Aluminum Agglomerate Size Measurements in Composite Propellant Combustion

K. Jayaraman and G. Boopathy

Abstract Experimental and numerical investigation have been done to evaluate the aluminum agglomerate size in AP/HTPB/Aluminum propellants and compared it with burning rate results. Bimodal AP particle size distribution is considered in the present work. The effect of aluminum size, aluminum content, fine AP size, fine AP/binder ratio and coarse AP size in aluminum ignition, accumulation and agglomerate formation during combustion, typically in their ranges, are focused. The burning rates were found to be higher for the propellants with lower fine AP/binder ratio. The agglomerate sizes for the propellants with 10 % Al was found to be higher than those with 15 and 18 % aluminum. Observing the agglomerate sizes and the burning rate trends, it can be concluded that the agglomerate sizes vary inversely as the burning rates.

Keywords Agglomerate · Composite propellant combustion · Aluminum propellant · Burning rates

1 Introduction

Aluminum is the most widely used metal due to its abundance, nonreactivity during mixing and storage, nontoxicity, and its ability to reduce H_2O and CO_2 to lower molecular weight gases such as H_2 and CO. Compared with other ingredients, the A1 particles have a unique tendency of igniting reluctantly and accumulating on the burning surface, thus forming relatively large agglomerates that burn relatively slow after leaving the burning surface.

K. Jayaraman (✉)
IIT Madras, Presently at ICARE-CNRS, Olreans, France
e-mail: jayaraman78@gmail.com

G. Boopathy
Department of Aeronautical, Vel Tech University, Chennai, India

R.P. Bajpai and U. Chandrasekhar (eds.), *Innovative Design and Development Practices in Aerospace and Automotive Engineering*, Lecture Notes in Mechanical Engineering, DOI 10.1007/978-981-10-1771-1_47

2 Experimental Details

2.1 Propellant Samples

Ammonium perchlorate (AP) used in the present work is obtained from Tamil Nadu Chlorates Ltd, Madurai, India. The purity of AP is >99 %, and it does not contain any anticaking agents. The micro-aluminum of 15 μm in size is obtained from MEPCO, Madurai, India. Hydroxyl terminated polybutadiene (HTPB) is used as a prepolymer, which functions as the hydrocarbon fuel. Di-octyl adipate (DOA) acts as plasticizer and toluene di-isocyanate (TDI) or isophorone di-isocynate (IPDI) plays the role of a curing agent. Three baseline formulations are taken for each case, i.e., non-aluminized, nano-aluminized, and normal aluminized: (1) fine AP/binder ratio = 60/40 and fine AP size of 20 μm; (2) fine AP/binder ratio = 60/40 and fine AP size of 5 μm; and, (3) fine AP/binder ratio = 65/35 and fine AP size of 5 μm. The effects of aluminum content, aluminum size and variation are studied.

2.2 Burning Rate Measurement

Burning rate measurements were performed over the pressure range from 1 to 12 MPa with the step of 1 MPa by using combustion photography method. The samples were ignited using hot nichrome wire. A window bomb is used for this purpose; it is a pressure vessel consisting of two windows, one to illuminate the sample and another used to view the combustion process by CCD camera. More than 60 % of the tests are repeated at least once, and burning rates obtained within a repeatability of 5 % is considered acceptable.

2.3 Agglomerate Collection and Size Analysis

The quench collection bomb is a stainless steel pressure vessel which is designed to withstand a maximum working pressure of 20 MPa. The Sauter mean diameter (SMD), which is a representative of the ratio of volume to the surface area, is considered to represent the nominal size of the agglomerates. Similarly, the arithmetic mean diameter (AMD) of the agglomerates is also presented in the nominal size plots.

3 Results and Discussions

3.1 Observations on Burning Rate Trends

1. Effect of Aluminum Content

Figure 1 shows the burning rate trends of the IPDI-cured propellant with fine AP/binder ratio 65/35, fine AP size of 5 μm, coarse AP size of 450 μm and total solids loading of 87.5 %.

2. Effect of Aluminum Size

The burning rate trends of IPDI-cured propellant formulation with a fine AP/binder ratio of 60/40 and the fine AP and coarse AP sizes of 20 and 450 μm is shown in Fig. 2.

3. Effect of Coarse AP Size

The effect of coarse AP size of the propellant is examined for coarse AP sizes of 450, 350 and 250 μm with 5/75 μm fine AP/binder ratio of 60/40 with the TDI-cured. The burning rates of the propellants are shown in Figs. 3 and 4.

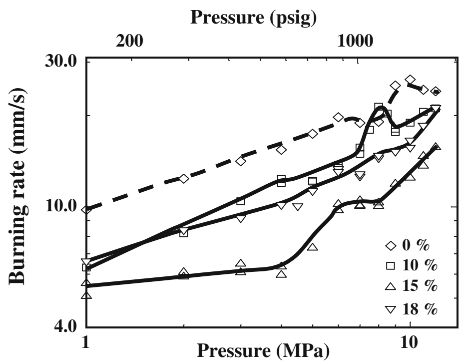

Fig. 1 Effect of aluminum content on the burning rates of IPDI – cured propellants with a fine AP/binder ratio of 65/35, m respectively μ the coarse and fine AP and Al sizes being 450 μm, 5 μm and 15

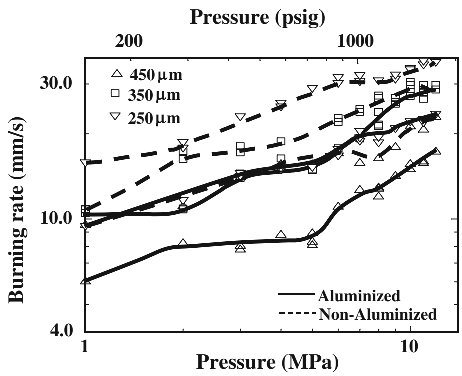

Fig. 2 Effect of aluminum size on the burning rates of IPDI-cured propellants with a fine AP/binder ratio of 60/40, containing 15% Al, with the coarse and fine AP sizes being 450 μm and 20 μm respectively

3. Effect of Fine AP/Binder Ratio

The burning rates of two propellant formulations with fine AP/binder ratios of 65/35 and 60/40, with TDI-cured and IPDI-cured are shown in Figs. 5 and 6 respectively.

4. Effect of Fine AP Size

Figures 5, 6 and 7 show the effect of fine AP size on the burning rates of propellants, with the variation in that parameter as 5, 20, 53 and 75 μm.

Observations in agglomerate sizes

The Sauter mean diameter (SMD) D_{32} and the arithmetic mean diameter (AMD) D_{10} are derived, and plotted against the pressure for comparison of variations in different formulation parameters.

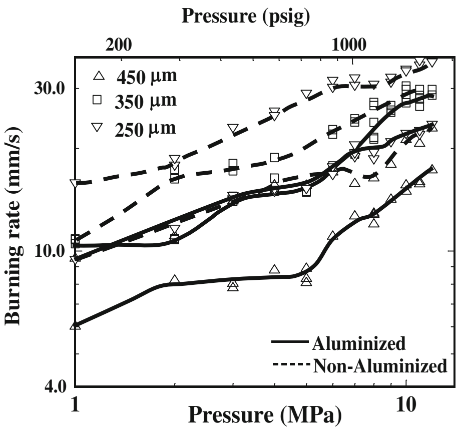

Fig. 3 Effect of coarse AP size on the burning rates on TDI-cured propellants with a fine AP/binder ratio of 60/40, m size. μthe fine AP size being 5 μm, containing 15% Al of 15

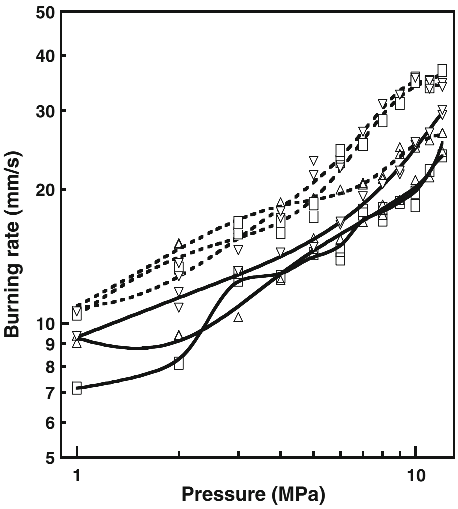

Fig. 4 Effect of coarse AP size on the burning rates on TDI-cured propellants with a fine AP/binder ratio of 60/40, m size. μ the fine AP size being 75 μm, containing 15% Al of 15

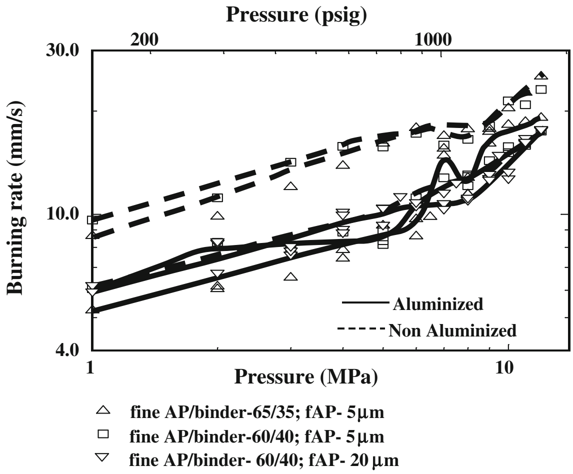

Fig. 5 Effect of fine AP/binder ratio and fine AP size on the burning rates for TDI-cured propellants with 450 µm coarse AP along with the non-aluminized burning rates

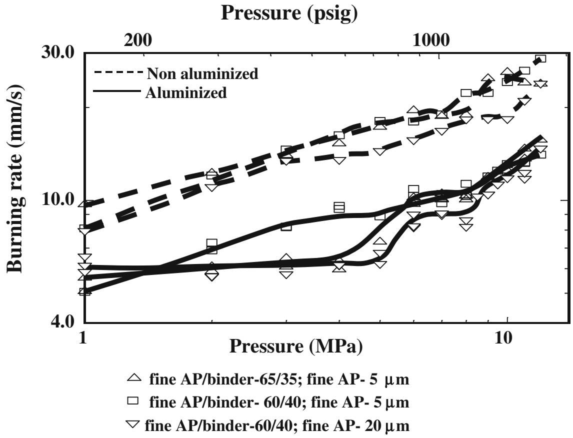

Fig. 6 Effect of fine AP/binder ratio and fine AP size on the burning rates for IPDI-cured propellants with 450 µm coarse AP along with the non-aluminized burning rates (Aluminized propellant-15% of 15 µm.)

1. *Effect of Aluminum Content.*
The influence of aluminum content on the agglomerate sizes can be seen in Fig. 8.

Effect of Aluminum Size
The arithmetic and Sauter mean diameters of agglomerate sizes are shown in Fig. 9, for various sized Al propellants.

2. *Effect of Coarse AP Size*
The agglomerate sizes are plotted against the operating pressure in Figs. 10 and 11.

Effect of Fine AP/Binder Ratio
The influence of fine AP/binder ratio can be seen in Figs. 12 and 13, for TDI and IPDI-cured propellants, respectively.

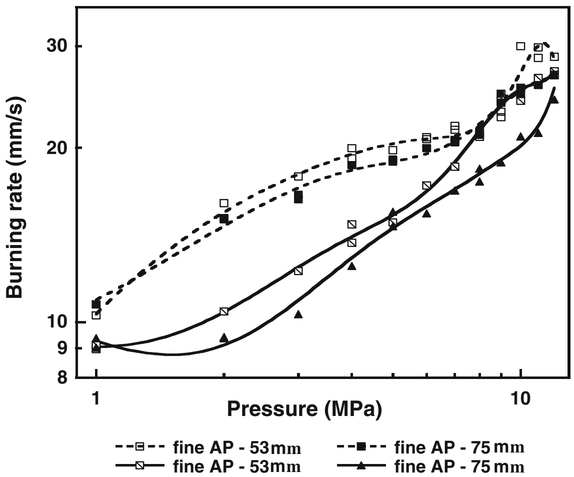

Fig. 7 Effect of fine AP size on the burning rates for TDI-cured propellants with 450 μm coarse AP along with the non-aluminized burning rates (Aluminized propellant-15% of 15 μm.) (Non-aluminized – dotted line; Aluminized – solid line)

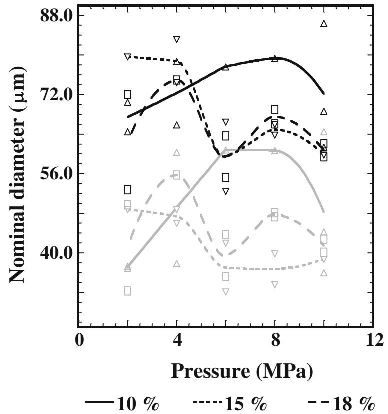

Fig. 8 Effect of aluminum content on the agglomerate sizes of IPDI – cured propellants with a fine AP/binder ratio of 65/35, the m respectively.(Grey – μ coarse and fine AP and Al sizes being 450 μm, 5 μm, 15 AMD and Black – SMD)

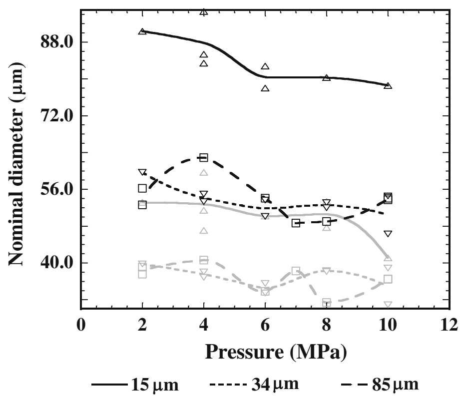

Fig. 9 Effect of aluminum size on the agglomerate sizes of IPDI-cured propellants with a fine AP/binder ratio of 60/40, containing 15% Al, with the coarse and fine AP sizes being 450 μm and 20 μm respectively. (Grey–AMD and Black–SMD)

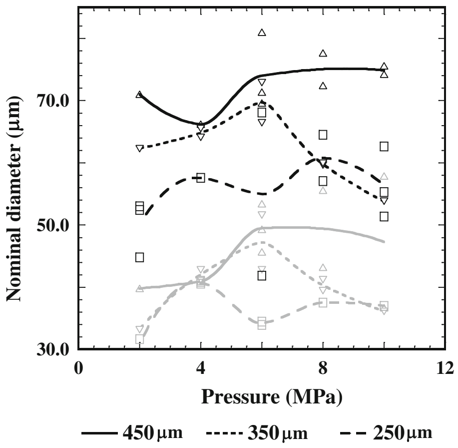

Fig. 10 Effect of coarse AP size on the burning rates on TDI-cured propellants with a fine AP/binder ratio of 60/40, m size. (Grey–AMD and ▯ the fine AP size being 5 µm, containing 15% Al of 15 Black–SMD)

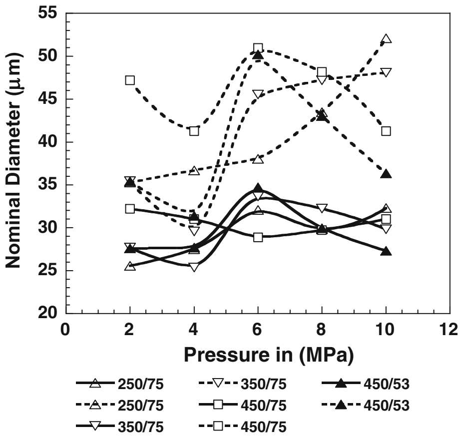

Fig. 11 Effect of higher size fine AP size on the agglomerate sizes for TDI-cured propellants, containing 15% of Al with 15 µm size (SMD – dotted line ; AMD – solid line)

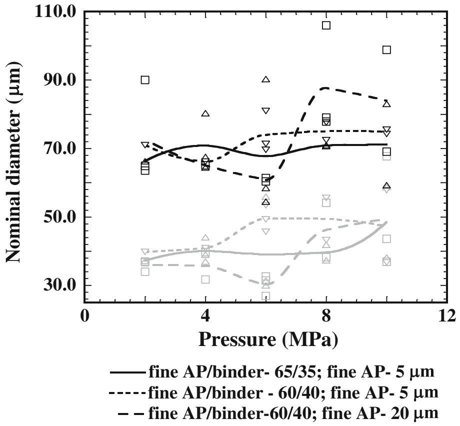

Fig. 12 Effect of fine AP/binder ratio and fine AP size on the agglomerate sizes for TDI-cured propellants with 450 µm coarse AP, containing 15% of Al with 15 µm size (Grey–AMD and Black–SMD)

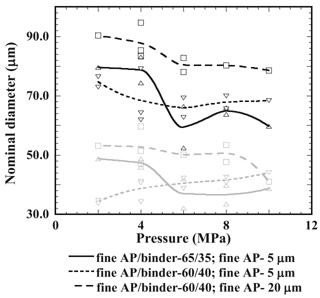

Fig. 13 Effect of fine AP/binder ratio and fine AP size on the agglomerate sizes for IPDI-cured propellants with 450 µm coarse AP containing 15% of Al with 15 µm size (Grey–AMD and Black–SMD)

3. Effect of Fine AP Size

The effect of fine AP size on agglomerate size is shown in Figs. 11, 12 and 13 by comparing the agglomerate trends between the propellants with 5, 20, 53, and 75 µm fine AP sizes.

4 Conclusions

When Al is added to the non-aluminized propellant keeping the fine AP/binder ratio constant, the burning rates dropped. This is due to accumulation of aluminum on the burning surface, which acts as a heat sink. The reduction is nonmonotonic with Al content; an increase from 10 to 15 % further reduces the burning rate, but a further increase to 18 % restores the burning rate somewhat. When 15 µm Al is used in the propellant, the burning rates dropped with respect to the non-aluminized propellant. When the size of the Al is increased to 34 µm, the burning rates have been increased. Further increase in the Al size to 85 µm did not increase the burning rates significantly. As the coarse AP size decreased from 450 to 350 µm, the burning rates of the propellant increased, but did not significantly change with further decrease in the coarse AP size to 250 µm. The agglomerate sizes were observed to be lower for higher parent aluminum size used in the propellant. With a decrease in the coarse AP size from 450 to 350 µm, the agglomerate sizes reduced considerably. But with further reduction in the coarse AP size to 250 µm, the agglomerate sizes are not appreciably varied. The agglomerate sizes were found to increase with increase in the fine AP/binder ratio. The propellants with smaller fine AP sizes showed lower agglomerate sizes; this is due to the restricted movement of the Al particles on the propellant surface due to tightly packed fine AP-binder matrix and the higher rates of reactions due to higher exposed oxidizer surface areas.

References

1. Babuk, V. A., Belov, V. P., and Khodosov, V. V. (1988), Study of the structure of Agglomerates with Combustion of Aluminized Mixed Condensed Systems, *Physics of Combustion and Explosion*, **24(4)**, 552–557.

2. Babuk, V. A., Vasilyev, V. A. and Malakhov, M.S. (1999), Condensed Combustion Products at the Burning Surface of Aluminized Solid Propellant, *Journal of Propulsion and Power,* **15 (6)**, 783–793.
3. Babuk V. A. and Vasilyev V. A. (2002), Model of Aluminum Agglomerate Evolution in Combustion Products of Solid Rocket Propellant, *Journal of Propulsion and Power*, **18(4)**, 814–823.
4. Cohen N. S. (1983), A Pocket Model for Aluminum Agglomeration in Composite Propellants, *AIAA Journal*, **21**, 720–725.
5. Dokhan A., Price E. W., Seitzman J. M. and Sigman R. K. (2001), The Effects of Aluminum Particle Size on the Burning Rate and Residual Oxide in Aluminized Propellants, *A. AIAA/ASME/SAE/ASEE Joint propulsion conference and Exhibit,* AIAA-2001–3581.
6. Grigoriev, V. G., Kutsenogy, K. P. and Zarko, V. E. (1981), Model of Aluminum Agglomeration in Combustion of Double-Base Composition, *Physics of Combustion and Explosion*, **14(4)**, 9–17 (in Russian).
7. Grigoriev, V. G, Zarko, V. E. and Kutsenogy, K. P. (1981), Experimental Investigation of Aluminum Particle Agglomeration in Condensed System Combustion, *Physics of Combustion and Explosion*, **17(3)**, 3–10 (in Russian).
8. Jayaraman K., Anand K.V., Bhatt D.S., Chakravarthy S.R., and Sarathi R. (2009), Production, Characterization, and Combustion of Nanoaluminum in Composite Solid Propellants, *Journal of Propulsion and Power*, **25(2)**, 471–481.
9. K. Jayaraman, K. V. Anand, S. R. Chakravarthy, and R. Sarathi, "Effect of Nano-Aluminium in plateau-burning and catalyzed solid propellant combustion", Combustion and Flame, 2009, Vol. 156, No. 8, pp. 1662–1673.
10. K. Jayaraman, S. R. Chakravarthy, and R. Sarathi, "Accumulation of nano-aluminium in the combustion of composite solid propellant mixtures", Combustion, Explosion and Shockwaves, 2010, 46, 21–29.
11. K.V. Anand, A. Roy, I. Mulla, K. Balbudhe, K. Jayaraman, S.R. Chakravarthy, Experimental data and model predictions of aluminium agglomeration in ammonium perchlorate-based composite propellants including plateau-burning formulations, *Proceedings of the Combustion Institute,* 34, 2013, 2139–2146.
12. Povinelli, L. A. and Rosenstein, H. A. (1964), Alumina Size Distributions from High Pressure Composite Solid Propellant Combustion, *AIAA,* **2**, 1754–1760.
13. Price, E. W. (1984), Combustion of Metallized Propellants, chapter 9 in *Fundamentals of Solid Propellant Combustion*, Kuo, K. K. and Summerfield, M. (eds.), Progress in Astronautics and Aeronautics, **91**, AIAA, Washington, DC.
14. Sambamurthi J. K., Price E. W., and Sigman R. K. (1984), Aluminum Agglomeration in Solid Propellant Combustion, *AIAA Journal*, **22**, 1132–1138.
15. Zarko, V. E. (1998), Metal Combustion in Rockets, Chapter 10, 301–353, *Modeling and Performance Prediction in Rockets and Guns*, Chakravarthy, S. R. and Krishnan, S. (eds.), Allied Publishers, Chennai, India.