Ignition and Combustion of Energetic Particles at Ultra-High Pressures and Heating Rates

Garrett P. Lee and Kenneth K. Kuo
High Pressure Combustion Lab, Pennsylvania State University
University Park, Pennsylvania, USA

1 Introduction

Although research into aluminum particle combustion has been going on for over 50 years, practically all research to date has taken place at pressures ranging from near atmospheric to those characteristic of rocket motors (< 10 MPa). As the pressures found in post-detonation environments characteristic of thermobaric explosives (TBX) are several orders of magnitude higher, new research is essential in order to design accurate predictive models that are capable of designing efficient TBX weaponry. To address this lack of data, a ballistic compressor was modified to produce peak pressures up to 690 MPa (100,000 psi) and maximum heating rates exceeding 10^6 K/sec to simulate a post-detonation environment. With the support of the Defense Threat Reduction Agency, a research program to investigate the ignition and combustion of energetic particles at ultra-high pressures and heating rates was conducted. In particular, the effects of the following variables on aluminum combustion were deemed to be paramount: particle size, the presence or absence of a nickel coating, and peak pressure and heating rate.

2 Method of Approach

Ballistic Compressor Concept

In order to properly illustrate the functioning of a ballistic compressor, Figure 1 is a cartoon schematic of the ballistic compressor at the High Pressure Combustion Lab (HPCL) before and after firing. Before firing, the selected energetic particles are loaded into the test section, which is then sealed. The test gas, if desired, is allowed to fill the compression tube and test section. An inert drive gas is then injected into the driver section and pressurized to the desired level. In order to trigger the ballistic compressor, the fast-acting valve is opened, which creates a pressure imbalance on the free piston, which then moves down the compression tube towards the test section, compressing the test gas. Once the pressure at the downstream end of the free piston exceeds the driving force, inertia carries the free piston towards the end of the compression tube, continuing to compress the test gas to a pressure far above that in the driver section. The free piston comes to a halt just before reaching the end of the compression tube, as shown in the bottom of Figure 1, and then reverses, pushed away from the test section by the high pressure of the compressed test gas towards its initial position. The piston oscillates along the compression tube until its motion is fully damped by friction. The main pressure spike is very short, on the order of a few milliseconds, requiring very fast equipment to record data about the combustion of energetic particles inside the ballistic compressor.

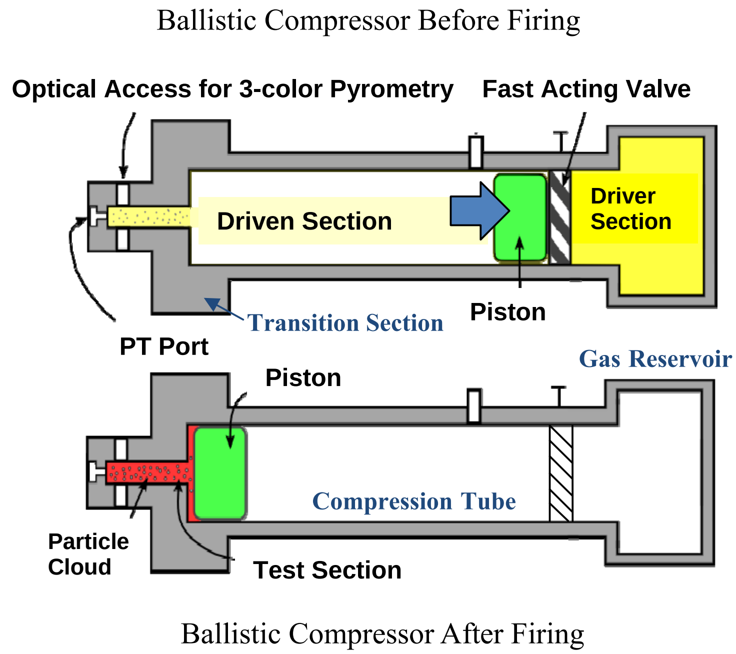

Figure 1: Cartoon schematic of operation of ballistic compressor both before and after firing

Modifications and Diagnostics

As the ballistic compressor at the HPCL was not originally designed for aluminum particle combustion research, several modifications were required. In summary, these modifications included the construction of a new test section with optical access of the test chamber via sapphire windows, pressure transducers, and a particle levitation system (later removed). A full history of these modifications may be found in the masters' theses of Matthew Sirignano [1] and Garrett Lee [2].

For this study, the ballistic compressor was equipped with two pressure transducers capable of measuring pressures up to 690 MPa (100,000 psi), as well as a three-color pyrometer to measure emitted light at wavelengths of 485 nm, 660 nm, and 850 nm. Original plans called for filters at 660, 750, and 850 nm to measure the combustion temperature of the aluminum particles, but problems with temperature measurement led to the use of a 485 nm filter used to confirm the production of AlO as an indication of aluminum particle ignition and combustion, as prior research had hypothesized [3].

Aluminum Test Samples

Four different types of energetic particles were used during the study of energetic particle combustion, and one type of inert particle was used as a control during the study. Nickel-coated Al particles were included, as earlier research at lower pressures indicated [4] that a nickel coating reduced the ignition temperature of Al particles. Table 1 summarizes different particle types used in this study.

Table 1: Summary of Al particles used in ballistic compressor tests

Material	Shape	Nominal Diameter	Supplier
Al	Round	32 μm	Technion
Al	Round	9 μm	Technion
Al w/ 5 wt% Ni coating	Round	32 μm	Technion
Al w/ 5 wt% Ni coating	Round	9 μm	Technion
Al_2O_3	Rough	9 μm	Micro Abrasives

3 Experimental Results

Test Matrix

In order to explore the behavior of aluminum particles at elevated temperatures and pressures, a test matrix of various pressures and particles was designed. The test matrix is shown in Table 2 below.

Table 2: Test Matrix

	9 µm Ni-Coated	9 µm Uncoated	32 µm Ni-Coated	32 µm Uncoated	9 µm Al_2O_3
20 kpsi	5	5	5	5	2
40 kpsi	2	2	3	3	1
60 kpsi	-	-	1	1	-

Unfortunately, due to damage to the sapphire viewing windows at 414 MPa (60 kpsi), only two runs were conducted at this pressure, one each of the 32 µm uncoated and Ni-coated particles.

Light Intensity Measurements

The light intensity at 485 nm during each run was recorded to allow for comparison purposes. The light intensities are normalized to an arbitrary scale, after calibration via a tungsten strip lamp over a range of temperatures. The intensities are highly non-repeatable between experimental runs, making comparison between individual runs difficult. This was due to several factors; the most significant factor being that in practically all of the tests, several particles would end up burning on the surface of the sacrificial sapphire window. However, the number of particles that would end up burning on the surface of the window varied heavily from one test to another. By looking at all of the runs for a particular particle type, however, some comparisons are possible. An example of these comparisons is shown below.

Figure 2 shows the light intensity traces of 32-µm uncoated Al particles on the left side and 32-µm Ni-coated Al particles on the right side. The light intensities of the 32-µm Ni-coated Al particles are far higher, even discounting the extremely high peak from Experiment 14, seen in light blue. This would indicate that a much more substantial section of the particle distribution underwent combustion when the particles were nickel-coated. The ignition timing seen on the right graph is earlier than that on the left, as well, indicating that the Ni-coated particles have a lower ignition temperature than the un-coated particles. The height of the light intensity peak from Experiment 14 was due to an unusually large collection of particles on the surface of the window.

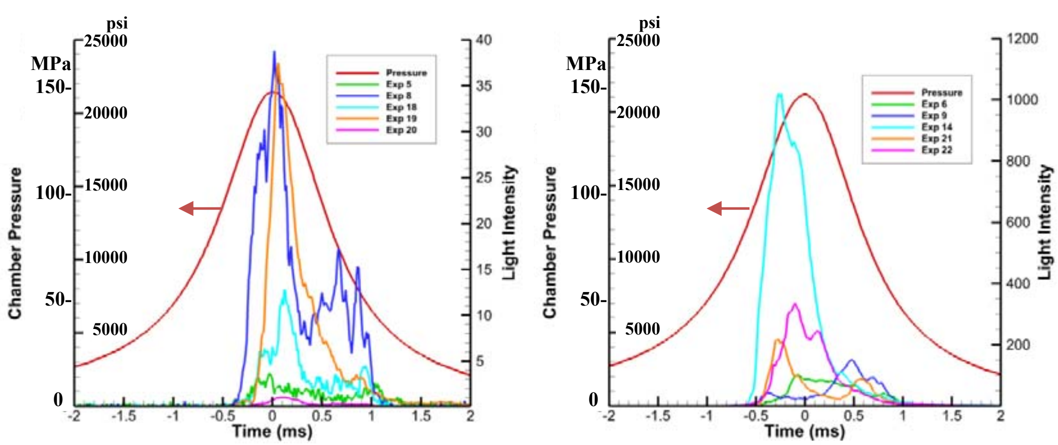

Figure 2: Light Intensity at 485 nm of 32-µm Al particles at 138 MPa (20 kpsi).
Left: Uncoated. Right: Ni-coated.

Light Intensity Ratio Measurements

The light intensities seen at 485 and 660 nm were compared to each other to determine if AlO was being formed during combustion. For the 485 and 660 nm emissions to be equal and due to blackbody radiation, the temperature calculated by Wien's approximation would be over 5000 K – far beyond the ballistic compressor's capabilities. Therefore, if the light intensity ratio of 485 nm/660 nm approaches or exceeds unity, then another phenomenon other than blackbody radiation, such as the formation of AlO, must be the cause. An example of these comparisons is shown below.

Figure 3 shows the light intensity ratio traces from P_{max}=276 MPa (40 kpsi) tests of 9 µm Al_2O_3 particles on the left and 9 µm Ni-coated Al particles on the right. Due to the low light intensity signal levels at low pressures, the light intensity ratios display extremely high noise on both sides of the pressure peak, and can be ignored. The ratio seen on the left side of Figure 3 remains well below unity, as would be expected of an inert particle. The ratios seen on the right side of Figure 3 start off with a value greater than 1, indicating the formation of AlO during particle ignition and combustion, but then rapidly decline to a value very similar to the light intensity ratios of the inert particles – most likely indicating that the particles burned out quickly and then radiated excess energy in a manner more consistent with the blackbody radiation curve.

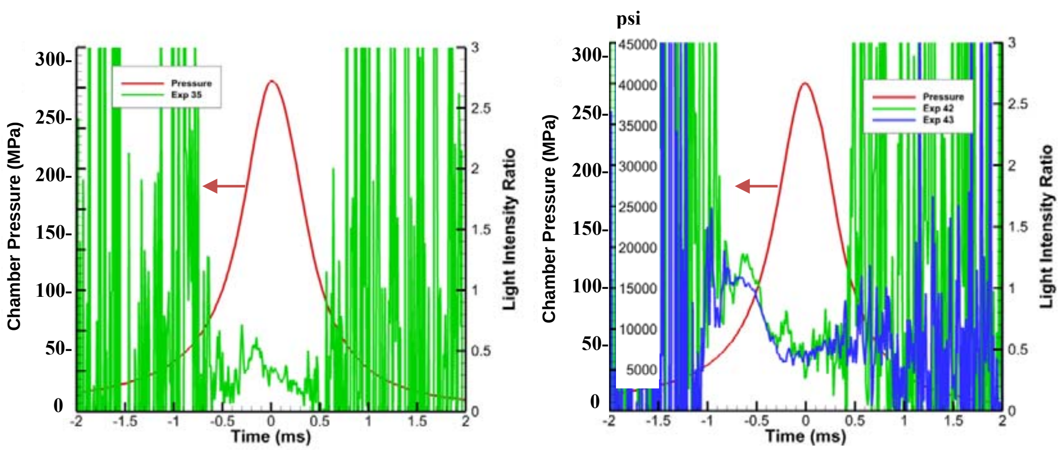

Figure 3: 485/660nm Light Intensity Ratio of 9-µm particles at 276 MPa (40 kpsi).
Left: Al_2O_3 particles. Right: Ni-coated Al particles.

These comparisons have not been made for the tests at 138 MPa (20 kpsi) due to low signal-to-noise ratios that prevented the drawing of any conclusions from those tests.

4 Conclusion

Ignition Timing

A summary of ignition times of various particles is shown in Table 3, where all times are defined as first discernible rise and are expressed in ms <u>before</u> peak pressure; thus, a larger value indicates an earlier ignition. From this table, it can be seen that the Ni-coated particles routinely ignite sooner than their uncoated counterparts.

Table 3: Ignition Times (Expressed as Time Before Peak Pressure) for Reactive Particles

P_{max}	9-µm Ni-coated Al particles	9-µm Uncoated Al particles	32-µm Ni-coated Al particles	32-µm Uncoated Al particles
138 MPa (20 kpsi)	1.24 ms	0.48 ms	0.59 ms	0.42 ms
276 MPa (40 kpsi)	0.89 ms	0.50 ms	0.52 ms	0.43 ms
414 MPa (60 kpsi)	-	-	0.50 ms	0.42 ms

Effect of Particle Size (9-µm vs 32-µm)

The 9 µm Al particles were observed to ignite sooner than their 32 µm counterparts regardless of coating or maximum pressure of the test. This is due to the increased specific surface area of the smaller particles, which allows for more efficient energy transfer from the compressed gas. Due to the high amount of scatter associated with the light intensities, any definitive statement comparing the observed light intensities of 9 µm versus 32 µm cannot be made with any certainty. A statement on a difference of ignition temperature between the two particle sizes cannot be made with any certainty, as the larger particles would require longer to reach a given temperature than their smaller brethren. This makes these results difficult to compare to previous investigations at lower pressures.

Effect of Nickel Coating (Ni-Coated vs Uncoated Particles)

The Ni-coated Al particles were observed to ignite sooner than their uncoated Al counterparts regardless of size or maximum pressure of the test. In 4 of the 5 test conditions, the Ni-coated particles displayed higher average intensities. The fact that the nickel-coated particles ignited sooner (thus indicating a lower ignition temperature) qualitatively agrees with previous investigations conducted at lower pressures.

Effect of Maximum Chamber Pressure (138 vs 276 vs 414 MPa or 20 vs 40 vs 60 kpsi)

The observed light intensities at 276 MPa (40 kpsi) were on the whole higher than those at 138 MPa, which is logical. The difference in intensities is especially pronounced when comparing the 32 µm uncoated particles during the 138 MPa and 276 MPa experiments. The ignition timing for the 276 MPa tests was later than that of the 138 MPa tests, which again is logical, considering the increased momentum of the free piston, which would tend to shorten the compression cycle.

Since few tests were run at 414 MPa, any comparison between the observed intensities at 414 MPa and 276 MPa would be invalid; however, the ignition timing was practically identical to the 276 MPa tests. This indicates that since the information desired about the burning particles is during the compression stroke, and there is very little difference between the pressure curves on the compression stroke of the 276 and 414 MPa tests, all of the desired information can be gathered at lower maximum pressures.

AlO Formation

The 485 nm/660 nm light intensity ratio traces from the reactive products were often much higher than those of the inert particles, which is indicative of the production of AlO during combustion.

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