vs 6 μm) burned without the aluminum igniting or agglomerating on the surface.

Introduction

THE studies summarized in this paper are directed at photographing the burning of aluminized propellants under crossflow conditions similar to those that exist in rocket motors and correlating the aluminum agglomeration process in terms of the rocket motor parameters. High-speed photographs (~2000 frames/s) were taken of the aluminum and aluminum oxide agglomerates forming on the surface, moving along the surface, and entering the flowfield, and the Al/Al_2O_3 agglomerates burning in the flowfield. Several laboratories (most notably the work at the Naval Weapons Center, e.g., Refs. 1-3) have obtained high-resolution photographs of aluminized propellants burning as strands in quiescent atmospheres and have photographed the agglomerates formed by burning strands. These photographs revealed many of the details of the metal burning processes isolated from the shearing forces of high-speed flow. However, to answer the questions that have been raised concerning Al/Al_2O_3 agglomerate size and combustion efficiency under rocket motor conditions (e.g., Ref. 4), the results obtained in quiescent atmospheres must be complemented by results obtained under crossflow conditions. Other investigators[4-7] have studied how formulation, pressure, and port geometry affect the size distribution of metal agglomerates under rocket motor conditions, but those investigations were not concerned with visualizing the combustion processes that produced the agglomerates.

Experimental Approach

High-speed color movies (~2000 frames/s) were taken of aluminized double-base propellants burning in a 7-cm-long window motor, which used two propellant slabs 0.6-cm wide. Photographing the burning aluminized propellants in a rocket motor flowfield presented several problems not encountered during the photography of strands burning in a quiescent atmosphere. First, the transparency of the windows in the motor (adjacent to the burning propellant) must be maintained. This was accomplished by using polymethylmethacrylate windows which ablate slightly, thereby removing the deposits which would normally build up on glass or quartz windows. Second, under typical motor conditions, the number of emitting Al/Al_2O_3 agglomerates is so great that an individual particle in the continuum cannot be examined. Futhermore, since the photographic depth of field is less than about 0.5 cm, photographing thick agglomerate clouds obscured the details of the agglomerates within the region of sharp focus. This depth of field and discrimination problem was overcome by photographing the flame zone above thin (~2 to 4 mm wide) strips of aluminized propellant cast between sections of nonaluminized propellant. In this manner, combustion processes of individual agglomerates could be visualized. In the field of view of the photography (~6 mm along the flow axis), there was little opportunity for the parallel gas streams (from the aluminized and nonaluminized propellants) to mix; the local environment of the burning aluminum (near the propellant surface) was approximately the same as it would have been if the entire propellant charge had been aluminized.

The experimental apparatus is shown schematically in Fig. 1a. Two configurations for observing the burning surface were used. In the first configuration, a side view was obtained, and the propellant was cast directly onto the window (see Fig. 1b). The width of the initial port passage was usually set to be 2 mm. In the second configuration, the view normal to the propellant surface was obtained and the propellant (viewed by the camera) was not bonded to the window (see Fig. 1c). The location of the portion of the propellant which was aluminized was varied to obtain the desired crossflow conditions. The motors were placed in a high-pressure window combustor which has a pair of 5×2-cm windows. Pressure level control was achieved by regulating the N_2 purge flow into the window combustor.

The results are for the type of plastisol double-base propellants described in Ref. 8. The formulation for the basic nonaluminized propellant is 53.7% nitrocellulose (NC), 39.3% trimethylolethane trinitrate (TMETN), and 7.0% triethylene glycol dinitrate. The aluminized propellant is the basic propellant with a total aluminum content of 13%. Three aluminum powders were used: 1) commercial grade Valley Metallurgical H-5, mean particle size 6μm; 2) commercial grade Alcoa 1220, mean particle size ~50μm; and 3) test specimen supplied by the Air Force Rocket Propulsion Laboratory, Edwards, Calif.[9] (this powder is referred to as AFCAM). AFCAM is commercial aluminum powder (mean

Presented as Paper 77-929 at the AIAA/SAE 13th Propulsion Conference, Orlando, Fla., July 11-13, 1977; submitted Sept. 1, 1977; revision received March 6, 1978.

Index categories: Fuels and Propellants, Properties of; Combusion and Combustor Designs; Solid and Hybrid Rocket Engines.

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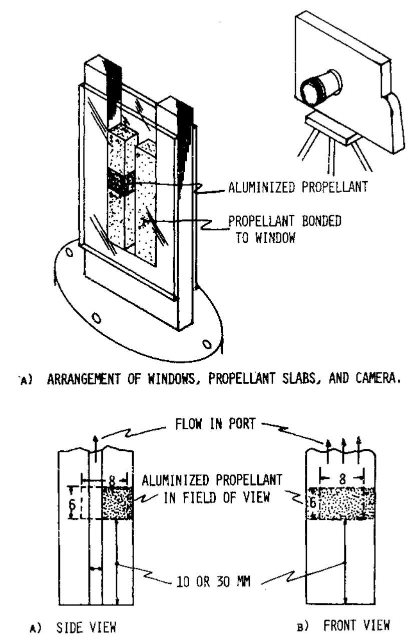

Fig. 1 Apparatus used to obtain photographs of aluminized propellants burning under crossflow conditions.

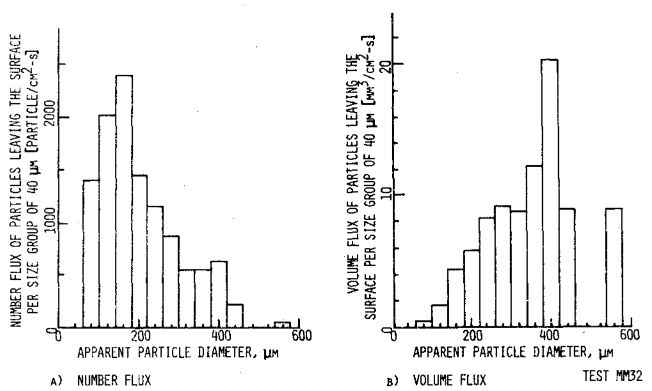

Fig. 2 Size distribution of agglomerates leaving the surface of aluminized (13% Al) double-base (NC/TMETN) propellant at 7.6 MPa (~1100 psi) and 6 m/s crossflow.

particle size 5 μm) treated with HF for the purpose of weakening the bond between the alumina layer and the aluminum inner core. The hypothesis is that by fracturing or flaking off the alumina layer during early stages of combustion, smaller agglomerates would be formed and more complete combustion would be achieved.

During a single test, a range of crossflow velocities occurred since the crossflow velocity decreased as the port cross-sectional area increased. The primary observables in the experiments are: the range of agglomerate dimensions on the propellant surface and in the freestream, frequency of collisions on the surface, stay time on the surface, number flux of particles, ignition location, and agglomerate axial velocity with respect to gas velocity.

The physical diameter of a burning agglomerate can be only approximated from the films since the intensity of the flame produces an image on the film which is larger than the corresponding physical diameter. Analysis of films taken over a range of f-stops and of the agglomerates adjacent to the propellant surface and in contact with each other indicate that the apparent diameter is about 20% greater than the physical diameter.

The burning agglomerates and particles form two identifiable particle distributions: the larger particles mostly in the 40-to 800-μm size range and the very small particles which are generally smaller than 10 μm. The distribution of smaller particles, which includes the Al_2O_3 smoke, tends to follow the gas velocity without lag. However, their diameter cannot be estimated because the dimensional uncertainty produced by the flame intensity is on the same order as their diameter. In this paper, attention is focused on the larger particle distributions. The distribution of larger particles includes nearly all of the aluminum mass.

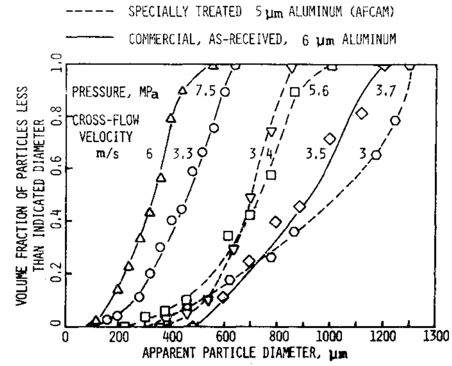

Fig. 3 Volume distribution of agglomerates for a range of motor pressures. Note: 1) decrease of agglomerate size with increasing pressure; 2) some tendency of decreasing particle size with increasing port flow velocity.

Results

Figures 2a and 2b are representative of the diagrams of the number and volume flux of the agglomerates leaving the surface. Similar diagrams were obtained over the full range of the test conditions and were used to calculate accumulated volume vs particle size (as shown in Fig. 3). Using the measured apparent agglomerate diameter and assuming that the aluminum in the agglomerates is largely unreacted, the mass flux from the surface was calculated and compared with mass flux based on the linear burning rate of the propellant (see Table 1). These results are another measure of the extent to which the apparent diameter exceeds the actual diameter. The following report on agglomeration phenomena vs working conditions is concerned with the fine aluminum powders (mean particle size of 5 to 6 μm).

Pressure Effects

The most prominent influence on the agglomerate size was found to be the chamber pressure. Actually, the combined effects of both the pressure and the burning rate are not separated. Table 1 summarizes the results obtained for strand and crossflow conditions for pressures between 3.8 and 7.6 MPa; prominent changes occur in many of the parameters. The average agglomerate size (of the larger particle distribution) decreases from ~650 μm at 3.8 MPa to ~220 μm at 7.6 MPa. The stay time of the agglomerates on the burning surface changes from 40-100 ms to 5-9 ms; the frequency of collisions decreases from ~70 to ~4 per 100 particles leaving the surface, and the number flux increases tremendously from 250 to 12,000 particles/cm^2-s. The same trends and approximate magnitude have been observed in both the commercial 6 μm aluminum and in the 5 μm AF-CAM. A qualitative picture of the pressure influence on the agglomerate size can be obtained from Fig. 4 which shows photographs of the residue collected from strand tests.

Similar trends were found by Pokhil et al.,[5] although their agglomerate sizes are smaller than those in this investigation (see Fig. 5). The Ref. 5 results were obtained from small rocket motors fired in a particle collection combustor.

Crossflow Speed Effect

When burning propellant strands in a vertical position, both the geometry and orientation contribute to the formation

Table 1 Summary of observations for 5- to 6-μm Al powder

Nominal pressure, MPa (psia)	3.8 (550)		5.6 (820)		7.6 (1100)		6.9 (1000)	
Aluminum type	VM[a] H-5	AFCAM	AFCAM	AFCAM	VM H-5	VM H-5	VM H-5	AFCAM
Test type	Crossflow	Crossflow	Crossflow	Crossflow	Crossflow	Crossflow	Strand	Strand
Gas velocity, m/s	~3.5	~6	~3	~4	~3.3	~6	...	...
Mean diameter of agglomerate distribution, μm								
Based on mass conservation	680	626	575	449	229	223	456	395
Apparent	797	640	654	591	332	252	548	535
Ratio	0.853	0.978	0.879	0.760	0.690	0.885	0.832	0.738
Largest agglomerate, μm	1200	1320	880	1100	640	560	1020	1000
Number flux, particle/cm^2-s	250	320	718	1503	11,280	12,340	1328	2048
Stay time on surface, ms	40 to 100	50 to 100	30 to 40	30 to 40	5 to 9	4 to 6		
Min. collisions on surface per 100 agglomerates leaving surface	70	61	30	25	4	5		
Test (MM series)	33	62	61	61	32	32	39P	58P

[a] Valley Metallurgical Corp., H-5, which has a mean weight diameter of 6 μm.

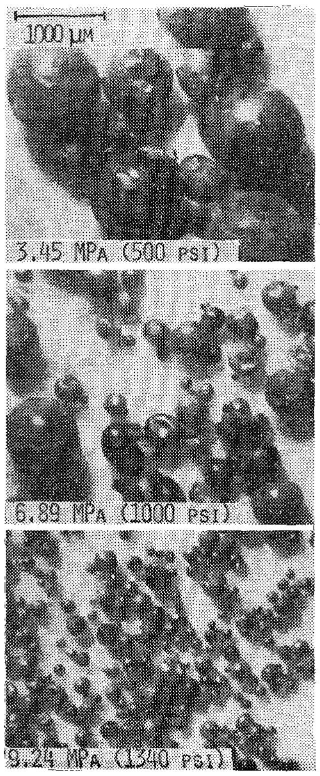

Fig. 4 Residue of aluminum particles from strands gives qualitative measure of the decrease of agglomerate size with increasing pressure.

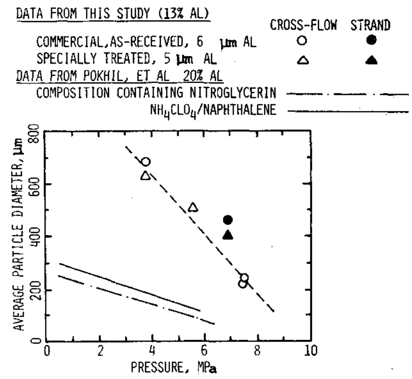

Fig. 5 Variation of average agglomerate size with chamber pressure.

of larger agglomerates than in the case of crossflow conditions. Since weight is proportional to diameter cubed and drag (at low Reynolds number) is linearly proportional to diameter, sufficiently large agglomerates tend to remain on the surface of burning strands.

Port flow velocity affects the stay time of the agglomerates on the surface in two ways: 1) by pushing the agglomerates along the surface and destabilizing them and 2) by aerodynamic lifting due to the concave shape of the agglomerates. The movement along the surface appears to weaken the adhesion force to the surface (the existence of such a force is discussed later) and shorten the stay time on the surface. In the low-speed region, the lifting force is relatively small, while the drag is comparable to the weight of the particles. Therefore, in the low-speed region, the crossflow effects depend on the geometry; when this flow acts against the weight, it may even enhance the agglomeration process by slowing the movement of the agglomerates and stabilizing the adhesion to the surface. Higher flow velocities shorten the stay time of the agglomerates on the surface and result in smaller agglomerates. Pokhil et al.[5] reported a similar dependence of decreasing agglomerate size with increasing transverse flow velocity above a crossflow of ~15 m/s. Typically, the crossflow in the present experiments varied between 15 and 2 m/s at 3.8 MPa and between 9 and 2 m/s at 7.6 MPa. Results show the tendency of decreasing the average agglomerate size with increasing crossflow velocity (see Table 1 and Fig. 3).

Other Observations

The aluminum particle size is an important factor in the agglomeration and combustion processes. Two regimes were

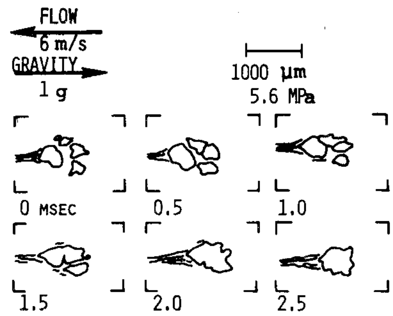

Fig. 6 Interpretation of high-speed film images showing several agglomerates merging. Note that gravity forces are approximately equal to drag forces.

observed. When the 6-μm aluminum powder is used, the particles are usually ignited on the surface and form large spherical burning agglomerates which remain on the burning surface (e.g., for as long as 100 ms at 3.8 MPa) and then enter the gas flow. The 50-μm powders are neither ignited on the surface nor form agglomerates on the surface; they move on the surface due to the crossflow of the gas and, then, abruptly leave the surface unignited. Ignition occurs in the gas stream and the diameter of the burning particles appears to be the same size as the aluminum powder.

Figure 6 is a series of sketches traced from one of the high-speed movies of the Fig. 1c configuration. It represents a rather typical sequence of several smaller agglomerates merging to form a larger agglomerate. Note that drag forces were nearly balanced by the gravity and surface tension effects.

The existence of an adhesion force is apparent from observing high-speed movies of burning aluminized propellants. Knowing the nature of the surface layer (i.e., molten) supports the interpretation of these observations. Other investigators recognize the surface adhesion[10] and are attempting to gain more information on it.

A distinctly different form of aluminum behavior on the surface was observed on several occasions in the lower pressure range, i.e., 3.8 MPa. Irregular-shaped layers of aluminum, as thick as 0.5 mm and several millimeters long, remained on the surface as the propellant burned. The layers were periodically stripped from the surface by the crossflow and tended to form unusually large agglomerates during the time interval they remained in the field of view. The more representative agglomeration process was that illustrated in Fig. 6.

Discussion and Conclusions

The experiments described in this paper permit the visualization of the combustion and agglomeration processes of aluminum particles emitted from the propellant surface under crossflow conditions. Quantitative measurements of the agglomerate distribution under various conditions are an important result of this investigation. The results presented in this paper are for one double-base propellant type, and, thus, broad generalization should not be made. Based on the present study and other investigations, an outline of the agglomeration phenomenon is offered in the following paragraphs.

The agglomeration phenomenon is a very complex process which includes several stages and is affected by many factors. It was found that any situation in which large amounts of aluminum particles are brought into close contact and maintained above a temperature threshold for a sufficient time, results in the agglomeration of the particles. Particles heated in ovens and hot stage microscopes, e.g., Refs. 3 and 11, as well as those associated with solid propellants experience agglomeration.

The most prominent result is the observation of decreasing agglomerate size with increasing chamber pressure. Other factors also affect the final agglomerate size. It was found that the absence of crossflow in strand experiments results in larger agglomerates. Under crossflow conditions, the coarser aluminum particles (e.g., 50 μm) did not form agglomerates on the surface and usually left the surface unignited; the finer aluminum powders (e.g., 6 μm) formed large, spherical agglomerates on the surface and ignited prior to leaving the surface.

The apparent stages in the agglomeration process are as follows: accumulation (into irregular shapes) in the thin molten surface layer as well as on the burning surface, heating on the surface followed by ignition, melting that results in spherical agglomerates, growing of the burning agglomerates while moving on the surface and collecting aluminum particles as they are exposed, and growing via collisions with other agglomerates. The last process is important in low-pressure motor conditions (e.g., 3 to 7 MPa) or when burning strands in quiescent conditions.

The stay time of the agglomerates on the surface, an important phase in determining the final agglomerate size, depends on the adhesion to the surface and the combination of forces acting against it, i.e., aerodynamic drag and lifting, pressure generated under the particle, etc. The chamber pressure has a prominent effect on those parameters.

Acknowledgment

This study is based on work performed under Grant 76-3104 issued by Air Force Office of Scientific Research. The authors wish to thank Chris R. Felsheim for his diligent work in preparing the propellants and experimental motors. The first author sincerely thanks the Lady Davis Foundation for awarding him a Postdoctoral Fellowship for partial support.

References

[1]Crump, J., "Behavior of Aluminum in Composite Propellants," in "Combustion of Solid Propellants and Low Frequency Combustion Instability," Naval Weapons Center, China Lake, Calif., NOTS TP4244, June 1967.

[2]Boggs, T. L., Mathes, H. B., Price, E. W., Kraeutle, K. J., Dehority, G.L., Crump, J.E., and Culick, F.E.C., "Combustion of Solid Propellants and Low Frequency Combustion Instability Progress Report," Naval Weapons Center, China Lake, Calif., NWC TP4749, June 1969.

[3]Crump, J. E., Prentice, J. L., and Kraeutle, K. J., "Role of Scanning Electron Microscope in the Study of Solid Propellant Combustion: II. Behavior of Metal Additives," *Combustion Science and Technology*, Vol. 1, November 1969, pp. 205-223.

[4]Geisler, R. L., Kinkead, S. A., and Beckman, C. W., "The Relationship between Solid Propellant Formulation Variables and Motor Performance," AIAA Paper 75-1199, Oct. 1975.

[5]Pokhil, P. F., Belyayev, A. F., Frolov, Yu. V., Logachev, V. S., and Korotkov, A. I., "Combustion of Powdered Metals in Active Media," Nauka, Moscow, 1972; also, FTD-MT-24-551-73, translated from Russian by Foreign Technology Division, Wright-Patterson Air Force Base, Ohio, Oct. 1973.

[6]Derr, R. L., Churchill, H. L., and Fleming, R. W., "Aluminum Behavior Near the Burning Surface of a Composite Propellant," *Proceedings of the 10th JANNAF Combustion Meeting*, Vol. III, CPIA Publication 243, Chemical Propulsion Information Agency, Silver Spring, Md., Dec. 1973, pp. 327-339; also, "Aluminum Behavior in Solid Propellant Combustion," Air Force Rocket Propulsion Laboratory, Edwards, Calif., Rept. AFRPL-TR-74-13, 1974.

[7]Micheli, P. L. and Schmidt, W. G., "Behavior of Aluminum in Solid Rocket Motors," Aerojet Solid Propulsion Company, Sacramento, Calif., Interim Rept. AFRPL-TR-76-58, Aug. 1976.

[8]Kubota, N., Ohlemiller, T. J., Caveny, L. H., and Summerfield, M., "Site and Mode of Platonizers in Double Base Propellants," *AIAA Journal*, Vol. 12, Dec. 1974, pp. 1709-1714.

[9]Geisler, R. L., Personal Communication, Air Force Rocket Propulsion Laboratory, Edwards, Calif., March 1975.

[10]Price, E. W., "Summary Report on JANNAF Workshop on Behavior of Aluminum in Solid Propellant Combustion," *Proceedings of 13th JANNAF Combustion Meeting*, Vol. II, CPIA Publication 281, Dec. 1976, pp. 453-459.

[11]Price, E. W. and Sigman, R. K., "Behavior of Aluminum in Solid Propellant Combustion," Georgia Insitute of Technology, Atlanta, Ga., AFOSR-TR-77-0050, Nov. 1976.