

# MINIATURIZATION OF EXPLOSIVE TECHNOLOGY AND MICRODETONICS

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**Abstract** Condensed phase explosives used in conventional explosive systems have a charge size on the order of a meter or a sizable fraction of a meter. We discuss a range of issues, theoretical, computational and experimental, required to scale the size of explosive systems downwards by a factor of one hundred to one thousand, applications and prospects for a ubiquitous new technology.

**Keywords:** Detonation, shock physics, compressible flow, miniaturization, explosives, new technology

## 1. Introduction

A detonation is a chemical reaction driven shock wave in molecularly premixed material called an explosive. The chemical energy released in the reaction zone behind the lead shock is converted into kinetic energy and pressure/volume work done by the reactants. Explosives can be gases, liquids and solids. Detonation pressures in organically based condensed phase explosives (typically made from nitrated hydrocarbons) are in the range of 300–400 Kbar (30–40 GPa), and can potentially induce hundreds of Kbars of pressure in inert materials for fractions of microseconds. Detonation shock speeds are on the order of 3–10 kilometers/sec. The thermodynamic cycle and high pressure, high compression states that can be induced in materials are unlike those that can be obtained with other thermo-mechanical systems, including lasers. Hence detonative processes offer unique methods of altering the state of material surfaces and can serve as a high energy density source for micro-devices. Properly engineered, stable explosive detonation fronts work in combination by a principle of synchronicity (i.e. the detonation is a phase-controlled explosion front) and detonations can generate precise

motion-controlled flows that can be used for materials processing and other applications.

## 2. Applications

While condensed phase explosives are used in military, mining and demolition applications, other less commonly known applications of explosives include their use for materials processing, precision cutting and pulsed power application. Specifically, detonation of explosive films can be used in surface treatment and hardening of materials. Other material processing applications include cladding and explosive welding, sintering, shock consolidation of powders and shock-induced chemical synthesis. Pulsed power applications include magnetic flux compression, pulsed detonation engines, explosive lasing and the generation of extremely high intensity light pulses. There are biomedical applications for detonation of micro-sized explosive charges that include lithotripsy and localized destruction of pathological tissue [1]. Explosive and pyrotechnic elements pervade satellite and aerospace systems and hence there is interest in the miniaturization of explosive systems for micro-aerospace and satellite platforms. Suitably controlled detonation fronts represent a basic technology with unique aspects. By establishing the basic parameters of micro-scale explosive systems it should be possible to design micro-scale devices for welding, cladding, pulsed power, surface treatment and so on (as mentioned above) in novel, ubiquitous and unforeseen ways. Micro-explosive systems hold the promise of being a basic enabling technology with wide-spread application.

Figure 1 shows a sketch of a experimental configuration being designed at the University of Illinois, in collaboration with Prof. W. Kriven (Material Science and Engineering, UIUC) and Prof. R. Adrian (TAM, UIUC), to study high pressure, temperature synthesis of ceramic materials. The initiator consists of a capacitance discharge unit (CDU) that fires a 10-micron thick wire (typically gold) or metallic film embedded in the detonable film. The electrical current dump causes the metal to expand from a nominally cylindrical or flat source as plasma and drive a shock wave into the film to start the chemical reaction in the film. The detonation supported shock wave sweeps across the sample and the detonation shock drives an inert shock into the donor material to do the localized processing of near surface material. Other initiation configurations include laser driven micro-flyers that induce shocks to start reaction.

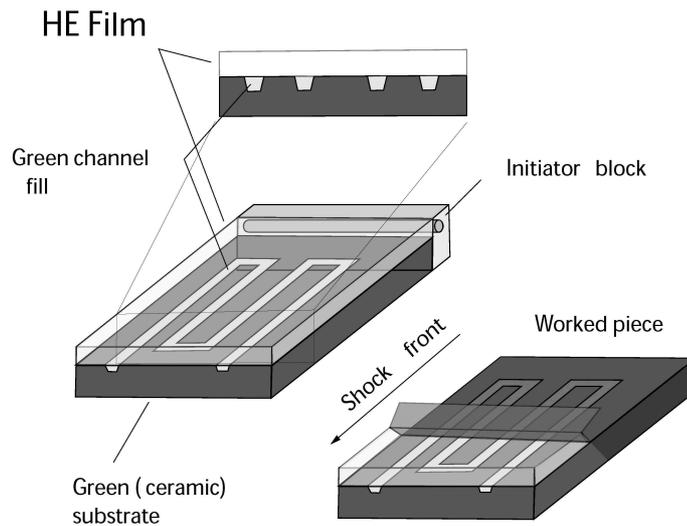


Figure 1. Micro-explosive system for materials processing of ceramics

### 3. Explosive System Scaling Arguments and Requirements

An explosive system includes the main charge (the secondary explosive), the initiation system (which includes the initiation train and booster made of primary explosives or electrical or optical laser initiators) and the inerts, upon which the explosive products act. Conventional macro-scale explosive system design paradigms exist for explosive systems that have dimensions on the order of a meter or sizable fraction of a meter. The question, what are the scaling principles for small-scale design that are consistent with existing large-scale design, can be addressed by dimensional analysis, based on the Euler equations and consideration of matching shock initiation and propagation experiments of small-scale systems to their large-scale counterparts. Scaling arguments, [2] show that extreme miniaturization by a scale reduction of current large-scale explosive systems by a factor of 100 to 1000 is possible. To employ existing large-scale design rules, the detonation reaction zone length scale must scale with the device dimension size. Short reaction-zone explosive materials (with small critical diameters) must be used for main charges. This means that one must select the main charge explosives from the list of primary explosives (used in large-scale initiator trains or detonators). Also one might consider using very short

reaction zone explosives that have never been considered for use in the past, because of safety considerations.

The other route to miniaturization uses explosive materials for propagation in sub critical charge dimensions. One expects to experience significant transients that do not fall in the existing quasi-steady design paradigms. This route requires a detailed understanding of transient detonation propagation.

#### **4. A definition of Microdetonics and the Initiation of Small Systems**

This brings us to a definition of the term “microdetonics” that we attribute to James E. Kennedy of Los Alamos National Laboratory. Kennedy’s definition of microdetonics is the detonation physics behaviors that are dominated by transient effects such as detonation acceleration, detonation spread and curvature effects that are commonly associated with initiation of explosives by small sources. This definition includes both small charges and small initiation sources, where transient phenomena is dominant.

Reliable and safe initiation systems for miniaturized systems can be built using existing exploding wire and exploding foil initiation systems with existing, well-understood electrical designs. Initiation energy is stored in a standard capacitance discharge unit. It is also possible to build optical initiation systems whereby energy is transmitted through an optical fiber to the explosive charge. Initiation system can be placed on chips, [3] and designed with standard photo-lithographic techniques, [4].

#### **5. New Science Needed to Enable the Technology**

In order to define the properties of the new explosive materials there is a need for a comprehensive linear and nonlinear stability theory for non-ideal detonation that can incorporate non-ideal equation of state and realistic reaction rate laws for condensed explosives. Recent efforts are underway to develop novel nano-engineering composite energetic materials and explosives that can be candidates for the miniaturized secondary charge. An entirely new linear stability theory for steady detonation has been developed by us at Illinois, [5] to guide design of miniaturized explosive systems in a rational way that incorporates descriptions of nonideal equation of state and reaction rate kinetics.

In order to define detonation propagation in small dimensions, one must understand the critical conditions required for ignition and propagation of detonation for both ideal and nonideal explosives [6]. This

includes the development of asymptotic theory for fast and sensitive chemical kinetics. It is important to understand aspects of detonation and shock diffraction and how that phenomena affects successful detonation propagation.

## High Resolution Multi-Material Simulation Technology is Required

Design of integrated systems requires modern high resolution, multi-dimensional and multi-material, time-dependent simulation. High fidelity simulation is an essential tool that is required to specify the geometry and select materials for miniaturized explosive system. Figure 2 shows a recent simulation of a “corner turning” experiment carried out by E. Ferm of Los Alamos National Laboratory. The corner turning experiment measures the transient effect of the change in confinement of detonation. The initial configuration of Ferm’s experiment has a 6 mm radius, 125 mm long cylindrical stick (donor charge) of explosive PBX-9502 joined to a wider/shorter 25 mm radius, 50 mm long (acceptor charge) cylinder of PBX-9502. The detonation is started and travels as a curved steady detonation in the donor. Once the detonation

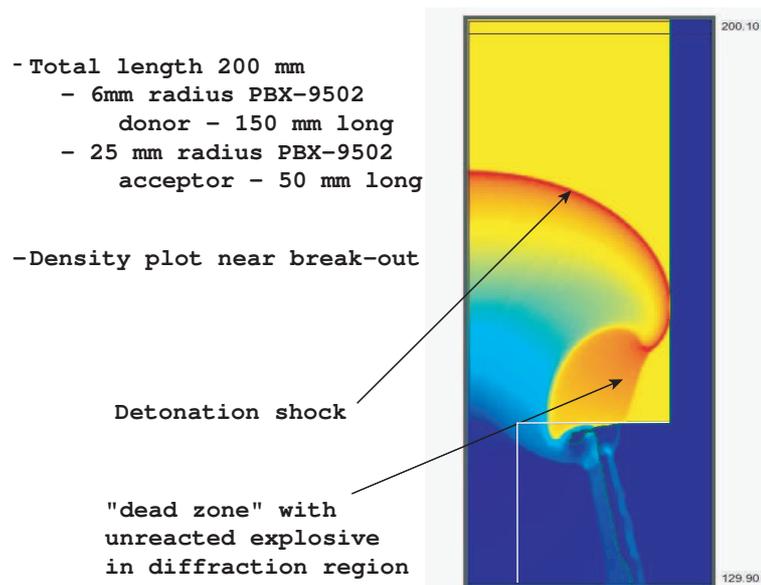


Figure 2. MULTIMAT Simulation: The density record of a corner turning experiment that shows the effects of detonation diffraction and the appearance of dead zones

in the donor charge enters the acceptor, the detonation must expand into the large acceptor region. Because the lateral boundary of the acceptor charge is perpendicular to the axial propagation direction of the detonation in the donor and that the lateral boundary is unconfined, a large depressurization (rarefaction) of the detonation occurs. When the reaction rate of the explosive is pressure sensitive, the depressurization effectively slows or stops the reaction in the region affected by the corner turning diffraction event. Hence a large region appears where the explosive does not burn. That region is dubbed a “dead zone”. Instead of reacting, the explosive in the dead zone is simply shocked. For microcharges or for initiation by small sources, the corner turning experiment is a generic configuration that must be studied in detail.

Figure 2 is a snapshot of a density record from a simulation carried out by members of our group (D. S. Stewart, B. Wescott and S. Yoo) with our UIUC-code MULTIMAT. Our simulation shows the detonation after the detonation in the donor has entered the acceptor. The explosive charges are initially adjacent to a very low density inert material (shown to the right). As the simulation progresses the material interface between the explosive products and the inert material expands. Our simulation show the appearance of large dead zone preceded by a low pressure shock in the diffraction region nearest the corner, connected to a fully emergent detonation in center and conforms closely to Ferm’s experiment. The code MULTIMAT uses high-resolution (4th order in space and 3rd order in time) compressible reactive flow solvers combined with a modern level-set treatment that represent interfaces to enable multi-material simulation required for microdetonic devices.

## High Speed Measurement and Other New Areas of Mechanics Research

The events of explosive technology take place at the limits of conventional experimental methods that measure mechanical quantities. Microdetonics is an area whose investigation will stimulate the creation of new measurement technologies. Recently our colleague, R. Adrian and his co-workers are working to develop PIV systems, [7] that can make capture motion events generated by shocks in optically accessible solids. These test solids can be used as a measuring instrument and a “full-field” witness plate to capture the energy and momentum transfer from adjacent shock materials that are under investigation. Unlike lower speed PIV systems that take full-field velocity measurements in water or air, full field measurements in the interior of solids have not been available experimentally. This emerging measurement technology should allow

for unprecedented improvements in understanding load transfer at the interface between materials.

The physics of exploding wire and foils involves the coupling of the mechanics of phase transformations and the magneto hydrodynamics. Target ceramic materials require new thermo-mechanical theories for ceramic formation under rapid high pressure/temperature loading. The theory of critical energy and pulse duration for initiation of detonation is at the heart of fundamental questions in reactive flow science. It is very likely microdetonic devices can be made for use for other basic material property investigations of a fundamental nature. In short, the area of microdetonics and the creation of precisely controlled miniaturized explosive systems will surely be coupled to fundamental advances in thermomechanics and have an impact on areas of technology that can use precision, high energy density output sources applied to materials with precision.

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