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CRITICAL CONDITIONS FOR IGNITION OF ALUMINUM PARTICLES IN CYLINDRICAL EXPLOSIVE CHARGES

David L. Frost[1], Samuel Goroshin[1], Jeff Levine[1], Robert Ripley[2], & Fan Zhang[3]

[1]*McGill Univ., Mech. Eng. Dep't., 817 Sherbrooke St. W., Montreal, Quebec, Canada H3A 2K6*
[2]*Martec Ltd., 1888 Brunswick St. Suite 400, Halifax, Nova Scotia, Canada B3J 3J8*
[3]*DRDC - Suffield, PO Box 4000, Stn Main, Medicine Hat, Alberta, Canada T1A 8K6*

Abstract. The critical conditions for the ignition of spherical aluminium particles dispersed during the detonation of long cylindrical explosive charges have been investigated experimentally. The charges consist of packed beds of aluminium particles, ranging in size from 3 – 114 μm in diameter, and saturated with sensitized liquid nitromethane (NM). The ignition conditions depend on both the charge and particle diameters with the most reactive particles corresponding to an intermediate size (~54 μm dia). With increasing charge diameter, three particle reaction regimes are observed: i) sub-critical (no particle reaction), ii) near-critical (reaction at isolated spots, or radial bands or rings), and iii) super-critical (continuous reaction of the particle cloud). To monitor the onset of aluminum oxidation, visible radiation from the charge is recorded, through a slit, with a line spectrometer.

Keywords: Aluminum particle ignition, combustion, metalized explosive
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INTRODUCTION

The effect of metallic particle additives on the detonation properties of liquid explosives has been investigated by a number of researchers [1-3]. Typically, adding particles reduces the detonation velocity and pressure due to heat and momentum transfer to the particles, although the critical charge diameter for detonation failure may decrease or increase, depending on the competing effects of the sensitization due to the formation of hot-spots and desensitization due to the dilution of the explosive by the added mass.

For a liquid explosive charge containing metallic particles, a second critical diameter can be identified: the critical charge diameter for which the particles ignite and react within the combustion products (CDPI). Above the CDPI, the residence time of the particles in the hot detonation products is sufficient to overcome the quenching effect of the unsteady expansion of the products such that the particles react. The CDPI will depend on the particle size and morphology as well as the particle material and oxidizing gases present. It should be noted that due to the high relative velocity between the particles and the hot combustion product gases, the particle ignition/reaction processes will be very different from the classical problem of metal particle ignition and reaction in a quiescent gas studied extensively since the 1960's.

The existence of a CDPI was observed in an earlier study [4] for cylindrical charges contained magnesium particles saturated with sensitized NM, and found to be a strong function of particle size. In the present work, the earlier experiments have been extended to the case of aluminum particles to determine the influence of particle material on the onset of particle reaction. Interpretation of the results is assisted with computations with a multiphase model.

EXPERIMENTAL

The charges consisted of 122-cm long glass tubes, with inner diameters ranging from 9 to 74 mm. The charges contained packed beds of spherical aluminum particles (Valimet, CA) ranging from 3 – 114 μm in diameter, and saturated with NM sensitized with 10% by weight Triethylamine. The detonation was initiated in a 10-cm high section of liquid at the top of the charge with a detonator and a 10-g C4 booster.

The optical diagnostics used in the present investigation consisted of a high-speed Phantom VII video camera, a 3-color pyrometer and a line spectrometer. To spatially resolve the light emission from the detonation front and combustion products, the pyrometer and spectrometer viewed a segment of the charge, 70 cm from the top of the charge, through a horizontal 2.5-cm slit constructed with black Bristol-board and located 60 cm from the charge.

Light was collected for the pyrometer and line spectrometer using two conventional 35-mm cameras, located 60 m from the charge. A description of the pyrometer and calibration procedure has been previously published [5]. The line spectrometer differs from a conventional broad-band spectrometer in that the light emission from only 3 wavelength bands was recorded. For the line spectrometer, the filter wavelengths were chosen to monitor the emission from gaseous aluminum oxide AlO which exhibits a characteristic emission spectrum. In particular, two of the filters were set at 450 nm and 568 nm to monitor the intensity of the continuous background spectrum. The third narrowband filter wavelength was chosen to be 488 nm which is close to the most intense AlO band (486.6 nm). By using a linear interpolation, the background continuous spectrum at 488 nm can be estimated (I_2) and compared with the peak intensity measured at 488 nm ($I_1 + I_2$). The ratio I_1/I_2 then gives a measure of the relative intensity of the AlO band and can be used to monitor the presence of aluminum oxidation.

RESULTS

Tests were carried out with the following different Valimet aluminum particle size designations (with corresponding Microtrac particle distribution for the batch used): H-2 (3.0±1.5μm); H-5 (8±4μm); H-10 (13±10μm); H-15 (20±10μm); H-30 (36±16μm); H-50 (54±21μm); H-60 (63±21μm); and H-95 (114±40μm). For the smallest particles (H-2), charges with a diameter of 41 mm id or less failed to detonate. For the largest particles (H-95), charges of 19 mm id or larger detonated, but the dispersed aluminum particles never ignited. For example, Fig. 1 shows the inert dispersal of H-95 particles from a 19-mm dia charge.

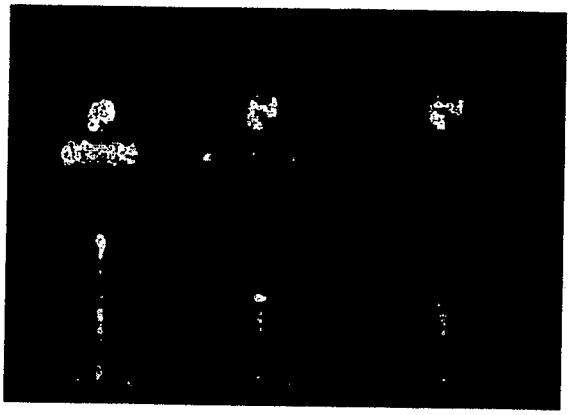

FIGURE 1. Detonation of 19-mm dia charge and dispersal of H-95 Al particles; 114 μs between frames.

For H-50 particles, particle reaction was evident with two morphologies: i) a near-critical regime in which discontinuous particle reaction occurs in the conical dispersed particle cloud at isolated regions (in the shape of spots, bands, or rings, perhaps associated with instabilities that develop at the particle cloud surface) which grow and eventually coalesce, or ii) a super-critical regime in which continuous reaction of the particle cloud occurs. These two regimes are illustrated in Fig. 2.

A summary of the dependence of the particle reaction behavior on charge and particle size is shown in Fig. 3. The boundary between the sub-critical (no reaction) and near-critical regimes is a U-shaped curve. In this figure, the H-2 (3 μm) and H-5 (8 μm) particles appear slightly more reactive than the larger H-10 and H-15 particles; this may be due to the fact that the particle mass fraction in the charge differs: 73±1% for H-2 and H-5 in comparison with 77±1% for all the larger particles.

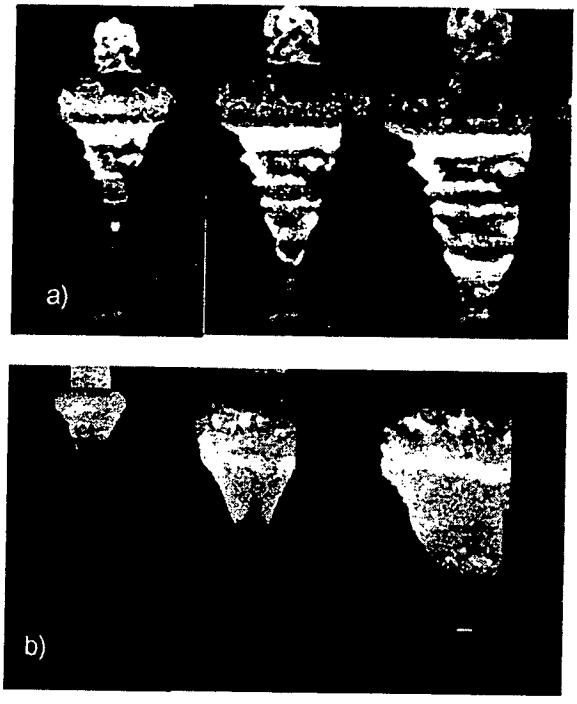

FIGURE 2. Particle reaction morphology for charges with H-50 particles: a) discontinuous reaction bands (or rings) for 34 mm dia tube; time between frames 57 μs, b) continuous particle reaction zone for 74 mm dia tube; time between frames 80 μs.

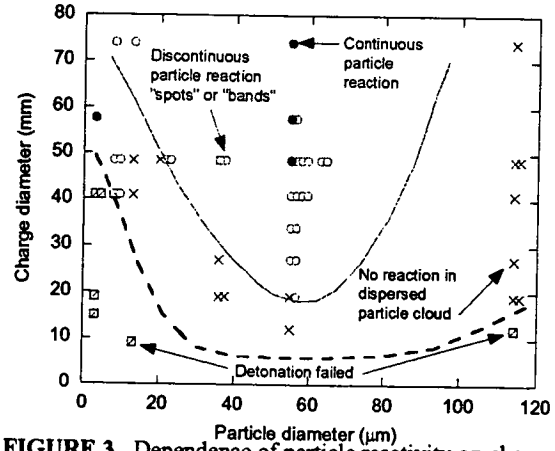

FIGURE 3. Dependence of particle reactivity on charge and particle diameter.

For the near-critical case of discontinuous particle reaction, there is some evidence from the line spectrometry that even in the "dark" zones, there is some aluminum oxidation taking place, which may be obscured by soot at the periphery of the expansion cone. For example, Fig. 4 shows the pyrometer intensity and ratio I_1/I_2 for H-60 particles in a 48.5 mm id tube in which the particle reaction is discontinuous.

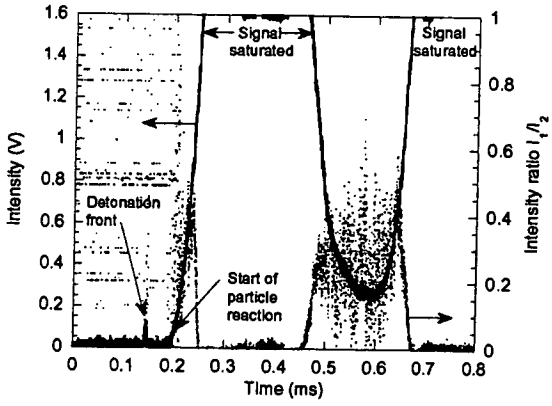

FIGURE 4. Light intensity and intensity ratio I_1/I_2 for 48.5 mm dia charge containing H-60 particles.

At a time of 0.15 ms, the detonation moves past the slit, then 50 μs later (corresponding to a distance of 250 mm behind the detonation which moves at a velocity ~ 5 mm/μs) intense particle reaction is visible. When a "dark" zone moves in front of the slit about 0.3 ms later, the overall light intensity drops, but the I_1/I_2 ratio at this point is about 0.3 which indicates the presence of gaseous aluminum oxides.

DISCUSSION

For the largest particles (114 μm), the residence time in the hot combustion products is not sufficient to induce particle reaction. However, the susceptibility for particle reaction is not solely dependent on particle size, given that an intermediate particle size reacted with the smallest tube diameter. Hence, the fluid mechanics of the particle dispersal process and subsequent mixing with the surrounding air must also be relevant to the particle reaction dynamics. The initiation of discontinuous particle reaction sites appears to be correlated with perturbations that develop on the particle cone surface (see Fig. 2a) which would

promote mixing with the nearby air which remains relatively hot due to the shock passage.

Results from the multiphase code calculations are shown in Figs. 5 and 6 for 54 μm particles in a 74 mm dia charge. Fig. 5 shows that the highest fluid temperatures are attained immediately behind the detonation front and behind the conical blast wave that is transmitted into the surrounding air. The expansion cooling of the products behind the detonation front is also evident.

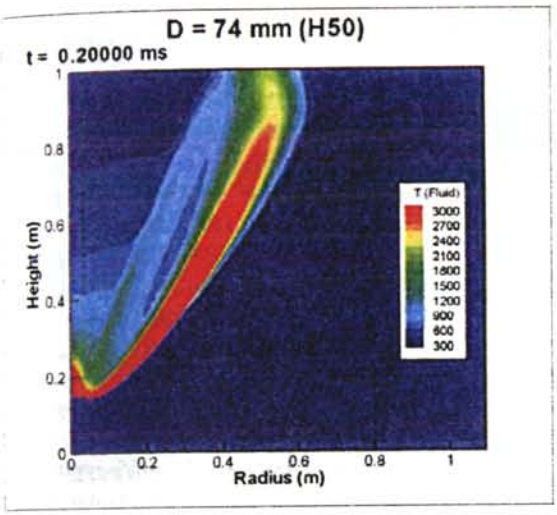

FIGURE 5. Fluid temperature during detonation of 1.1-m long, 74-mm dia charge containing H-50 (54 μm) particles. The detonation front, moving from top to bottom, is near the bottom of the charge at the time shown (0.2 ms).

Fig. 6 shows the variation of particle size due to the reaction of the particles. When the particles reach a threshold temperature (the Al melting point of 933 K is used), reaction of the Al particles is initiated. Note from Fig. 6, that the burning particles are concentrated near the outer region of the conical particle cloud (some of which have penetrated the shock front), where the particle number density is low and the fluid temperature is high, whereas the particles in the central core remain unburnt. Similar calculations with a 19-mm dia charge exhibit negligible particle reaction due to the more rapid expansion cooling of the combustion products, consistent with experimental

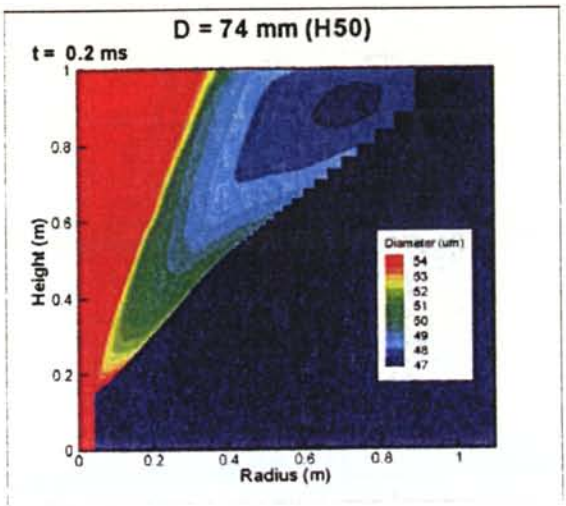

FIGURE 6. Variation in particle size due to burning during detonation of 74-mm dia charge with 54 μm particles. The particles in the central region remain unburnt.

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