Hot Spot Ignition Mechanisms for Explosives

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Introduction

A great many gases, liquids, solids, and mixtures are capable of exploding. A list of such substances would include not only what are regarded as "conventional" explosives but also gas and dust mixtures which can be ignited and grow to a full explosion under certain circumstances. If we exclude the military use of explosives in a wartime situation, it is usually this second category (gas explosions in homes or in mines; accidents in chemical plants) which cause the greatest loss of life and unwanted damage.

The explosive event is usually divided into various stages: ignition, the growth of deflagration (burning), the deflagration to detonation transition (DDT), and the propagation of detonation. Of course, if you put a large amount of shock energy into an explosive, there can be enough heating from adiabatic compression in the shock front to propagate a detonation immediately. This, though, requires very high pressures (tens of gigapascals) and is usually only met in "designed" systems. In many situations, and most accident scenarios, reaction starts at localized "hot spots" and develops from these. In other words, it is not necessary to heat all of the explosive but only small volumes. If in these small volumes the release of chemical energy is greater than that dissipated by heat losses, then the reaction grows. It is this ignition stage, which is relevant to all reactive systems which might explode, that this paper is concerned with.

In general it is thought that explosive initiation is thermal in origin. Mechanical or electrical energy is envisaged as being converted into heat in localized regions by a variety of mechanisms with the formation of "hot spots". Over the years a large number of "hot spot" mechanisms have been proposed. There is no single dominant process since the mechanism or mechanisms which operate depend on the energy input and the physical properties of the explosive. In considering any particular system it is important to understand the various "hot spot" formation processes and the mechanical, thermal, and chemical properties of the explosive. The sizes, temperatures, and durations of *critical* hot spots (i.e., those that can cause ignition) are clearly interdependent. However, Bowden and Yoffe,[1,2] working in this laboratory, have presented convincing evidence that "hot spots" need to have dimensions of typically 0.1–10 μm, durations of 10^{-5}–10^{-3} s, and temperatures of greater than ~700 K. This has important practical consequences since it means that processes which produce "hot spots" with sizes <0.1 μm (fission fragment tracks etc.) would cause some decomposition but quench too quickly to produce ignition.

The main mechanisms that have been suggested for ignition are

(i) adiabatic compression of trapped gas spaces;
(ii) other mechanisms involving cavity collapse such as viscous or plastic heating of the surrounding matrix material or, for very high shock collapse pressures, hydrodynamic shock focusing;
(iii) friction between sliding or impacting surfaces, or between explosive crystals and/or grit particles in an explosive;
(iv) localized adiabatic shear of the material during mechanical failure;
(v) viscous heating of material rapidly extruded between impacting surfaces;
(vi) heating at crack tips;
(vii) heating at dislocation pileups;
(viii) spark discharge;
(ix) triboluminescent discharge; and
(x) decomposition, followed by Joule heating of metallic filaments.

The above processes all involve the conversion of mechanical or electrical energy to thermal energy. Some workers have suggested additional mechanisms based on tribochemical or molecular fracture mechanisms, but there is little experimental support for such processes.

Experimental

There is not space to discuss comprehensively all the various techniques which have been used to study "hot spots". More information can be obtained from the books by Bowden and Yoffe[1,2] and the reviews by Field and colleagues.[3,4] However, it is clear that understand-

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(1) Bowden, F. P.; Yoffe, A. D. *Initiation and growth of explosives in liquids and solids*; Cambridge University Press: Cambridge, 1952; reprinted 1989.
(2) Bowden, F. P.; Yoffe, A. D. *Fast reactions in solids*; Butterworths: London, 1958.
(3) Field, J. E.; Swallowe, G. M.; Heavens, S. N. *Proc. R. Soc. London* 1982, *A382*, 231.
(4) Field, J. E.; Bourne, N. K.; Palmers, S. J. P.; Walley, S. M. *Philos. Trans. R. Soc. London* 1992, *A339*, 1.

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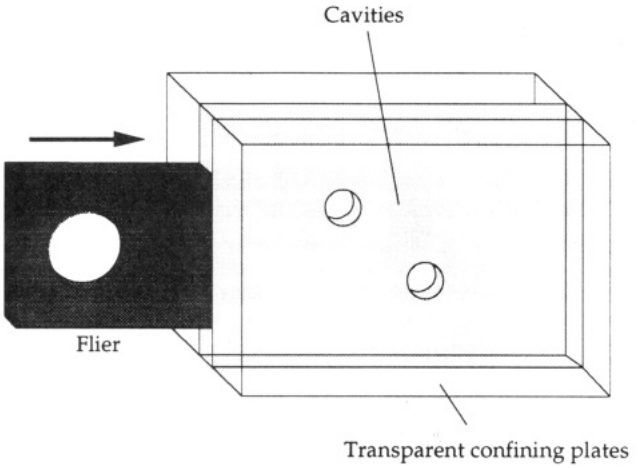

Figure 1. Impact geometry for two-dimensional experiments. Other experimental arrangements can be seen in ref 8.

ing explosive phenomena has been greatly assisted by direct observation of events using high-speed photography.

(a) Gas Space Collapse. In their studies of the role of gas space collapse, Chaudhri and Field[5] used an aquarium technique. Gas bubbles were positioned near explosive crystals and collapsed by weak shocks (of order 0.1 GPa), with the whole event recorded by high-speed photography. In this "model" experiment it was possible to use different-sized bubbles and different gas contents and to collapse the bubbles in various ways (for example, in thermal contact with the explosive crystals, separated from the crystal, and so on). This research established that, for the size range (50-μm to 1-mm diameter) and collapse times (few microseconds) studied, the adiabatic heating of the gas in the bubble was important.

A different arrangement has been used by Dear and Field[6,7] and Bourne and Field[8,9] for their studies of cavity collapse. The first step was to take a gel layer (it can be either inert or reactive) and to cut out any chosen array of cavities. A shock was then introduced into the layer either by impact or from a plane wave generator (see Figure 1). High-speed framing or streak photography was used to record the shock interaction with the cavities and their collapse. An advantage of this essentially two-dimensional geometry is that processes occurring inside the cavities can be recorded. The shocks were visualized using schlieren optics.

(b) Drop-Weight Impact. Drop-weight impact is conventionally used in explosive studies to assess the hazard property (sensitiveness) of a sample to low-velocity impact. Figure 2 illustrates an instrumented drop-weight apparatus which can be used to obtain stress–strain data at strain rates of order 10^2–10^3 s^{-1}. The system rests on a large blacksmith's anvil, A, which provides an almost ideal rigid support for the load cell, which measures the impact force. The cell is a 12.7 mm × 12.7 mm steel roller, R_1, which has four flats

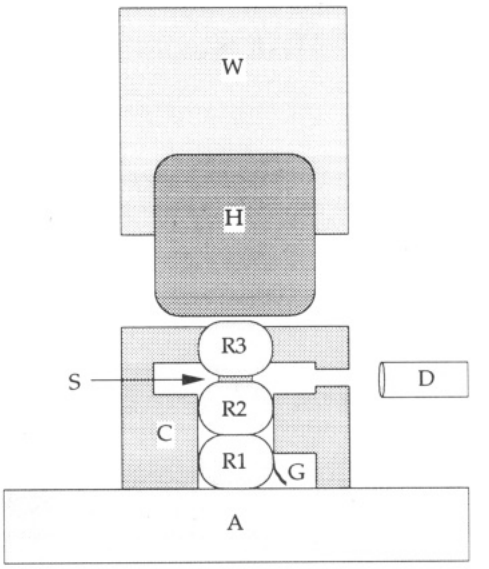

Figure 2. Instrumental drop-weight apparatus. W is the weight; A is the anvil; R_1, R_2, and R_3 are the steel rollers, the lowest being the load cell having strain gauges G; S is the specimen; and D is the light detector.

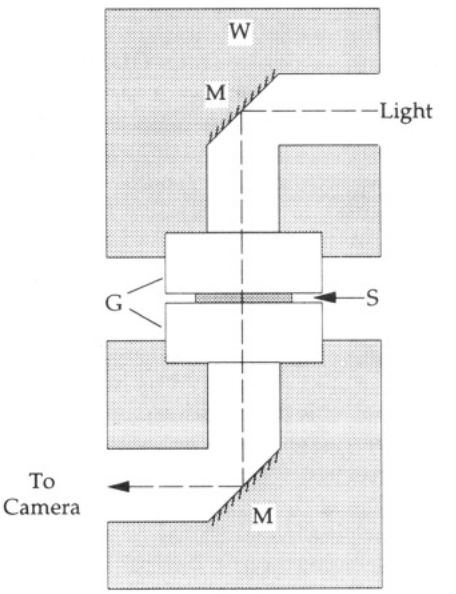

Figure 3. Transparent anvil drop-weight apparatus. W is the weight; M is a mirror; G are toughened glass anvils; and S is the specimen.

machined on it axially on opposite sides of the roller on which are mounted two pairs of strain gauges. An impact cell is formed by two further rollers, R_2 and R_3, stacked on top of the load cell, and a sample, S, is placed between this pair, the whole arrangement being impacted by a weight of 2.5 or 4.7 kg. The sample area is chosen to be just slightly greater than the area of the rollers so that there is no need to make assumptions about volume conservation. Knowledge of the mass of the weight combined with double integration of the force–time data produces force–displacement information which is then converted to a stress–strain curve.[10]

Figure 3 shows a transparent anvil drop-weight apparatus. Typically, 25-mg samples in the form of

(5) Chaudhri, M. M.; Field, J. E. *Proc. R. Soc. London* **1974**, *A340*, 113.
(6) Dear, J. P.; Field, J. E. *J. Fluid Mech.* **1988**, *190*, 409.
(7) Dear, J. P.; Field, J. E.; Walton, A. J. In *Nature* **1988**, *332*, No. 6164, 505.
(8) Bourne, N. K.; Field, J. E. In *Proceedings of the 9th Symposium (International) on Detonation*, Portland; Office of Naval Research: Washington, DC, 1989; p 869.
(9) Bourne, N. K.; Field, J. E. *Proc. R. Soc. London* **1991**, *A435*, 423–435.
(10) Heavens, S. N.; Field, J. E. *Proc. R. Soc. London* **1974**, *A338*, 77.

liquids, powders, pressed disks, polymer-bonded explosives (PBXs), or propellants are compressed between toughened glass anvils with an impact velocity of a few meters/second. The drop-weight (mass 5 kg) which carries the upper anvil is guided by three rods to ensure a planar impact. Shortly before contact, the mirror in the weight comes into alignment to complete the optical path from the light source to the high-speed camera.

(c) Heat Sensitive Film Technique. This technique was first suggested by Coffey and Jacobs.[11] It is based on the use of an acetate sheet coated with a sensitive layer which darkens on exposure to heat. For very short duration heat pulses ($<10^{-4}$ s), the film color is yellowish-brown rather than black, and the degree of darkening increases as the contact time is increased, until the film is fully blackened. Film darkening is a function of both temperature and time; therefore, to use the film to estimate the temperature achieved during deformation, one must know the time over which the deformation occurred and then refer to a set of calibration curves (darkening as a function of time and temperature) for the film. To use the calibration to obtain a temperature in an impact experiment, it was necessary to measure the time during which the darkening took place. These measurements can be made by using the transparent anvil arrangement described above. Results describing the calibration and giving the temperatures achieved during the deformation, shear banding, and fracture of a range of polymers can be found in Swallowe et al.[12]

Results

(a) Rapid Collapse of Gas Bubbles. The voidage present in many classes of explosives has long been recognized as a sensitizing agent to ignition by impact and shock. This has prompted the addition of artificial cavities to insensitive energetic materials, particularly ammonium nitrate (AN), in commercial applications. Bowden and co-workers[1,2,13,14] have shown that gas bubbles and their adiabatic collapse are key factors in the sensitivity of liquid explosives. The gas bubbles play an important role both in the transition from deflagration to low-velocity detonation and in the subsequent propagation of the low-velocity detonation. For solid explosives impacted in the drop-weight test, it has been shown that the gas content has an effect, particularly if the explosive is in the form of an annular layer. The specific heat of the gas was found to be important, as would be expected if adiabatic heating was involved. As noted above, Chaudhri and Field[5] showed that bubbles with diameters of millimeter size down to ca. 50 μm collapsed by a relatively low strength shock (ca. 0.1 GPa) could ignite sensitive explosives. This work and that by Starkenberg[15] confirms that gas-phase heating is a dominant mechanism when large cavities are collapsed relatively slowly.

It was first suggested by Kornfeld and Suvurov[16] that cavities might collapse asymmetrically and produce a liquid jet. Thus, there are a variety of mechanisms, in addition to gas compression, which can potentially cause ignition, for example, viscous heating in the matrix material and heating produced by compression of material downstream of the cavity on impact of the liquid jet.[17,18] Jetting has been observed for a wide range of cavity sizes. In general, the jet velocity increases as the radius of curvature of the cavity surface decreases. However, Frey[19] has concluded that viscoplastic work is the most efficient mechanism for producing high temperatures and that only for small cavities of size less than 1 μm will heat conduction away from the "hot spot" be significant.

Figure 4a shows three frames taken from a sequence in which a 12-mm cavity containing air is collapsed by a 0.26-GPa shock. The exposure time for each frame is ca. 0.5 μs. The gelatin sheet, of thickness ca. 2 mm, was held between poly(methyl methacrylate) (PMMA) blocks and the shock introduced by flier-plate impact. In frame 1, the incident shock, S, is passing over the cavity from below. The schlieren was adjusted to reveal density variations in the air within the cavity. The initial dappled appearance of the air is due to a low-amplitude compression wave traveling ahead of the main shock and induced by the blast of air traveling ahead of the flier-plate. An air shock, A, can be seen traveling away from the downstream wall at the acoustic velocity for air. Frame 2 is representative of an intermediate stage of collapse. The air shock has reflected from the upstream wall, returned, and reflected from the involuted upstream wall and is traveling back across the cavity. The upstream wall is deforming to form a jet which crosses the cavity at constant velocity. The detailed shape of the air shock is a consequence of the temporal changes in its confinement. By frame 3, the jet has hit the downstream wall, sending out a shock wave into the surrounding fluid, and has separated two lobes of compressed gas: in a three-dimensional situation this would be a torroid. As a consequence of jet penetration of the downstream wall, a pair of linear vortices subsequently form and travel downstream.

Figure 4b shows a single frame, exposure time ca. 60 ns, from a sequence in which two 6-mm cavities are collapsed by a 1.88-GPa shock from a plane wave generator. A schematic diagram shows the position of the two cavities relative to the shock and the relevant features of collapse. The left-hand cavity is in the process of collapsing, and a liquid jet can be seen crossing the cavity at an estimated 5 km s^{-1} (measured from other frames in the sequence). This frame shows that, at elevated pressures, the jet velocity can *exceed* the shock velocity. Since a shock is generated when the jet impacts the downstream cavity wall, this provides a mechanism for signals to propagate ahead of the incident shock! In the second cavity, two flashes of light, L, are visible, corresponding to the trapped lobes of gas. The light emission is believed to result from luminescence in the gas caused by adiabatic compression. For lower collapse pressures, the light emission

(11) Coffey, C. S.; Jacobs, S. J. *J. Appl. Phys.* **1981**, *52*, 6991.
(12) Swallowe, G. M.; Field, J. E.; Horn, L. A. *J. Mater. Sci.* **1986**, *21*, 4089.
(13) Bowden, F. P.; McOnie, M. P. *Proc. R. Soc. London* **1967**, *A298*, 38.
(14) Coley, G. D.; Field, J. E. *Proc. R. Soc. London* **1973**, *A335*, 67.
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(16) Kornfeld, M.; Suvorov, L. *J. Appl. Phys.* **1944**, *15*, 409.
(17) Mader, C. L. *Phys. Fluids* **1965**, *8*, 1811.
(18) Mader, C. L. In *Proceedings of the 8th Symposium (International) on Detonation*, Albuquerque; Office of Naval Research: Washington, DC, 1985; p 42.
(19) Frey, R. B. In *Proceedings of the 8th Symposium (International) on Detonation*, Albuquerque; Office of Naval Research: Washington, DC, 1985; p 68.

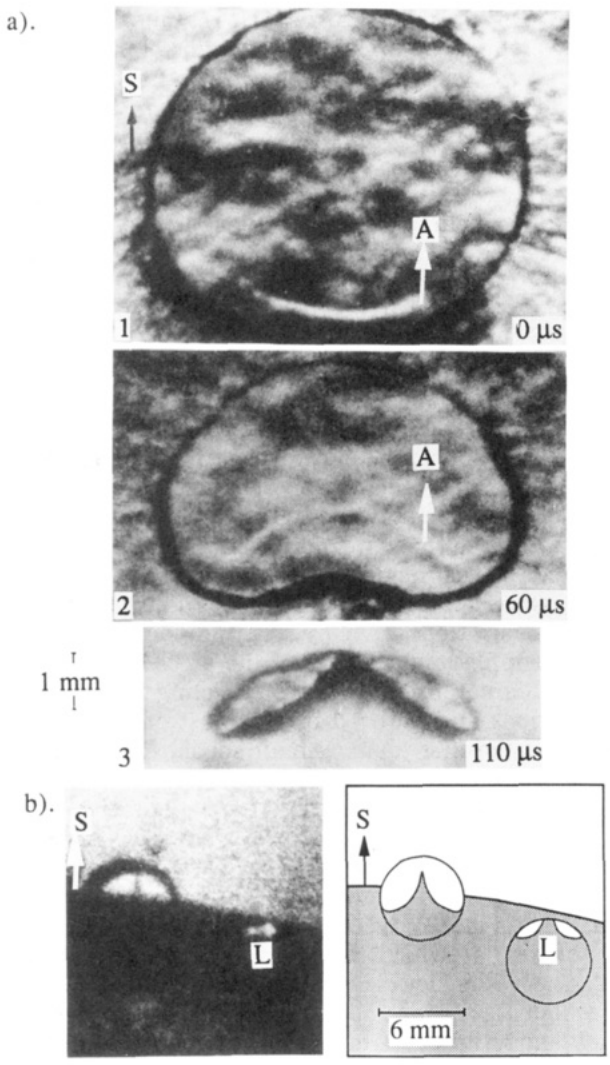

Figure 4. The asymmetrical collapse of cylindrical air-filled bubbles in gelatin. (a) The incident shock, S, of pressure 0.26 GPa, collapses a 12-mm cavity. Note the air shock, A, bouncing within the cavity and the formation of a jet which strikes the downstream wall in frame 3, isolating two lobes of gas. (b) The shock, of strength 1.88 GPa, collapses a 6-mm cavity. The jet crosses the left-hand cavity faster than the incident shock. A second cavity on the right has already collapsed, and two points of light are seen from the trapped lobes of luminescing gas. Reprinted with permission from ref 9. Copyright 1991 Royal Society.

can be detected by image intensification techniques.[7] The luminescence suggests temperatures in excess of ca. 1000 K.

Figure 2 in ref 9 shows that the jet impact can also cause light emission, probably caused by violent shock heating of a pocket of gas trapped between the jet and the cavity wall.

Dear and Field[6] show a great many sequences of different arrays of cavities collapsing in inert gels. Figure 5 is an example of the collapse of a rectangular array of 3-mm cavities collapsed by a 0.26-GPa shock entering from below. Each individual cavity shows jet formation, jet impact, lobe formation, and vortex production. Of particular interest is the layer by layer nature of the collapse. For a close-packed array, the shock energy is effectively absorbed and then reradiated layer by layer, giving a collapse wave velocity which can be very much lower than the shock velocity for low-velocity shocks and possibly equal to or higher than the shock velocity

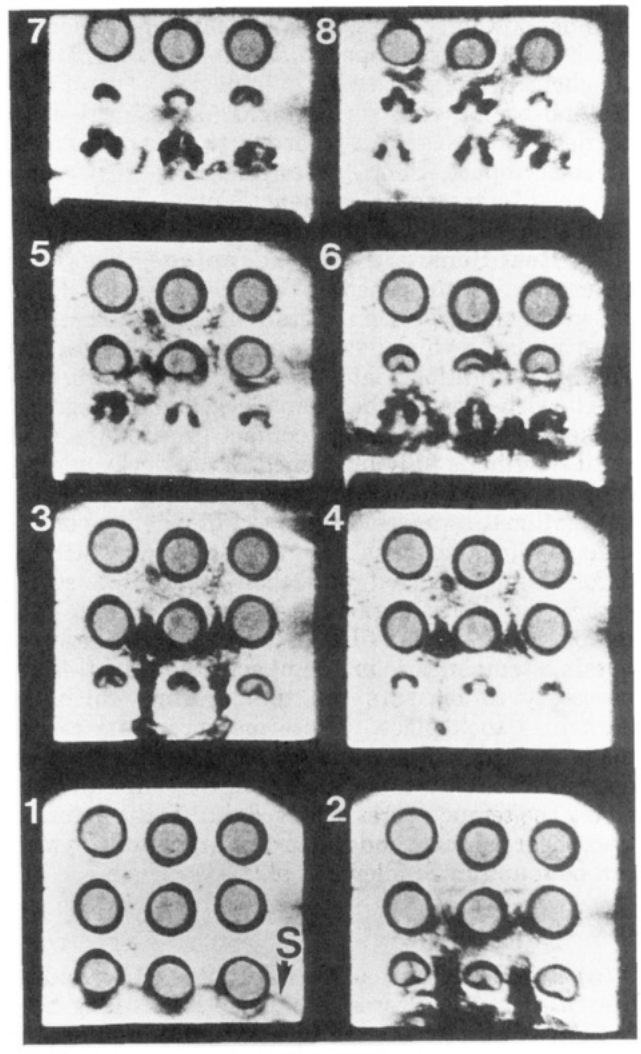

Figure 5. Rectangular array of nine 3-mm cavities collapsed by a shock wave, S. Note the layer by layer collapse. Interframe time: 4.25 μs. Reprinted with permission from ref 6. Copyright 1988 Cambridge University Press.

for very high strength shocks. Such densities of array are very close to what is found with commercial explosives which have added gas bubbles or microballoons to increase their sensitivity.

To summarize a complex area: For large cavities, collapsed relatively slowly, adiabatic heating of the gas is important. If very high shock pressures are involved, then the "hot spot" produced by jet impact can be significant. For smaller cavities down to 1-μm diameter, viscous and plastic heating mechanisms dominate.[19] In general, bubbles and cavities sensitize reactive materials.

(b) Localized Adiabatic Shear. Afanas'ev and Bobolev[20] and Winter and Field[21] have shown that if plastic deformation is localized into bands of dimensions of the order of 1 μm or more, then "hot spots" can be formed which cause ignition. Further evidence has been provided by Frey[22] and Field et al.[3,23,24]

Figure 6 shows the result of a drop-weight experiment on a layer of pentaerythritol tetranitrate (PETN) when

(20) Afanas'ev, G. T.; Bobolev, V. K. *Initiation of solid explosives by impact*; Jerusalem Israel Program for Scientific Translations: Jerusalem, 1971.

(21) Winter, R. E.; Field, J. E. *Proc. R. Soc. London* **1975**, *A343*, 399.

(22) Frey, R. B. In *Proceedings of the 7th Symposium (International) on Detonation*, Annapolis; Office of Naval Research: Washington, DC, 1981; p 82.

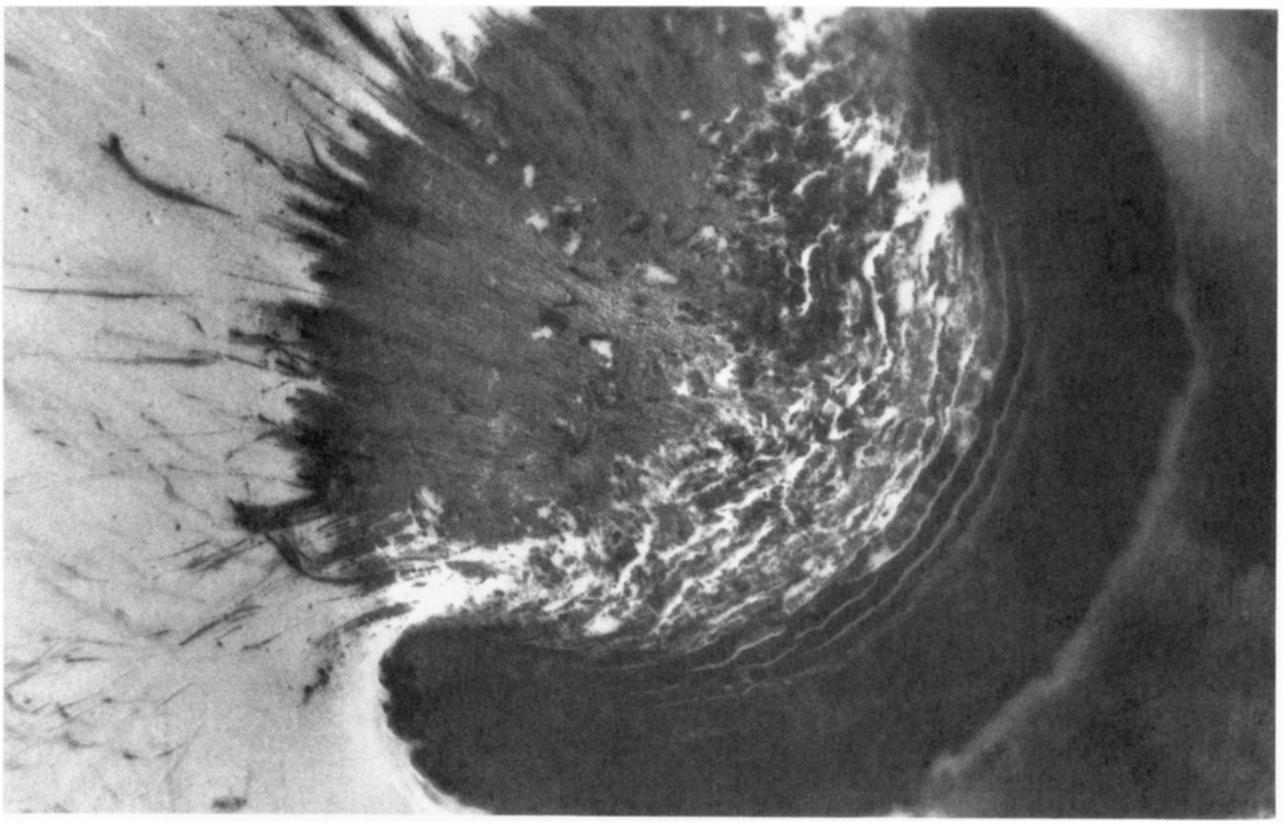

Figure 6. Heat-sensitive film record of an impact of PETN. Original in color. Clear evidence of shear banding and associated ignition. Width of figure: 14 mm. Reprinted with permission from ref 4. Copyright 1992 Royal Society.

heat-sensitive film was used. The original is in color, but the black and white reproduction shows the key features. Where there has been fast reaction, the products have removed much of the heat-sensitive layer, but where the film remains, it is a deep orange-brown. To the right there is a great arc of banding, and where the heat-sensitive layer remains attached, it varies from light brown to almost black, all indicative of high temperatures. The ignition also clearly starts from the region where the bands are located. Figure 7 shows four frames from a sequence in which a 25-mg layer of PETN was impacted from a height of 1.3 m. The PETN layer first sinters and becomes transparent. The shear banding appears as faint vertical lines in frame 1 onward. Note the way the ignition propagates preferentially along the bands, confirming that they are hotter than the surrounding material.

Figure 8 is a heat-sensitive film viewed by reflected light (the original is in color) after an impact on cyclotetramethylene tetranitramine (HMX). The patterns consist of families of approximately parallel bands, some of which bifurcate. The bands appear white since the thin layer of heat-sensitive film has split. However, the dark colors are indicative of high temperatures. The hottest regions occur at the junction of the bands. Similar bands have been found in HMX layers and a range of PBXs impacted from just subcritical heights.[24]

The upper trace in Figure 9 is a pressure/time record for an impact on cyclotrimethylene trinitramine (RDX) taken with the instrumented drop-weight apparatus (Figure 2). The load drop is indicative of rapid plastic flow in the sample. The lower trace records the light output and shows that ignition follows the mechanical failure by shear banding.

(c) Dislocation Mechanisms. Coffey and Armstrong[25,26] have shown that dislocation pileups can produce "hot spots". However, the question arises as to whether such "hot spots" reach the critical parameters to cause ignition during impact or shock loading. If the localization remains on a few adjacent planes (i.e., well below micron dimensions), then ignition would be unlikely. We have impacted single crystals of explosives in our transparent anvil drop-weight apparatus (see Figure 14 of ref 3 and Figures 4 and 5 of ref 4). Following impact there is intense fragmentation (and presumably dislocation motion), compaction of the powder, and finally rapid plastic flow of a sintered layer. All the sequences show that ignition takes place only when the layer is compacted, compressed, and sheared at a high stress value. The flow stress in the layer is high because of the constraining effect of the anvils. For example, application of the Mises yield criterion to a thin layer of thickness h and diameter d between two rigid anvils gives the following relation for the yield pressure p_y (Schroeder and Webster[27]):

$$p_y = \sigma_y\{1 + (d/3\sqrt{3}h)\} \quad (1)$$

where σ_y is the flow stress for uniaxial loading. Note that for small h and large d, $p_y \gg \sigma_y$.

(23) Field, J. E.; Palmer, S. J. P.; Pope, P. H.; Sundarajan, R.; Swallowe, G. M. In *Proceedings of the 8th Symposium (International) on Detonation*, Albuquerque; Office of Naval Research: Washington, DC, 1985; p 635.

(24) Field, J. E.; Parry, M. A.; Palmer, S. J. P.; Huntley, J. M. In *Proceedings of the 9th Symposium (International) on Detonation*, Portland; Office of Naval Research: Washington, DC, 1989; p 886.

(25) Coffey, C. S. *Phys. Rev.* **1981**, *B24*, No. 12, 6984.

(26) Coffey, C. S.; Armstrong, R. W. *Shock waves and high strain rate phenomena in metals*; Meyers, M. A., Murr, L. E., Eds.; Plenum: New York, 1981.

(27) Schroeder, W.; Webster, D. A. *J. Appl. Mech.* **1949**, *16*, 289.

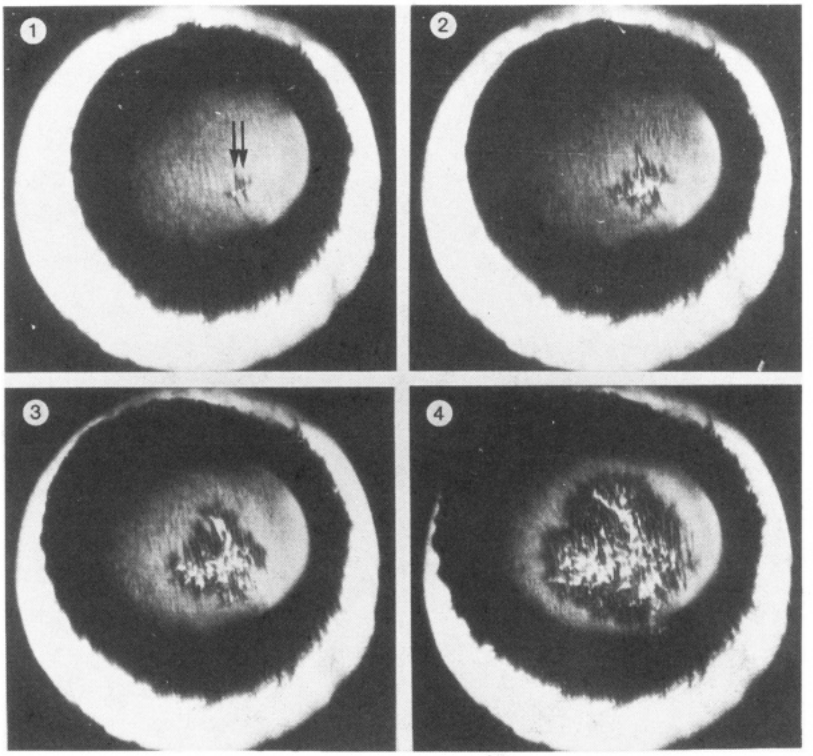

Figure 7. Impact on a 25-mg PETN sample from a drop height of 1.3 m (shear bands are arrowed in frame 1): (1) 0, (2) 7, (3) 14, and (4) 21 μs. Field of view: 20 mm. Reprinted with permission from ref 4. Copyright 1992 Royal Society.

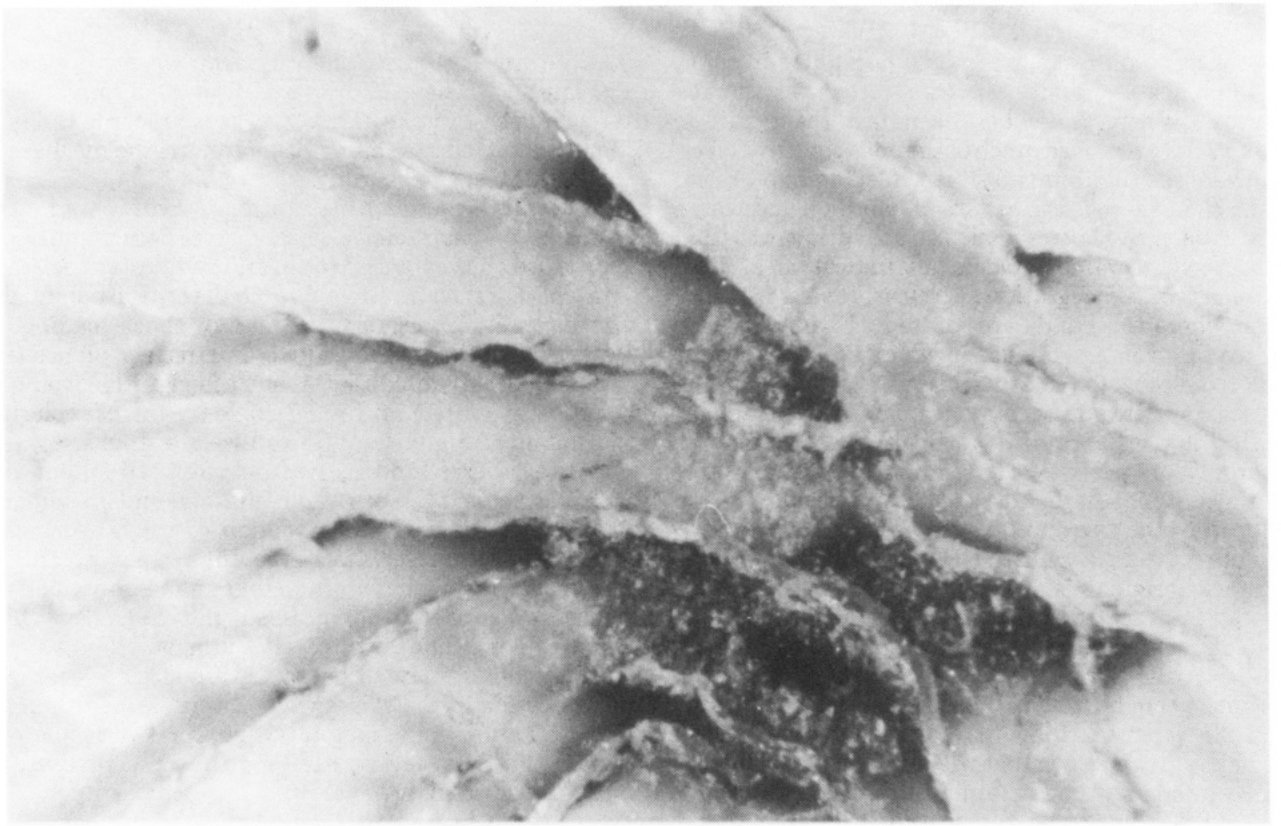

Figure 8. Heat-sensitive film recovered after impact of HMX showing branching of the shear bands and discoloration where branching occurs. Original in color. Width of figure: 6 mm. Reprinted with permission from ref 4. Copyright 1992 Royal Society.

The ignition process, in this impact velocity range, appears to be by "macroscopic" shear banding as with powdered, pelleted, or PBX samples: such bands may cut across regions containing many small compacted crystals. Dislocations would move at the early stage of impact and at relatively low stresses, and our photographic results show no ignition at this stage. Experiments performed in our laboratory (Krishna Mohan et al.[28]) in which small, 100-μm diameter, particles impacted single crystals of PETN and RDX at 150–

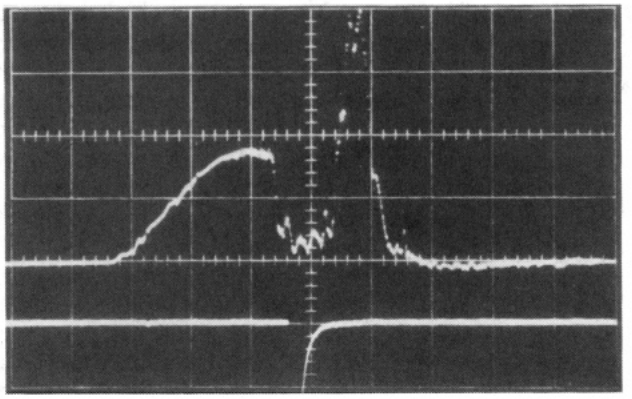

Figure 9. The upper curve is a pressure–time trace for an RDX sample impacted from a drop height of 0.2 mm. The lower trace records, with the aid of a light detector, the instant of ignition. Vertical scale: 0.43-GPa divisions. Reprinted with permission from ref 3. Copyright 1982 Royal Society.

200 m s^{-1} have shown that linear arrays of dislocations can be formed. However, ignition did not take place. Experiments in which single crystals have been *shock* loaded[29] show that the crystallographic dependence of shock initiation sensitivity is due to the anisotropy of the plastic flow under these conditions.

(d) Friction. The ignition of an explosive by frictional rubbing is a well-established ignition mechanism. The basic idea is that when two solids rub or impact together, the "hot spot" temperature at the interface is determined by the solid with the lower melting point; when melting starts, this "quenches" the "hot spot" to that value. Properties such as thermal conductivity and hardness are important, but only as a second-order effect. By choosing grits of different melting points and measuring the impact sensitiveness, Bowden and Gurton[30] were able to measure "hot spot" ignition temperatures for a range of explosives. Chaudhri[31] has also argued convincingly that stab-initiation (caused by driving a needle into an explosive compact) is basically frictional. The needle picks up a layer of adhering crystals as it enters, and the "hot spot" is caused by frictional rubbing between the adhered layer and other crystals. The very sensitive explosives used in stab-initiation devices (called primaries) usually have high melting points.

Research by Swallowe and Field[32] shows that the Bowden and Gurton model, which works well with hard, high-melting-point additives, needs some qualification since certain soft, low-melting-point solids, such as polymers, can also sensitize explosives. Polymers that sensitize are those that fail catastrophically by fracture or localized shear, and that have a low specific heat, latent heat, and thermal conductivity. "Hot spots" in these polymers, produced during rapid deformation, can greatly exceed the polymers' softening point.

(e) "Hot Spots" at Crack Tips and Other Mechanisms. It is well-known that the intense stress field at the tip of a propagating crack can cause plastic deformation, and "hot spot" temperatures and sizes in metals and some polymers can be high. The evidence for this was discussed in detail by Field et al.[3] However, these authors did not consider that the mechanism was a viable one for the ignition of explosive crystals, and experimental evidence by Chaudhri and Field[33,34] in which fast cracks were passed through sensitive primary explosives, without causing ignition, supports this. The basic reason is because the energy involved is too low to give the necessary temperature *and* size of "hot spot". These two factors are interrelated, but for a temperature of ca. 650 K a required "hot spot" radius of ca. 10 μm is predicted for PETN, while at ca. 850 K the required radius is reduced to ca. 0.1 μm. The fracture surface energies, γ, of PETN, RDX, and HMX are very low,[35,36] with values of only ca. 0.1 J m^{-2}, and those of other explosives are likely to be similar. This is very low compared with polymers such as polycarbonate (PC), PMMA, and steels that fracture in a quasi-brittle mode. Values of γ for these are typically several hundred J m^{-2}, and the radius of the heated zone is typically several tens of microns. The conclusions are that the crack tip "hot spot" in an explosive crystal is not a viable ignition mechanism, but in a suitable particle embedded in an explosive sample or in a toughened composite explosive, it is.

The importance of other mechanisms such as viscous flow and triboluminescence discharge was discussed fully in ref 3. The conclusion then was that viscous heating can be a contributory mechanism but rarely causes ignition by itself.

(f) PBXs and Propellants. In general, the strengths of the propellants are lower than those of PBXs, but they fail at much larger strains. Since the amount of energy absorbed during deformation is proportional to the area under the stress–strain curve, the bulk heating with propellants is greater than for PBXs. High-speed photography of PBXs igniting in a drop-weight test shows that they do so after a pressure drop associated with the onset of plastic flow.[23] By contrast, we have found that propellants which ignite in a drop-weight test do so after extensive flow and near the periphery. We suggest that the mechanism of ignition for the propellants we have studied is the addition of bulk heating, viscous heating (the anvils are very close at the time of ignition so that material flows through a narrow channel), plus adiabatic heating by trapped gas at the periphery.[4] This explanation is reinforced by the considerably greater sensitivity of annular specimens under impact conditions and of samples with voids.

Low temperatures sensitize many propellants. Ignition occurs at lower strains than at room temperature,

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but since the peak stresses are much larger, the area under the stress–strain curve remains large. Localized shear failure can be important in this situation.[4]

Conclusions

A variety of techniques have been developed for studying the strength, deformation, and ignition properties of explosives. The visual evidence provided by high-speed photography is invaluable since the physical events taking place are complex and not easily quantifiable. A number of "hot spot" mechanisms for ignition exist, but which mechanism dominates depends on the form of the material (for example, with or without voids, size of voids, etc.) and the physical, thermal, and reactive properties of the sample at the temperature involved. Ignition appears to be invariably thermal in origin, with mechanical or electrical energy converted into heat at local "hot spots". The sizes suggested by Bowden and Yoffe for critical "hot spots" (see Introduction) are supported by the present data. A critical "hot spot" may be achieved by a combination of different mechanisms which act *additively*; for example, there may be a bulk (viscous) heating term which is added to by cavity collapse. There are mechanisms which produce "hot spots" but not necessarily *critical* "hot spots" for ignition, for example, the "hot spot" at a crack tip in an explosive crystal (though note that a crack tip in a polymer particle embedded in an explosive may cause ignition), dislocations moving in a single crystal following low-velocity impact, or a fission fragment track.

Further Reading

A book which summarizes chemical formulas and data on explosives is ref 37 by Meyer. A recent Royal Society Discussion, also published as a book,[38] has important papers on the chemistry of explosives and reaction schemes.

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