MINIATURIZATION OF EXPLOSIVE TECHNOLOGY AND MICRODETONICS

D. Scott Stewart*
Department of Theoretical and Applied Mechanics, University of Illinois, USA ,dss@uiuc.edu

Summary 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, and applications and prospects for a ubiquitous new technology.

BACKGROUND

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 donor 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 mentioned.

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 typical experimental configuration being studied at the University of Illinois. 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 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.

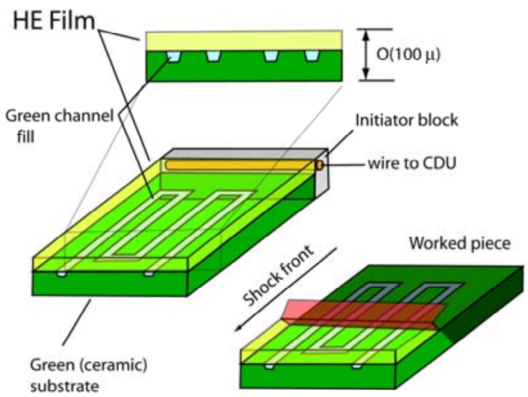

Figure 1. Micro-explosive system for material processing

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. 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.

Short reaction-zone explosive materials (with small critical diameters) must be used for main charges in order to use the well-known design paradigms for large-scale devices. 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 in the past that have never been considered for use because of safety considerations. 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.

Subcritical charge dimensions (used with main charge explosives that have longer reaction zones might be used successfully, but one expects to experience significant transients that do not fall in the existing quasi-steady design paradigms. Notably, one might expect to see the dynamic consequence of galloping instability or low velocity detonation.

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 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 [3]. We will briefly describe new work based on asymptotic theory of fast and sensitive chemical kinetics. It is important to understand aspects of detonation and shock diffraction and how that phenomena affects successful detonation propagation.

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. We describe some of the high-resolution solvers that we use that are combined with level-set methods for interfaces and the Ghost Fluid Method to enable multi-material simulation required for microdetonic devices.

We will give an overview of the subject and discuss some of the basic configurations and operating conditions of micro-explosive systems and integrated theory simulation and experiments by our extended research group of colleagues at Illinois and the US National Laboratories.

Acknowldegements This work is supported by the US Department of Energy, DOE/LANL, and the US Air Force Research Laboratory, AFOSR-Mathematics and Eglin AFB, Florida

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