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Towards the miniaturization of explosive technology — Source link

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Towards the Miniaturization of Explosive Technology

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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. This paper addresses a range of issues required to scale down the size of explosive system by a factor of one hundred to one thousand.

1 Introduction

Condensed phase explosives have traditionally been used in military, mining and demolition applications in which the charge size is on the order of a meter or a sizable fraction of a meter. An explosive system includes the main charge (the secondary explosive) the initiation system (which includes the initiation train and the booster, made of primary explosives) and the inerts, which confine the explosive or are the objects upon which the explosive products act. Figure 1 shows a radiograph of shaped explosive jet charge, [Lambert, D., 2001]. In this application a detonation wave is initiated and the detonation in the explosive collapses an embedded, cone shaped, copper metal liner. The copper liner is squeezed to the center line of the charge by the coherent action of the detonation wave and the collision of the metal in the center, inertially confined by the large pressure behind, causes a streaming metal jet to emerge on the centerline. The action is similar to the coordinated closing of one's hands in a swimming pool to squirt a water jet at one's little sister. The dimension of the charge is on the order of 100 millimeters. The tip of the emerging metal jet travels at speeds near 10 kilometers/sec. Explosive line cutters used in demolition applications and explosive separators, used in satellite and aerospace applications, work on the same principle and send out a jetting sheet of collapsed metal liner to cut on a line.

Figure 2 shows a sketch of the welding application of explosives. An explosive is layered over a donor metal sheet separated by an air gap. Below lies a layer of acceptor metal. A detonation is initiated in the explosive and the expansion of the detonation products drives the donor metal down into the acceptor. The collision causes a severe local deformation and presumably melting of the two metals. The flow in the metals causes them into intertwine, possibly due to a local Kelvin-Helmholtz instability, and the following release rarefaction behind the joining region causes the metals to freeze and joins them together in a weld.

Other less commonly known applications of explosive include sintering, shock consolidation of powders, shock induced chemical synthesis, pulsed power through

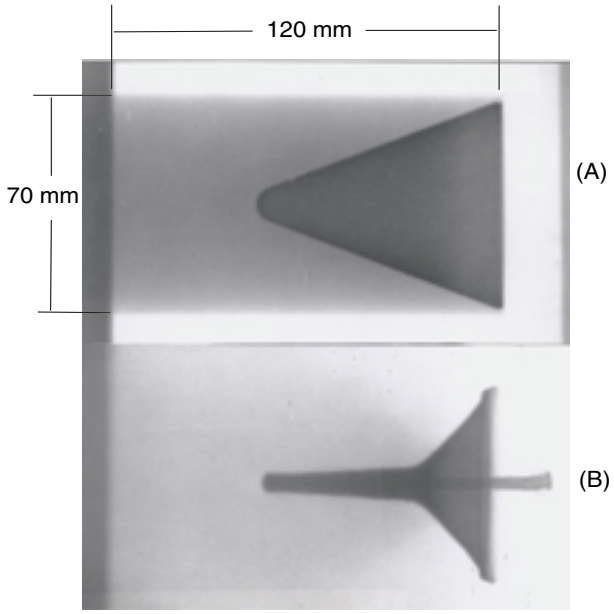

Fig. 1. Radiograph of a shaped jet charge courtesy, D. Lambert, [Lambert, D., 2001]. A) Before firing. B) Jet formation from liner collapse after firing

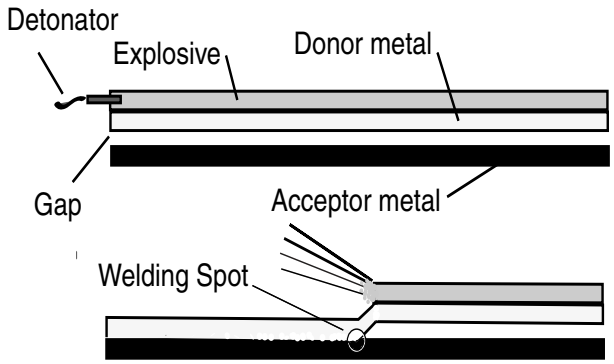

Fig. 2. Sketch of the explosive welding process

magnetic flux compression, explosive lasing and the generation of extremely high intensity light pulses, [Davis, W. C., 1998]. An important example of commercially important synthesis is Dupont's well-known commercial process to make diamonds from explosively driven shock-compression of graphite, [Meyers, M. 1994].

Many solid explosives are made from from nitrated hydrocarbons. The basic molecule of the explosive HMX is a nitrated benzene ring. Detonation pressures

in organically based condensed phase explosives 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 front speeds are on the order of 5 - 10 kilometers/sec. The thermodynamic cycle and high pressure, high compression states that can be induced in donor materials is unlike those that can be obtained with other thermomechanical systems, such as lasers. Stable explosive detonation fronts properly engineered, work in combination by a principle of synchronicity, (i.e. the detonation is a phase-controlled explosion front) where the precise motion of the detonation shock induces controlled flows and material states in the adjoining (inert) materials to produce the desired action.

The unique aspects of condensed explosives is associated with extraordinarily high energy density. As an example for those unfamiliar with high explosives, consider the chemical energy contained in an approximately 3 inch diameter, by 3 inch high, right circular cylinder (coffee cup-sized) filled with an explosive like HMX. The volume is approximately $V \approx d^3 = 1 \times 10^{-3} m^3$. The density of HMX is about $2 \times 10^3\, Kg/m^3$ and the chemical energy of combustion is about $5 \times 10^6\, Joules/Kg$, so that the total available energy stored in the explosive is approximately $10 \times 10^6\, Joules$ or 10 Mega-Joules. If purely converted to oppose earth based gravity, this is enough energy to lift a 100 Kg man approximately 10 Km straight up. If we took a 100 μ ($10^{-4}\, m$) slice of the same 3 inch diameter charge, the stored energy content is still $10 \times 10^3\, Joules$ (or 10 kilo-Joules).

For conventional explosive system applications, which includes military, mining and materials processing applications, the charge dimension is usually on the order of a sizable fraction of a meter in width, length or extent with $d \sim O(1)\, m$, (say). The corresponding length of the detonation reaction zone for a steady, one-dimensional, ZND, Chapman-Jouguet wave, is a fraction of a millimeter with $\ell_{RZ} \sim O(1\, mm)$ so that the scale ratio of the device size to the reaction zone length, d/ℓ_{RZ} is huge and typically $O(1000)$ or larger. Therefore the detonation front thickness is extremely thin relative to the geometric proportions of the engineering device.

Suitably controlled detonation fronts represents a basic technology with unique aspects. Since explosive systems have unique capabilities, there is interest in the miniaturization of explosive system for aerospace and satellite applications, other defense applications and materials processing applications. Miniaturized explosive system can be used for cutting, cladding, lasing, pulsed power and magnetic flux compression, drilling, and explosive switches, materials processing and synthesis and a host of other as yet unenvisioned applications on a reduced scale. At the time of this writing there are existing and emerging programs at various U.S. national labs.

This interest in miniaturization and recent activity leads to the following questions. How does one make reliable detonation systems with sufficient performance that are very small? (Here the word *make* means that one must make the entire system, which includes the initiation system, the main charge and embedded or exterior inerts. One must tackle the issues associated with manufacture of the system and possible synthesis of the energetic material constituents.) What

are the scientific issues in the realm of detonation physics and materials science that need to be addressed? What is meant by small?

Let's briefly address this last question first. A steady, Chapman-Jouguet reaction zone length for a typical condensed explosive on the order of a millimeter or smaller. For HMX this length ℓ_{RZ} is approximately $0.1\,mm = 100\,\mu$. At smallest end we consider miniaturized device dimensions as small as a typical reaction zone thickness for secondary explosives (main charges) that are used in conventional large-scale devices. So we expect that the explosive system might be built on length scales from $O(1\,m)$ to $O(10^{-4}\,m)$ which is a four decade span. Building explosive system with sizes appreciably below 1 meter requires a rethinking of the design paradigms that are currently used and that have been historically developed mostly by empirical means. This leads us to the question of what are the scaling principles that are consistent with the current $O(1\,m)$ design paradigms? Scaling analysis is a systematic way to organize answers to the previous question. Next we briefly review what is currently required in explosive system design, followed by a scaling arguments.

2 Elements of Standard Explosive System Design

The elements of explosive system design can be grouped into four broad categories. *Ignition.* Can you start the detonation? *Propagation and Performance.* The detonation wave propagates and interacts with the working materials, (i.e. the confining metals, plastics and other inerts). *Manufacturing and Materials Issues.* For a chosen design, how do you pick the explosives and inert elements and how is the system assembled or manufactured? *Safety and Reliability.* Both the initiation train and the main charge must be safe from accidental ignition and have safe modes built in. The materials must be safe to work with.

The two most critical issues for small devices are *Ignition* and *Propagation and Performance.* For large-scale explosive systems that are shock initiated, the most commonly measured characteristic length is the *run to detonation* length. The run to detonation length is measured from the point in the explosive where the input shock enters, and is determined by the following experiment. A plane shock is introduced at one end of the condensed explosive and the distance that it takes from one end for a detonation shock to appear in the explosive, x_*, is noted as a function of the shock input pressure, P_s. The results are recorded in a standard correlation $log_{10}(P_s/p_0) = A - B\,log_{10}(x_*/\ell_0)$ where p_0 is usually 1 GPa and ℓ_0 is usually 1 millimeter.

To describe *Propagation and Performance* in large-scale systems one must look at basic ZND theory and its extension to multi-dimensional, time-dependent evolution. Specifically this includes looking at the effect of detonation shock curvature which is well-described by the theory of detonation shock dynamics, a theory which the author (DSS) and J. Bdzil of Los Alamos have jointly developed since 1984. The reader is referred to a topical review for a summary overview, [Stewart D. S. 1998]. The detonation shock dynamics theory is an asymptotic theory that is derivative of the full Euler equations for a reactive flow, and it

gives rise to explicit asymptotic estimates of the shock dynamics, detonation flow states, effects of confinement and the critical diameter effect. Recently, in the context of this theory we are studying detonation extinction and diffraction.

For both *Ignition* and *Propagation and Performance* one has explicit estimates of characteristic lengths, time scales and states generated by the explosive for conventional large-scale applications. This suggest looking for explicit scaling relations that relate a model system (which we will take to be the large-scale systems on the $O(1\,m)$ scale) to a *prototype* system (which we take to be the reduced scale or miniaturized explosive system). If the scaling laws hold for the design of reduced-scale systems then one can use the existing design paradigms. It is almost obvious that such scaling laws require the use of explosives with much smaller reaction zones for the small-scale systems (and we will make a more rigorous argument for this in the next section). Then miniaturized systems will require the selection of a new class of energetic materials for the main (secondary) charge; explosives not normally selected as secondaries in large-scale applications. However for reasons of availability, previous knowledge and saftey, it will be desirable to use large-scale secondary explosives in miniaturized devices that have dimensions below the critical size required for steady, stable detonation propagation in the large-scale secondary explosives. Engineering explosive devices with subcritical dimensions requires a greater understanding of the role of unsteady transients.

These considerations suggest that there are two basic routes to miniaturization:

- Application of the established design paradigms developed at the large-scale to the small-scale. (This route focuses quite heavily on selection of energetic materials with short reactions zones for the secondary (main charge) and in-situ manufacturing and/or in-situ sensitization of the explosive to load the main charge in the miniaturized device.)
- Use of explosives materials for propagation in subcritical geometries. (This route requires a much greater understanding of transient detonation propagation than is currently available in the literature.

3 Scaling Arguments

Next we deduce scaling relations for *Propagation and Performance* based on quasi-steady, weakly-curved, ZND, detonation theory, i.e. from the detonation shock dynamics theory. The scaling arguments given here can be deduced directly from the Euler equations, but are illustrated in terms of detonation shock dynamics which is simple, direct and fairly easy to understand.

3.1 Propagation

Consider detonation propagation in a rate stick, shown in Fig. 3. which is a right cylindrical charge of explosive with diameter d, confined by a cylindrical tube of

inert material such as metal or plastic. The radius of the stick is $R = d/2$. Theoretical analysis based on the weak curvature asymptotics, where the detonation reaction zone is assumed to be thin relative to the radius of curvature of the detonation shock, leads in the simplest case to the conclusion that the normal detonation shock velocity D_n is a function of the total curvature κ which can be expressed as an intrinsic relation $D_n = D_{CJ} - \alpha(\kappa)$, [Stewart & Bdzil (1988)], [Bdzil & Stewart (1988)]. The function $\alpha(\kappa)$ is a property of the explosive, which in turn is modeled by the assumed form for the equation of state $e(p, \rho, \lambda)$ and the reaction rate law $r(p, \rho, \lambda)$, used in the Euler equations that define the hydrodynamic model of the explosive. The variable λ is a reaction progress variable for an single exothermic reaction. For the simplest case possible, we take this relation to be linear and write it as $D_n = D_{CJ} - a\,\kappa$.

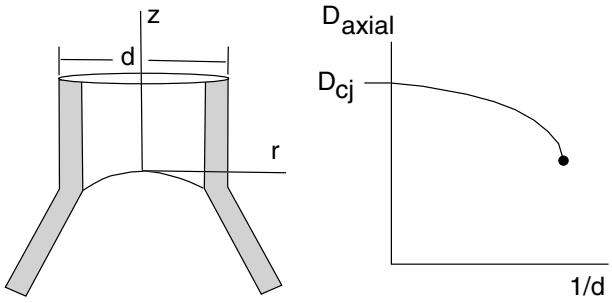

Fig. 3. A typical rate stick and its diameter effect curve

We introduce the shock surface described simply in terms of cylindrical coordinates, $\psi(z, r, \theta) = z - D_{CJ}t - z_s(r, \theta, t) = 0$. Combined with the general definition of the normal velocity $D_n = -(\partial\psi/\partial t)/|\nabla\psi|$ and the definition of the total curvature defined by the divergence of the shock normal $\hat{n} = \nabla\psi/|\nabla\psi|$ as $\kappa = \nabla \cdot \hat{n}$, the shock dynamic equation of the specific form $D_n = D_{CJ} - a\,\kappa$ is a nonlinear parabolic equation in the shock displacement z_s. Further, consideration of the confinement by the inert at $r = R$, shows that the shock angle is prescribed constant relative to the outward normal of the confinement boundary. Here we represent this condition as $\partial z_s/\partial r = -\delta$ at $r = R$. The angle δ is found from a shock polar match calculation, which uses the equation of state of the unreacted explosive and the equation of state of the inert. Hence δ is a quantity that is dependent on the explosive confinement pairing and its value represents the coupling influence of the inert on the interior shock dynamics of the explosive. The constant δ is dependent of the ambient density of both the explosive and the inerts and their respective equations of states.

Now let a tilde superscript represent a dimensional quantity and a plain variable represent a dimensionless variable. The dimensional formulation for the shock displacement can be formulated as

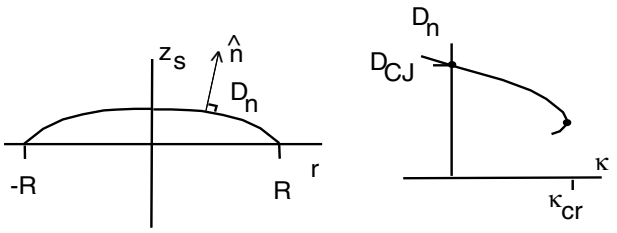

Fig. 4. The shock locus in terms of z_s and a typical $D_n - \kappa$ relation for a condensed explosive

$$\tilde{D}_n = \tilde{D}_{CJ} - \tilde{a}\,\tilde{\kappa} \quad \text{subject to} \quad \frac{\partial \tilde{z}_s}{\partial \tilde{r}} = -\,\delta \quad \text{at} \quad \tilde{r} = \tilde{R}\,. \tag{1}$$

If one takes a simple reactive flow model for the explosive where the reaction rate takes simple depletion form $\tilde{r} = \tilde{k}(1-\lambda)^{\nu} g(\tilde{p}, \tilde{\rho})$, theory [Stewart & Bdzil (1988)] shows that, $\tilde{a} = \tilde{D}_{CJ}^2 b/\tilde{k}$, where we recognize a characteristic reaction zone length as $\tilde{\ell}_{RZ} = \tilde{D}_{CJ} b/\tilde{k}$ and the effective shock dynamic diffusivity can be represented as $\tilde{a} = \tilde{D}_{CJ}\tilde{\ell}_{RZ}$. The constant b depends on an integral of g through the reaction zone.

Now we scale this problem with respect to the device dimension and introduce the (plain) quantities, $\tilde{D}_n = \tilde{D}_{CJ}\, D_n\,, \tilde{z} = \tilde{R}\, z\,, \tilde{r} = \tilde{R}\, r\,, \tilde{\kappa} = \kappa/\tilde{R}\,.$
The scaled DSD problem is written as

$$D_n = 1 - a\,\kappa \quad \text{subject to} \quad \frac{\partial z_s}{\partial r} = -\,\delta \quad \text{at} \quad r = 1\,. \tag{2}$$

Now let a m-subscript represent the (large-scale) model and the p-subscript represent the (small-scale) prototype then dimensional similarity between the two systems require

$$a_p = a_m \quad \text{and} \quad \delta_p = \delta_m\,,$$

the first of which leads to the most restrictive scaling relation

$$\frac{(\tilde{\ell}_{RZ})_p}{(\tilde{\ell}_{RZ})_m} = \frac{\tilde{R}_p}{\tilde{R}_m}\,. \tag{3}$$

Note that the requirement that $\delta_m = \delta_p$ is less restrictive since all the materials for both the model and prototype are solids with comparable equations of states and densities.

One can discover the same scaling laws from higher order detonation shock dynamic theories that retain higher order derivatives. In [Aslam and Stewart, 1999], we showed that a DSD evolution equation of the general (dimensional) form $\dot{D}_n = C^2(D_n)[-\kappa + F(D_n)]$ where $\dot{D}_n$ is the shock acceleration normal to the shock, and previous approximation to the shock dynamics is recovered in the form $\kappa = F(D_n)$. The numerical solution of this higher order DSD approximation can be shown to duplicate the motion of the shock obtained from direct

numerical simulation of the Euler equations in converging and diverging (diffracting) geometries. If we repeat the scaling arguments on this high-order equation we obtain the same result, (3). The underlying connection is through the full Euler equations.

Critical Curvature The diameter effect for rate sticks is that the axial detonation velocity drops as the size of the charge (diameter) of the charge is decreased, see Fig. 3B. Theory again shows that this is related to existence of critical curvature in the intrinsic $D_n - \kappa$ relation for an explosive, shown in Fig. 4B. And in turn, this is related to the state sensitivity of the exothermic reaction rate. In this case D_n is not monotonically decreasing with increasing curvature but rather there is a maximum (critical) value of the curvature, κ_{cr}. Using large activation energy for an explosive gas modeled by the ideal equation of state and Arrhenius reaction rate law of the form $\tilde{r} = \tilde{k}(1-\lambda)^{\nu} e^{-\tilde{E}/(\tilde{c}^2/\gamma)}$, where $\tilde{c}^2$ is the sound speed squared, γ is the ratio of specific heats, $\tilde{\mathcal{R}}$ is the gas constant and $\tilde{c}^2/\gamma = \tilde{\mathcal{R}}\tilde{T}$ identifies the standard temperature dependence found in the Arrhenius factor, we showed that the dimensionless normal shock velocity curvature relation can be given by formulas

$$\kappa = \frac{e^{B\theta(D_n-1)}}{D\,\theta}(1 - e^{A\,\theta(D_n-1)}) \tag{4}$$

with $D_n = \tilde{D}_n/\tilde{D}_{CJ}$, the $\kappa = \tilde{\kappa}\tilde{\ell}_{IZ}$ and where the characteristic (induction zone length) is given by $\tilde{\ell}_{IZ} = \tilde{k}^{-1}\tilde{D}_{CJ} exp(\theta/c_s^2)/\theta$, and the scaled activation energy is defined by $\theta = \gamma\tilde{E}/\tilde{D}_{CJ}^2$ and A, B and D are constants that depend on γ. If we match the critical curvature (or diameter) of the large scale (model) and miniaturized (prototype) systems, we must require that approximately $(\kappa_{cr})_m = (\kappa_{cr})_p$ which leads to the requirement that

$$\frac{\tilde{E}_p}{(\tilde{D}_{CJ}^2)_p} = \frac{\tilde{E}_m}{(\tilde{D}_{CJ}^2)_m}\,. \tag{5}$$

Given that a global activation energy, $\tilde{E}$ can generally be defined for an explosive from other experiments, such as thermal explosion or cook off experiments that define time to ignition, we anticipate that (5) is general criteria that must hold between similar condensed phase systems.

3.2 Initiation and Unsteady Propagation

As previously mentioned, run to detonation experiments are used to characterize detonation initiation by sustained shock waves. If we assume that the shock input pressure to the explosive is $\tilde{P}_s$, that the explosive has an initial density $\tilde{\rho}_0$, the Chapman-Jouguet detonation velocity $\tilde{D}_{CJ}$ and a rate law with a pre-exponential factor $\tilde{k}$ and a global activation energy $\tilde{E}$, then one proposes a experimental dependence for $\tilde{x}_*$ of the form

$$\tilde{x}_* = f(\tilde{P}_s, \tilde{\rho}_0, \tilde{D}^2_{CJ}, \tilde{k}, \tilde{E})\,. \tag{6}$$

Standard dimensional analysis shows that this relationship can be written in the dimensionless form

$$\frac{\tilde{x}_*\,\tilde{k}}{\tilde{D}_{CJ}} = F\left(\frac{\tilde{P}_s}{\tilde{\rho}_0\tilde{D}^2_{CJ}}\,, \frac{\tilde{E}}{\tilde{D}^2_{CJ}}\right) \tag{7}$$

Dimensional similarity between model and prototype again leads to the scaling relation (5) and the conclusion by this simple argument is that dimensional similarity of the model and prototype system during the shock ignition phase is consistent with the previous scaling argument, derived for the propagation phase.

If we accept the arguments of this section, the main charge (secondary) explosives of the miniaturized system are in the same class of materials as the primary explosives for the large-scale system. As an example, the very sensitive primary explosive lead azide, has a failure diameter of approximately 60 μ [Anderson, E., 1993] and would be a candidate for a main charge explosive in the miniaturized system. Therefore to use existing large-scale explosive design paradigms for the reduced-scale systems, one must consider using sensitive (i.e. short reaction zone length) explosives. Many explosive compounds have not been considered for used in large-scale systems because of their sensitive nature, or like lead azide, are only used as primary explosives in large-scale initiation trains or detonators.

The safety hazards associated with short reaction zone explosives can be mitigated by the fact that very small amounts of explosive are required in the main charge due to the size reduction. For miniaturized devices, one should consider in-situ manufacturing and sensitization techniques similar in logic to those use in large-scale commerical mining mining which bring sensitizing agents to the explosive mix to be added at the time of use.

4 Initiation of Miniaturized Systems and Dynamic Transients

Shock initiation of a miniaturized main charge does not necessarily require a complex initiation train that contain elements of even smaller, miniaturized primary explosives. Shock initiation can be accomplished with exploding wire or foil initiation systems, which can be designed to be fail-safe. Bridgewire or exploding foil initiators can be designed to fire only after sufficient voltage and amperage is applied to a firing point or line that is in contact with the miniaturized main charge. The initiation energy is stored in a standard capacitance discharge unit (CDU) firing set. Electrical circuits can be placed on chips by standard photolithographic and vapor deposition techniques. Hence miniaturized initiation systems can be designed by entirely electrical means and made reliable.

An important area of research is how the blast wave from the exploding foil or wire couples to the explosive material. Even though criteria have been developed for ignition of energetic materials, the theory of ignition of a detonation wave from an expanding blast largely does not exist in the theoretical literature and must be further developed.

Figure 5 shows an example of an experiment currently being designed by University of Illinois scientists (DSS and others) and colleagues at the U. S. Air Force Research Laboratory (Eglin AFB) (J. C. Foster and others) to study coupling aspect of exploding bridgewire ignition of explosive films. In this experiment an approximately 100 micron diameter exploding wire is embedded in a similar thickness explosive film. The explosive film is deposited onto a ceramic or metal donor plate. The bridgewire initiator is attached to a capacitance discharge unit which is used to fire the wire and start the reactive wave in the film. Standard high speed (rotating camera) and direct photography are used to record the subsequent events. More complex instrumentation of the experiment with embedded gauges is possible with this configuration.

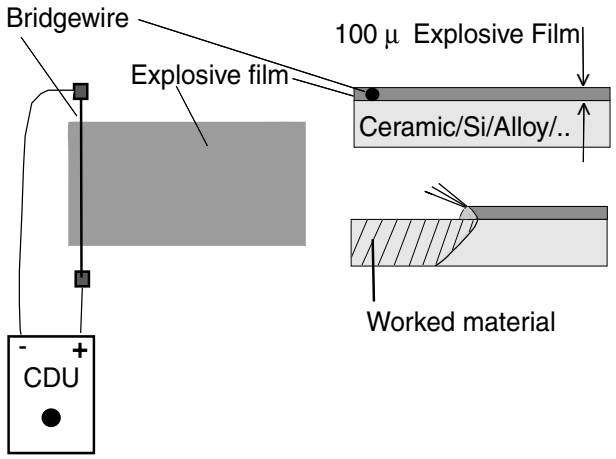

Fig. 5. Diagram of an experiment to test initiation and propagation of explosive films

Detonation Limits, Failure and Unsteady Propagation For explosives charges that have sub-critical dimensions well below their critical diameter, one can expect to see unsteady phenomena. Very little is known in a detailed sense about transient detonation dynamics, the effect of non-ideal equation of state, the relation of the dynamics to solid properties of the energetic materials, (especially important at low stimulus ignition) and the thermal decomposition kinetics of the explosives. For example, a theory of detonation stability does not exist for non-ideal explosives in the same sense that it does for ideal gas phase detonations with single step exothermic reactions. Almost all that is well-understood in detonation theory has been developed for ideal systems.

However, we can still take some guidance about the character of detonation transients in systems with sub-critical dimensions from experiments of gaseous detonation in small tubes. According to Strehlow [Strehlow, 1984], the most common instability in subcritical tubes is a galloping instability. A simple sketch of a galloping instability is displayed in an $x-t$ plane shown in Fig. 6A. Particularly noteworthy is the fact during a galloping instability there is a substantial lag between the shock and the following reaction zone, which leads to oscillations where the reaction zone nearly decouples from the leading shock and then suddenly accelerates to catch up. Strehlow reports that in gases, the period of the spatial period oscillation is on the order of 60 diameters. In explosive films of sub-critical thickness t, after line initiation (by a bridgewire say), we anticipate that one might observe striations in witness plate patterns left by detonation. A sketch of such an anticipated observation is shown in Fig. 6B.

Another possible instability that we might anticipate for miniaturized systems with subcritical dimensions is low velocity detonation. Here the detonation still travels sonically, but it has a velocity with is much closer to the sound speed of the unreacted explosive with pressures that are maybe as low as 25 percent of the CJ pressure. However these slower waves can still deliver large pressures to adjacent inerts and they well may be quasi-steady and hence very controllable for the anticipated purposes of materials processing applications.

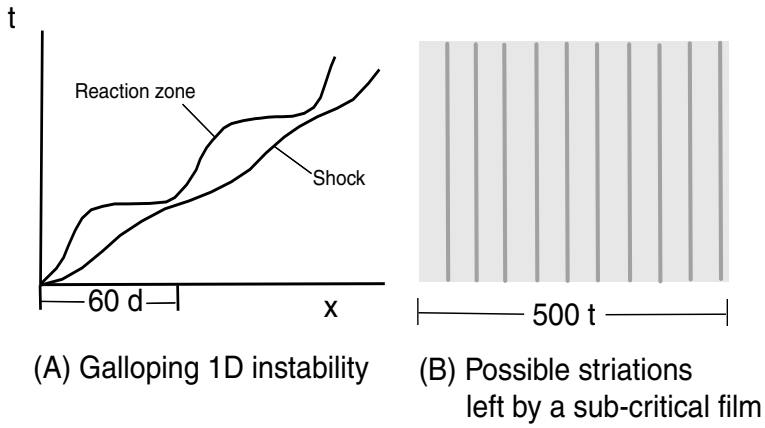

Fig. 6. Propagation instabilities in sub-critical dimensions

5 Summary and Conclusions

Here is a summary of the main points and conclusions made in this article.

- Extreme miniaturization by scale reduction of current large-scale explosive systems by a factor of 100 to 1000 is feasible.

- There are good prospects for the manufacture of mininaturized explosive systems that include applications such as welding, sintering, jet formation, cutting, chemical synthesis and material processing, pulsed power, etc.
- The expansion of condensed explosive products can generate unique thermodynamic cycling of adjacent materials that is likely unattainable by alternative processes, which is especially important for materials processing applications.
- Short reaction-zone explosives materials (with small critical diameters) must be used for main charges in order to use the well-known paradigms that currently are used to design large-scale devices. This means that one must select the main charge materials 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.
- Very small scale devices that use short reaction zone explosives, will also use very small amounts of explosive materials. So the safety problem associated with handling can be addressed by in-situ synthesis or a-posterior sensitization of very small amounts of explosive. The logic of manufacture is essentially the same as that used in commercial mining where the explosive charge is sensitized in the hole by the addition of sensitizing agent. One anticipates using existing embossing technology or other techniques of laying down films to accomplish this.
- Miniaturization will need the invention of a class of designer explosive materials that can be manufactured in situ. This may mean that gradient properties can be built into the materials.
- 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.
- There is a need for a comprehensive stability theory for non-ideal detonation that can reflect non-ideal equation of state and realistic reaction rate laws for condensed explosives. The development of this new theory is necessary to guide design of miniaturized explosive systems in a rational way.
- There is a need to develop a detailed theory and carry out simulations of shock ignition of detonation for both ideal and nonideal explosives. One should be guided and informed by John Lee's extensive work in the ignition of detonation in gases, [Knystautas and Lee, 1976]
- High resolution, multi-dimensional and multi-material, time-dependent simulation are essential tools that are required to specify the geometry and select materials for miniaturized explosive system.

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