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Particle size and gas environment effects on blast and overpressure enhancement in aluminized explosives

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Abstract

Aluminized RDX-based explosives were detonated under controlled conditions while varying particle size and atmosphere in an effort to quantify the contribution of aerobic and anaerobic Al reaction to blast and overpressure. Early time reaction of aluminum acts to enhance the primary explosive blast, and this reaction is approximately half aerobic and half anaerobic (i.e. oxidation by detonation products and/or nitridation), suggesting that very rapid early-time mixing occurs in explosive fireballs. Particle size effects are surprisingly negligible over the range of 3–40 μm , which implies that conventional scaling laws for aluminum combustion provide less insight than previously assumed. Quasi-static pressures obtained in the time period from 5 to 10 microns after detonation suggest that oxidation of aluminum is complete in the presence of 20% oxygen. However, for nitrogen environments, oxidation only proceeds to half its theoretical maximum, except for the smallest (3 μm particles) for which oxidation was nearly complete. These results demonstrate that oxidation of aluminum in aluminized explosives is robust in anaerobic environments, and that simulation efforts cannot neglect anaerobic channels, even though aerobic oxidation provides the greatest energy release.

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1. Introduction

Aluminum has been added to explosives for several decades in an attempt to increase energetic output and warhead performance. The oxidation of aluminum with high explosive detonation products is far more energetic than the decomposition of the high explosive itself, though reaction occurs on a much longer timescale. As a result of this timescale disparity, there is an optimal amount of aluminum (usually about 20–30%) that can be

added to explosive formulations, above which performance is degraded. Development of such explosives has been largely empirical, with advancements achieved through a combination of limited fundamental modeling and extensive experimentation. Detailed understanding of the reaction mechanism and kinetics of aluminum reaction may enable design of explosives with higher aluminum content, resulting in significantly improved energy release without blast performance degradation.

The most critical question in the combustion of Al in aluminized explosives is under what conditions and time scales the aluminum reaction occurs, and on what critical parameters do these reaction kinetics depend. For the purposes of this

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Table 1

A proposed breakdown of the reaction regimes for aluminum in an aluminized explosive. Increases are with respect to an explosive with inert additives.

Phase	I	II	III	IV
Key characteristic	Reaction in detonation wave	Blast wave driving	Reaction in fireball	Late time oxidation
Approximate reaction timescale	μs	10–500 μs	1–100 microns	0.5–2 s
C–J pressure increase	Yes	No	No	No
Primary blast increase	Yes	Yes	No	No
Thermobaric overpressure increase	No	No	Yes	No
Oxidation in residue	Yes	Yes	Yes	Yes

study, we consider four phases of aluminum combustion, as determined by the effects of that combustion on the target. In principle, Al combustion can occur immediately behind the detonation wave in the solid explosive, and we assign this as Phase I combustion. Such combustion would contribute to the detonation pressure observed at the edge of the high explosive, manifesting itself in greater force on the external casing, and thus higher fragment velocities. After detonation breakout, the air blast wave forms and can be driven by any further reaction in the explosive products, such as Al combustion with detonation products or entrained oxygen. Blast-wave-driving reaction of Al after detonation breakout is assigned as Phase II reaction. Continued reaction of Al with air and/or detonation products can occur after blast wave departure. If the reaction produces measurable overpressure in the vicinity of the fireball that can generate work on the target (e.g. the thermobaric effect), we assign this as Phase III reaction. Slow oxidation of dispersed Al that does not produce overpressure or target damage is assigned a Phase IV. These assignments, which are by no means the only way to classify aluminum reactions, are listed along with their measurable effects in Table 1.

Phase I reaction of Al has generally been considered insignificant. Several studies [1–3] have shown that the detonation velocity of aluminized explosives is not increased significantly over that of the bare explosive, suggesting that Al reaction is much slower than reactions occurring in the detonation wave. Such an observation is consistent with the experimental work on aluminum combustion that suggests that timescales for oxidation, even under extreme conditions, are generally orders of magnitude larger than detonation reaction times [4–6]. However, some recent work by Balas and Baker [7,8], suggests that under certain circumstances reactions of Al in some formulations are fast enough to show measurable increases in Chapman–Jouget (CJ) pressures resulting in enhanced ‘case pushing’ effects. The effect appears only in certain formulations which the authors denote “combined effects” explosives, and the

group has proposed a theory that accounts for the effect [8].

Phase II, or blast-driving, reaction is a much more well-known effect. Previous studies have shown that primary blast wave strength, as measured by peak pressure and/or positive phase impulse, can be enhanced by addition of aluminum to explosives [1–3,9]. This effect is already applied to fielded warhead systems, though the details of the reaction remain poorly understood. For isolated Al particles at the 20 μm scale, for which enhanced blast effects are readily observed, reaction times in highly oxygenated environments are of the order of a few milliseconds, with significantly longer times for reaction in detonation products such as H_2O and CO_2 . Yet blast waves in even kg-scale charges separate from the fireball at times that can be much less than 1 milliseconds [10], leaving seemingly insufficient time for Al reaction. However, some physical effects exist that may enhance Al reactivity at early times. For example, the extreme pressures in the detonation wave can deform particles upon passing over them, leading to increases in surface area and possibly breakage or removal of part of the passivating oxide layer. In addition, immediately after breakout, pressures are extremely high in the detonation products (of the order of GPa), and thus, even though Beckstead suggests only a small pressure exponent on burning time ($t = P^{-0.1}$) [4], reactivity at these pressures may be up to an order of magnitude higher than at ambient pressure. Furthermore, temperatures immediately after breakout, at least in the outer regions of the emerging fireball can be extraordinarily high ($>10,000$ K) for at least 10 μs [11,12], leading to enhanced transport and chemical kinetics. Lastly, the work of Carney et al. [9] suggests that mixing of Al with ambient air at early times may be very rapid due to a highly turbulent interface and particles that are accelerated past the blast wave.

After detachment of the shock wave from the fireball, further reaction of metal additives will not enhance the primary blast, but may increase fireball temperature and lead to localized overpressure in the vicinity of the fireball. This thermobaric

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