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Hot-Spot Ignition Mechanisms for Explosives and Propellants [and Discussion]

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Hot-spot ignition mechanisms for explosives and propellants

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This paper describes the response of explosives to stress and impact and in particular the mechanisms of 'hot-spot' production. Samples in the form of single crystals, powder layers, pressed pellets, gels, polymer bonded explosives (PBXs) and propellants have been studied. Techniques used include a drop-weight facility with transparent anvils which allows photography at microsecond framing intervals, an instrumented drop-weight machine, a miniaturized Hopkinson bar system for high strain rate property measurement, laser speckle for studying the deformation and fracture of PBXs, an automated system for analysing speckle patterns and heat sensitive film for recording the positions and temperatures of hot spots. Polishing and staining methods have been developed to observe the microstructure of PBXs and failure during quasi-static loading. Ignition, when it occurred, took place at local hot-spot sites. Evidence is discussed for a variety of ignition mechanisms including adiabatic shear of the explosive, adiabatic heating of trapped gases during cavity collapse, viscous flow, friction, fracture and shear of added particles and triboluminescent discharge.

1. Introduction

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 one since the mechanism (or mechanisms) which operate depend on the energy input and the physical properties of the loaded 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, temperature and durations of *critical* hot spots (i.e. those that can cause ignition) are clearly interdependent. However, Bowden & Yoffe (1952, 1958) have presented convincing evidence that hot spots need to have dimensions of typically 0.1 to 10 μm, durations of 10^{-5} to 10^{-3} s and temperatures of greater than *ca.* 700 K. This has important practical consequences since it means that processes which produce hot spots with sizes less than 0.1 μm (fission fragment tracks, etc.) would cause some decomposition but quench too quickly to produce ignition. This paper describes research on hot-spot mechanisms and also the development of techniques which allow the mechanical and ignition properties of explosives to be studied.

(*a*) *Hot-spot mechanisms*

The main mechanisms that have been suggested for ignition are:

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(i) adiabatic compression of trapped gas spaces (Bowden *et al.* 1947*a*; Bowden & Yoffe 1952, 1958; Coley & Field 1973; Chaudhri & Field 1974; Starkenberg 1981); this mechanism would also include the extra energy obtained by the elimination of surfaces (Dubnov *et al.* 1971);

(ii) other mechanisms involving cavity collapse include viscous or plastic heating of the surrounding matrix material (Frey 1985) and, for very high shock collapse pressures, hydrodynamic shock focusing (Mader 1965, 1985);

(iii) viscous heating of material rapidly extruded between the impacting surfaces of grains (Eirich & Tabor 1948; Rideal & Robertson 1948; Bolkhovitinov & Pokhil 1958; Heavens 1973);

(iv) friction between the impacting surfaces, the explosives crystals and/or grit particles in the explosive layer (Bowden *et al.* 1947*b*; Bowden & Gurton 1949*a*, *b*; Bowden & Yoffe 1952, 1958; Chaudhri 1976);

(v) localized adiabatic shear of the material during mechanical failure (Afanas'ev & Bobolev 1971; Heavens & Field 1974; Winter & Field 1975; Swallowe & Field 1982; Frey 1981);

(vi) heating at crack tips (Field *et al.* 1982);

(vii) heating at dislocation pile-ups (Coffey 1981; Coffey & Armstrong 1981);

(viii) spark discharge (Wyatt *et al.* 1958);

(ix) triboluminescent discharge (Field *et al.* 1982);

(x) decomposition followed by Joule heating of metallic filaments (Tang & Chaudhri 1984).

The above processes all involve the conversion of mechanical or electrical to thermal energy. Some workers have suggested additional mechanisms based on tribochemical or molecular fracture mechanisms (Taylor & Weale, 1932; Ubbelohde 1948; Garner 1958; Fox 1970). As discussed later, we have found no support for such ignition mechanisms.

2. Experimental

(*a*) *High-speed photography: transparent anvil drop-weight apparatus*

Advances in the understanding of explosive phenomena have been greatly assisted by direct observation of events using high-speed photography. The ability to obtain both temporal and spatial resolution during impact has been particularly valuable in establishing the sequence of events. The transparent anvil drop-weight arrangement used in the present work was originally used by Blackwood & Bowden (1952) and has more recently been extensively used by Heavens, Field, Swallowe and others (Heavens & Field 1974; Swallowe & Field 1982, Field *et al.* 1982, 1985, 1989; Krishna Mohan & Field 1984; Krishna Mohan *et al.* 1984). Typically, 25 mg samples of material, in the form of powders, pressed discs, PBXs or propellant samples, are compressed between toughened glass anvils with an impact velocity of a few m s^{-1}. The drop weight (mass 5 kg) which carries the upper anvil is dropped from a height of up to 1.5 m and is guided by three rods to ensure a planar impact. Shortly before contact, the mirror within the weight comes into alignment to complete the optical path from the xenon flash light source, through to the high-speed camera. The AWRE (Atomic Weapons Research Establishment) C4 rotating mirror camera used for these studies, is of the continuous access variety so that synchronization is not required. The full length of film (140 frames) is scanned in approximately 1 ms so that the duration of the flash also functions as a shutter.

The early studies showed that the initiation of explosive samples usually occurs

after rapid radial flow (greater than *ca.* 100 m s^{-1}) unless sensitizing grits are present. Valuable data that can be extracted from the photographs are therefore the radius and flow velocities as functions of time. Rapid flow can occur as a result of mechanical failure of the sample but while this may be true in some cases, it is not a necessary precursor. If the material is weak so that it generates negligible retardation to the falling weight and deforms at constant volume, then high radial velocities are a natural outcome. In addition to the bulk plastic behaviour, other physical processes such as fracture, jetting, bulk plastic flow, localized adiabatic shear, melting and elastic recovery can be observed under favourable conditions. Explosive reaction is visible since it is self-luminous. Although photographs present a large amount of information, they cannot usually tell the whole story without corroborative evidence from other sources such as dynamic stress measurement.

(*b*) *Instrumented drop-weight apparatus*

A second drop-weight machine is available with instrumented steel anvils. The system rests on a large blacksmith's anvil, which provides an almost ideal rigid support for a small load cell to measure the impact force. The cell is of in-house design being made from a 12.7 mm × 12.7 mm steel roller, which has four flats 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 stacked on top of the load cell and samples are placed between this pair, the whole arrangement being impacted by a weight of 2.5 or 4.7 kg. The dynamics of the system have been described in detail earlier (Heavens & Field 1974), but a comparison with the behaviour of a direct impact Hopkinson bar (§2*c*) is illuminating. Unlike the Hopkinson bar, the dynamics of the drop-weight system do not require explicit account to be taken of stress wave propagation. The pressure bar in the smallest of our miniaturized Hopkinson apparatuses is made deliberately long at 150 mm, so that a stress wave can be observed without interference from reflections. The drop-weight load cell is much shorter, being 25 mm including the protective roller on top of it, but the timescale over which it operates is 400 μs compared with 16 μs for the pressure bar. Consequently there are many stress wave reflections in the load cell and its behaviour is therefore effectively *quasi-static*. A further facility which is used with 25 mg samples when initiation is expected is the detection of electrical conductivity between the anvils. This can detect ionized gas and temporally pinpoint the initiation of explosion. Alternatively, ignition is detected by monitoring light output with a photo-cell.

(*c*) *Miniaturized Hopkinson bar*

In a conventional Hopkinson bar system (see, for example, Kolsky 1963), the specimen is placed between two long, cylindrical rods. A stress pulse is then sent down the input bar and gauges record incident, reflected and transmitted waves. From these records, it is possible to obtain the stress–strain behaviour of the specimen at strain rates of *ca.* 10^3 s^{-1}. A few years ago in this laboratory, Gorham (1979) developed a direct impact (no input bar) miniaturized system. Initially, a high-speed camera was used to measure strains, but this is not essential and stress–strain curves can be obtained from the gauge records on the output bar following an analysis given by Pope & Field (1984). The advantages of the new apparatus are that strain rates up to *ca.* 10^5 s^{-1} can be achieved and high strength specimens investigated. Results on a range of PBXs are described in Field *et al.* (1985).

(*d*) *Brazilian test and laser speckle for tensile strengths and strains to failure*

The Brazilian test geometry and laser speckle photography have been used to study the tensile strengths and rupture strains of a variety of PBX compositions at strain rates of *ca.* 10^{-4} s^{-1}. A full discussion of these techniques and results obtained with them has recently been submitted for publication (Palmer *et al.* 1992). Preliminary results can be found in Field *et al.* (1985, 1989).

(*e*) *Heat sensitive film technique*

The technique used in this work was first suggested by Coffey & Jacobs (1981). 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 (less than 10^{-4} s) the film colour 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 so, 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 were made by using the transparent anvil arrangement described above (§2*a*). Experiments were carried out by placing the film on the glass anvils with the sensitive side in contact with the sample. 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.* (1986).

(*f*) *Microstructure and fracture paths in PBXs*

Polishing and staining techniques have recently been developed to study the relation between the microstructure of PBXs and their fracture routes when broken in the Brazilian test under quasi-static conditions. A post-failure examination of the fracture route through the microstructure, provides a valuable insight into the fracture mechanisms. It is not, however, usually possible to determine where failures initiate, or the order in which events occur during crack propagation. A technique has therefore been developed using a computer operated camera (Olympus OM2 with motor drive), attached to a microscope stage to record photographic sequences of the microstructure at the centre of a sample during a Brazilian test (see Palmer *et al.* 1992).

(*g*) *Cavity collapse*

In their experiments on gas bubble collapse, Chaudhri & Field (1974) placed gas bubbles near explosive crystals in an aquarium and then observed photographically the collapse and ignition processes by low strength shocks; typically 0.1 GPa. In recent studies (Dear & Field 1988; Dear *et al.* 1988; Bourne & Field 1989, 1991) a two-dimensional (2D) gel technique has been used. The advantage of using such a method is that details of processes occurring within the cavity may be followed without the refraction problems associated with viewing through a three-dimensional curved wall. The research included both inert and reactive gels.

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3. Results: hot-spot mechanisms

(*a*) *Rapid collapse of gas spaces*

The voidage present in many classes of explosive has long been recognized as a sensitising 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 coworkers (Bowden *et al.* 1947*a*; Yoffe 1949; Bowden & Yoffe 1952, 1958; Bowden & McOnie 1967; Coley & Field 1973) 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 (Watson *et al.* 1965; Hay & Watson 1968; Coley & Field 1973). For solid explosives impacted in the drop-weight test Yoffe (1949) and Bowden & Yoffe (1952) showed that the gas content had an effect, particularly if the explosive was 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. Their interpretation has been criticized by Russian workers (Andreev *et al.* 1955; Bolkhovitinov 1959; Afanas'ev & Bobolev 1971), who pointed out that with such a low impact velocity (a few metres per second) the gas spaces are more likely to be compressed isothermally. Photographic work (Heavens & Field 1974; Field *et al.* 1982), however, gives clear evidence for very rapid deformation of material, at a few hundreds of metres per second, in this test. This effectively removes the objection of the Russian school, since there is a distinct possibility of gas spaces being trapped in the deforming layer which, if locally perturbed, could collapse rapidly. In their photographic work on gas bubble collapse Chaudhri & Field (1974) showed that bubbles with diameters of millimeter size down to *ca.* 50 μm collapsed by relatively low strength shock (*ca.* 0.1 GPa) could ignite sensitive explosives. This work and that by Starkenberg (1981) shows that gas phase heating is a dominant mechanism when large cavities are collapsed relatively slowly.

It was first suggested by Kornfeld & Suvorov (1944) 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 (Mader 1965, 1985). Frey (1985) 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.

Dear & Field (1988) and Dear *et al.* (1988) have made an extensive study of the collapse of arrays of 2D cavities in *inert* gels by shocks of strength *ca.* 0.26 GPa, they found that each individual cavity involutes producing a high-speed jet which isolates the rapidly compressed gas into two lobes; image intensifier records (Dear *et al.* 1988, fig. 4) show that the gas in these lobes is hot enough to luminesce. An important feature is that the first row of cavities in a cavity array effectively shielded the other rows. The second row of cavities only collapsed when reached by shocks arising from the collapse of the first row. The density of cavities in this research is similar to that of micro-balloons in a commercial explosive and many features of the shock propagation would be the same.

More recent research (Bourne & Field 1991) shows the effect of stronger shocks of strength 3 GPa passing over single cavities and cavity arrays. There was evidence for

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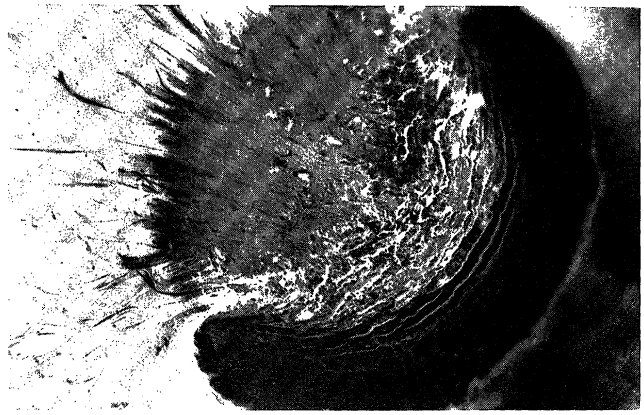

Figure 1. Heat sensitive film record of an impact of PETN. Original in colour. Clear evidence of shear banding and associated ignition. Width of figure 14 mm.

a flash of light where the jet impacts the far cavity wall and two flashes of light from the collapsing gas lobes. The duration of the high temperatures giving rise to this luminescence was less than 1 μs. Sequences showing the collapse of cavities in reactive emulsion systems can also be found in Bourne *et al.* (1989, 1991).

(*b*) *Localized adiabatic shear*

Afanas'ev & Bobolev (1971) and Winter & Field (1974) have shown that if plastic deformation is localized into bands of dimensions of the order of a micrometre or more then hot spots can be formed which cause ignition. Further evidence has been provided by Frey (1981), Field *et al.* (1982, 1985, 1989) and Krishna Mohan *et al.* (1989).

Figure 1 shows the result of a drop-weight experiment on a layer of pentaerythritol tetranitrate (PETN) when heat sensitive film was used. The original is in colour 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 2 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 (*a*) onwards. Note the way the ignition propagates preferentially along the bands confirming that they are hotter than the surrounding material.

Figure 3 is a heat sensitive film (HSF) viewed by reflected light (colour original) 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 HSF has split. However, the dark colours 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 sub-critical heights (Field *et al.* 1989). Several attempts have been made in the past to assess the temperature rise in shear bands (Frey 1981; Dienes 1986). Grady & Kipp (1987) have derived expressions of shear band spacing, width, and

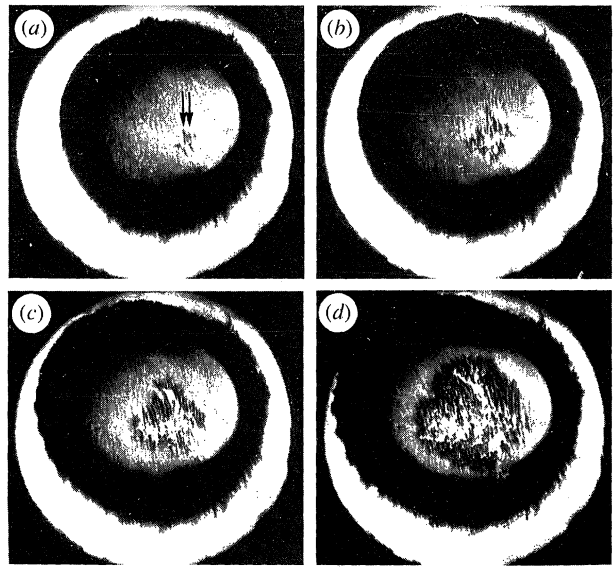

Figure 2. Impact on a 25 mg PETN sample from a drop height of 1.3 m; shear bands are arrowed in frame (*a*). (*a*) 0, (*b*) 7, (*c*) 14 and (*d*) 21 μs. Field of view 20 mm.

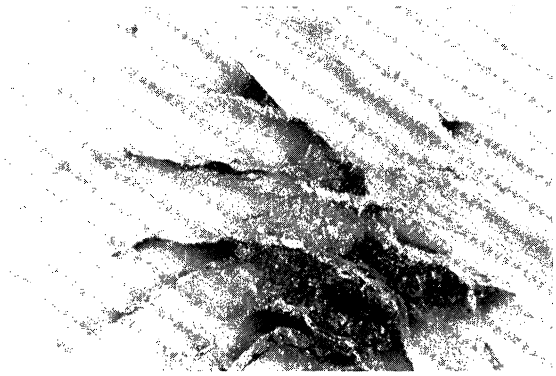

Figure 3. Heat sensitive film recovered after impact of HMX showing branching of the shear bands and discolouration where branching occurs. Original in colour. Width of figure 6 mm.

growth times based on a catastrophic growth model of unstable thermoplastic shear. Their expressions relate the shear band characteristics with the thermal properties of the material and the dynamic loading data. A comparison between the predictions of their model and experimental data on explosives has been made by Krishna Mohan *et al.* (1989). In drop-weight impact band spacings are typically a few 100 μm and band widths typically 1 to 10 μm.

(*c*) *Dislocation mechanisms*

Coffey & Armstrong (Coffey 1981; Coffey & Armstrong 1981), have shown that dislocation pile ups 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 micrometre dimensions), then ignition would be unlikely. We have impacted single

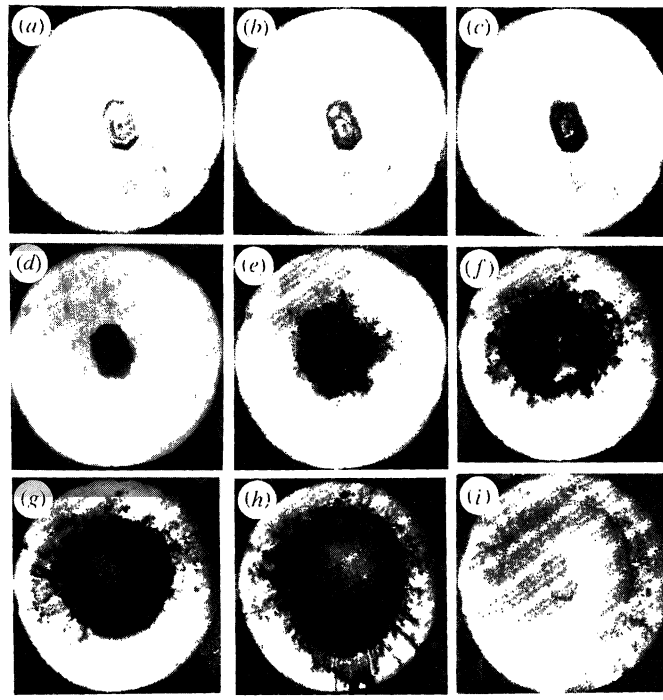

Figure 4. Selected frames from a high-speed photographic sequence of the rapid deformation of a crystal of PETN. Times of each frame: (*a*) 0, (*b*) 7 μs, (*c*) 14 μs, (*d*) 28 μs, (*e*) 175 μs, (*f*) 315 μs, (*g*) 350 μs, (*h*) 385 μs, (*i*) 441 μs.

crystals of explosives in our transparent anvil drop-weight apparatus (see figures 4 and 5 of this paper and also fig. 14 of Field *et al.* 1982). Figure 14*a* shows a PETN crystal just before impact. In subsequent frames there is intense fragmentation (and presumably dislocation motion) compaction of the powder and finally rapid plastic flow of a sintered layer. There is overwriting in frame (*i*) so that the original position of the crystal is seen as well as faint shear bands in the almost transparent layer. Ignition did not take place, though in fig. 14 of Field *et al.* (1982) it occurred at the shear banding stage. Figure 5 is for HMX and again there is intense fragmentation before compaction of a powdered layer. Consistent with our earlier research (Heavens & Field 1974; Field *et al.* 1982, 1989) the layer never becomes transparent, though we have shown that shear banding takes place. Ignition occurs in frame (*e*) and most, but not all, of the sample is consumed by frame (*i*). These and other sequences show that ignition only takes place 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 & Webster 1949)

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

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

The ignition process, in this impact velocity range, appears to be by 'macroscopic' shear banding as with powdered, pelleted or polymer bonded samples: such bands may cut across regions containing many small compacted crystals. Dislocations

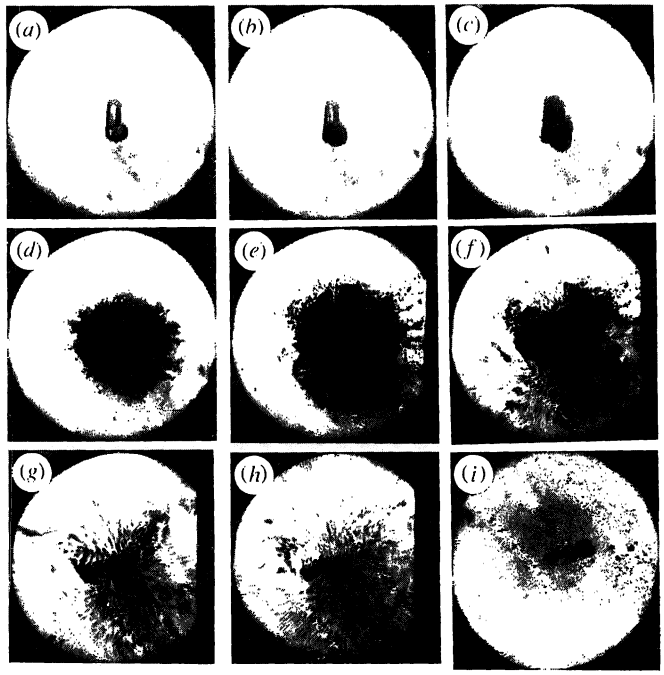

Figure 5. Selected frames from a high-speed photographic sequence of the rapid deformation of a crystal of β-HMX. Times of each frame: (*a*) 0, (*b*) 49 μs, (*c*) 105 μs, (*d*) 350 μs, (*e*) 448 μs, (*f*) 455 μs, (*g*) 462 μs, (*h*) 469 μs, (*i*) 490 μs.

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.* 1989) in which small, 100 μm diameter, particles impacted single crystals of PETN and RDX at 150 to 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 (Dick *et al.* 1991) show that the crystallographic dependence of shock initiation sensitivity is due to the anisotropy of the plastic flow.

(*d*) *Friction*

The ignition of an explosive by frictional rubbing is a well-established ignition mechanism (see, for example, Bowden *et al.* 1947*a*, *b*; Ubbelohde 1948; Bowden & Gurton 1949*a*, *b*; Bowden & Yoffe 1952, 1958). 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 & Gurton were able to measure hot-spot ignition temperatures for a range of explosives. Chaudhri (1976) 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 the impact and the hot spot is caused by frictional rubbing between the adhered layer and other crystals. The explosives used in stab-initiation devices are usually primaries with high melting points.

Research by Swallowe & Field (1982) shows that the Bowden & Gurton model, which works well with hard-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 polymer's softening point (Fuller *et al.* 1975; Swallowe *et al.* 1986).

(*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.* (1982). However, these authors did not consider that the mechanism was a viable one for the ignition of explosive crystals, and experimental evidence by Chaudhri & Field (1970) and Chaudhri (1989) 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 inter-related, 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 (Rideal & Robertson 1948). The fracture surface energies, γ, of PETN, RDX and HMX are very low, with values of only *ca.* 0.1 J m^{-2} (Hagan & Chaudhri 1977; Palmer & Field 1982), 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 100 J m^{-2}, and the radius of the heated zone is typically several tens of micrometers. 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 composite toughened explosive then it is.

The importance of other mechanisms such as viscous flow and triboluminescence discharge were discussed fully in Field *et al.* (1982). The conclusion then was that viscous heating can be a contributory mechanism but rarely causes ignition by itself.

4. Results: impacts on propellants

There is only space to discuss our research on propellants briefly. Several different formulations of propellant of three basic types were available for study: (i) a conventional cast double-base propellant (CDB), (ii) elastomer modified cast double base propellants (EMCDBs), and (iii) a composite modified cast double base propellant (CMCDB). In addition, the EMCDBs were provided in extruded form (EDB). The casting powders (consisting of small discs 1 mm thick and 1 mm diameter) were also available. Two techniques were used in this study: (i) stress–strain curves were obtained at strain rates of *ca.* 10^3 s^{-1} both at room temperature (*ca.* 300 K) for all compositions using a scaled-up version of the Hopkinson bar described in §2*c*, and at liquid nitrogen temperatures (*ca.* 100 K) for the EMCDBs using the instrumented drop-weight apparatus described in §2*b*; (ii) high-speed photography of propellant samples rapidly deformed in the transparent anvil apparatus described in §2*a*. Specimens were available as discs *ca.* 5 mm diameter and *ca.* 2 mm thick.

In general, the room temperature peak strengths of the propellants examined are at the low end of the scale of the PBXs we have studied before: 40–80 MPa as opposed

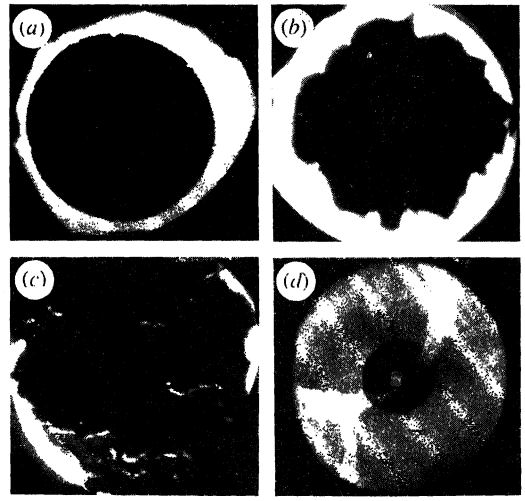

Figure 6. Single frames selected from the high-speed photographic sequences of the rapid deformation of 5 mm diameter, 2 mm thick discs of various EMCDBs to show the sorts of behaviour observed. Times given are measured from the start of deformation. Each frame is exposed for *ca.* 2 μs. (*a*) Smooth flow (700 μs); (*b*) jagged periphery (490 μs); (*c*) debonding (560 μs); (*d*) sensitization caused by punching a hole in the middle. This frame exhibits overwriting enabling the initial state (the dark annulus) to be compared with the final state (the grey area with channels formed by the deflagration event). Note that the channels begin at the site of the original hole.

to 70–150 MPa (Field *et al.* 1985), but most could deform to much larger natural strains $2\ln(d/d_0)$, (greater than 0.8 as opposed to 0.05). Thus the energy available for bulk heating of the samples, which is proportional to the area under the stress–strain curve, is greater. Most of the compositions tested exhibited a monotonic increase in stress to the values given above, though some exhibited load drops at a characteristic strain. The EMCDBs exhibited dramatically different mechanical behaviour below their glass transition temperature of *ca.* 210 K. The maximum stress they could support was greater than could be supplied by the Hopkinson bar, so their low-temperature stress–strain curves had to be obtained using the instrumented drop-weight apparatus. To ensure the specimens did not warm up before they could be tested, the two steel rollers that sandwich the specimen were also cooled to liquid nitrogen temperatures. The third roller was instrumented with relatively temperature insensitive foil gauges, and also it was only in thermal contact with the cold rollers for 20 s or so. Low temperature stress–strain curves exhibit larger peak stresses (by factors in the range 3 to 10) and lower and more variable failure strains (0.2 to 0.3).

The aim of the high-speed photographic study was to determine the mechanisms that render propellants vulnerable to initiation by impact under certain conditions. First, solid discs of the various compositions were deformed in the drop weight apparatus. Three different forms of behaviour were identified for the EMCDBs: (i) smooth flow (figure 6*a*); (ii) jagged periphery (figure 6*b*); (iii) internal debonding (figure 6*c*). Only one of the EMCDBs ever showed deflagration when tested in this form and that only a very weak one once in five drops due to the periphery of the disc becoming jagged and trapping air which was subsequently adiabatically compressed. None of the other EMCDBs showed deflagration (five drops performed on each). By contrast, the CMCDB deflagrated three out of five times and the conventional CDB

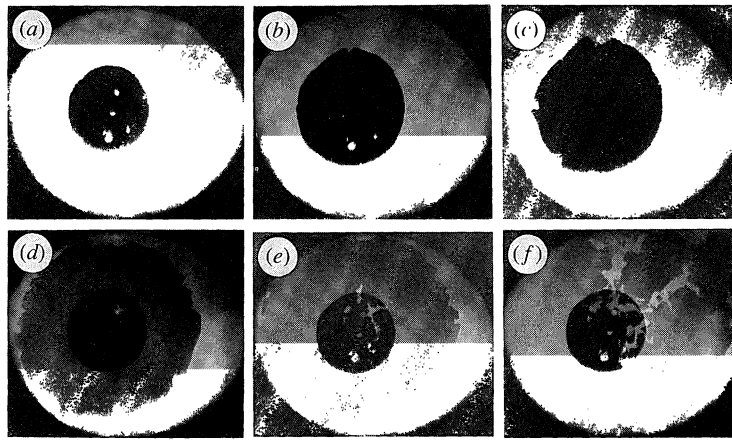

Figure 7. Selected frames from a high-speed photographic sequence of the rapid deformation of a disc of extruded elastomer modified double base propellant (same composition as figure 6*c*). The viscoelastic recovery after extrusion led to the formation of voids which can be seen to be sources for deflagration. The same composition in cast form did not deflagrate (five drops performed). Note that the voids close completely before deflagration initiates. Overwriting can be seen in the last three frames. Times of each frame (measured from the start of deformation): (*a*) 0, (*b*) 210 μs, (*c*) 266 μs, (*d*) 336 μs, (*e*) 350 μs, (*f*) 378 μs.

once out of ten times, these being quite intense but localized deflagrations on the periphery of the deformed discs. Their behaviour was quite different when a gas space was introduced by punching a 2.5 mm hole in the centre of the discs. All compositions, including the EMCDBs, now deflagrated every time, often quite violently. The deflagration started *after* the hole had collapsed but from the original site of the hole (figure 6*d*). EDBs with holes present due to viscoelastic recovery after extrusion also showed this phenomenon (figure 7). Deforming the EMCDBs at a temperature below their glass transition temperature also sensitized them (figure 8), though in this case deflagration was not obtained in every drop. Deflagrations when they did occur were, however, very violent.

5. Conclusions

(i) A variety of techniques have been developed for studying the strength, deformation and ignition properties of explosives.

(ii) The visual evidence provided by high-speed photography is invaluable since the physical events taking place are complex and not easily quantifiable.

(iii) 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.

(iv) 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 & Yoffe for critical hot spots (see §1) are supported by the present data.

(v) 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.

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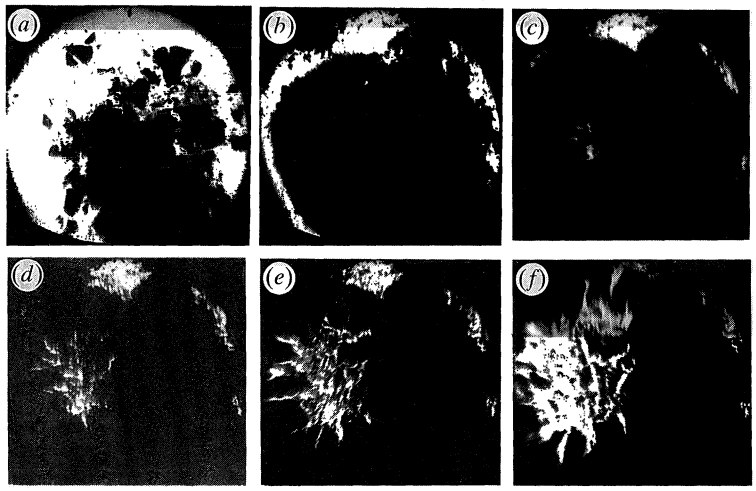

Figure 8. Selected frames from a high-speed photographic sequence of the rapid deformation of a disc of EMCDB at 100K. In the original film, the flash triggered late so that the initial fragmentation was not captured. Times of each frame (measured from the first clear frame): (*a*) 320 μs, (*b*) 696 μs, (*c*) 704 μs, (*d*) 712 μs, (*e*) 720 μs, (*f*) 728 μs.

(vi) There are mechanisms that 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 (§3*e*), a fission fragment track (§1) or dislocations moving in a single crystal following low velocity impact (§3*c*).

(vii) In general, the strengths of the propellants are lower than 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, this means that the bulk heating with propellants is greater than for PBXs. High-speed photography of PBXs igniting shows that they do so after a pressure drop associated with the onset of plastic flow. By contrast, propellants that ignite 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. This explanation is reinforced by the considerably greater sensitivity of annular specimens under impact conditions and of samples with voids.

(viii) Low-temperatures sensitize EMCDBs. Ignition occurs at lower strains than at room temperature, 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.

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Discussion

J. M. Smallwood (*Southampton University, U.K.*). Do the concepts of hot-spot ignition and the mechanisms discussed apply to materials such as pyrotechnics where two or more reactant dusts are closely mixed?

J. E. Field. The answer is yes: the idea of hot spots is a general one. Reaction will propagate if the heat produced by chemical reaction exceeds that lost by dissipative process such as conduction, etc.

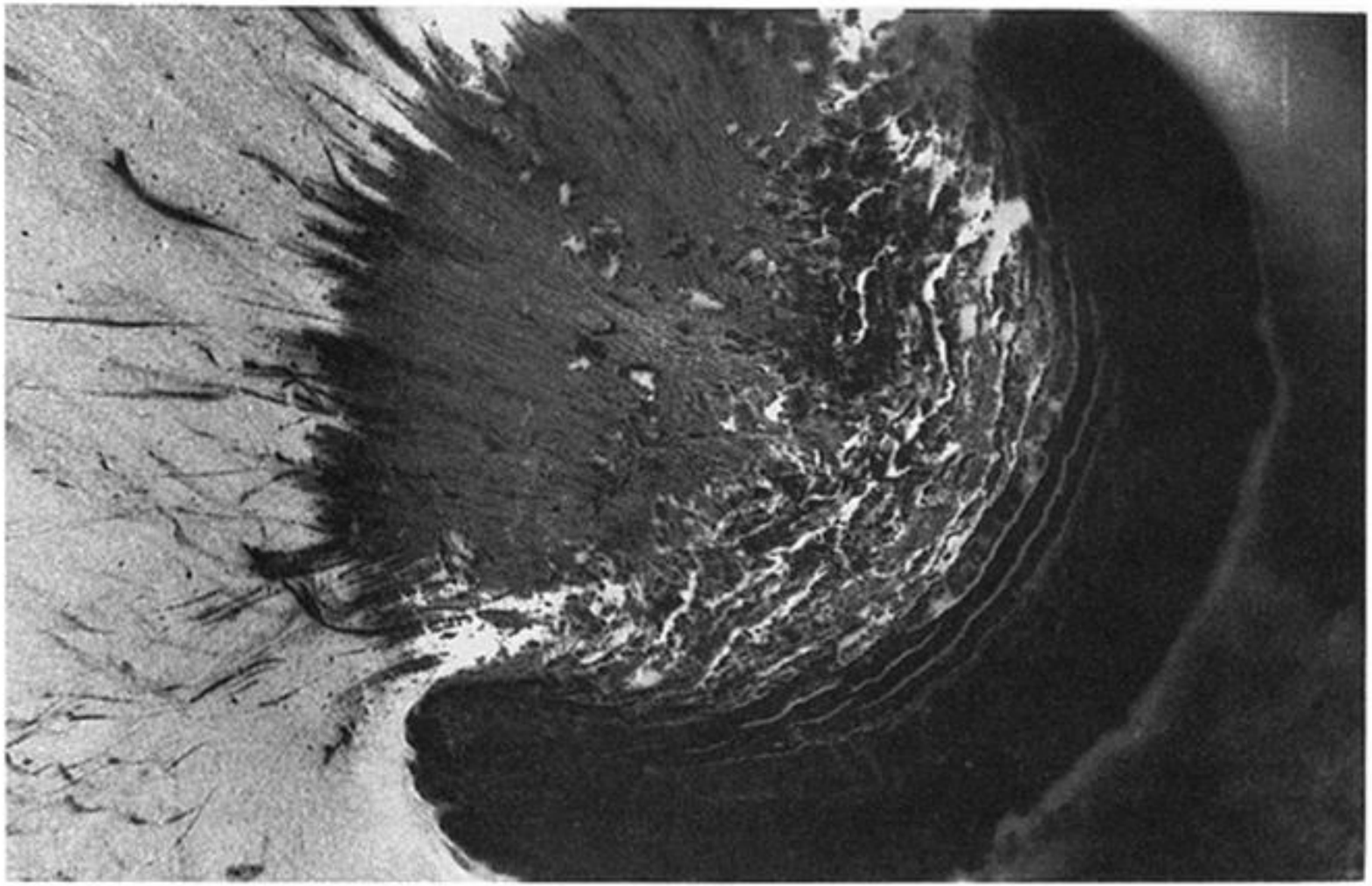


Figure 1. Heat sensitive film record of an impact of PETN. Original in colour. Clear evidence of shear banding and associated ignition. Width of figure 14 mm.

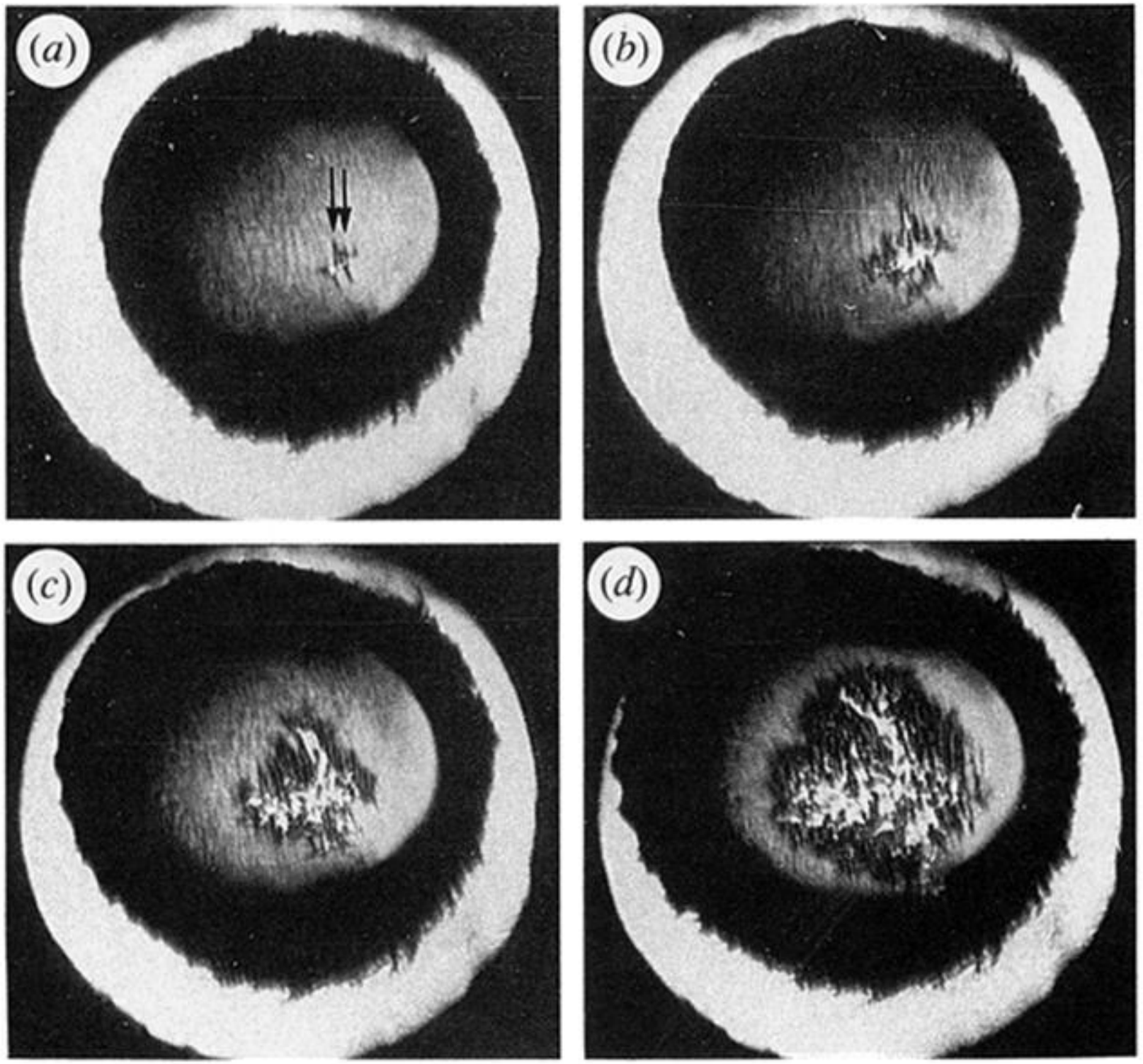


Figure 2. Impact on a 25 mg PETN sample from a drop height of 1.3 m; shear bands are arrowed in frame (*a*). (*a*) 0, (*b*) 7, (*c*) 14 and (*d*) 21 μs. Field of view 20 mm.

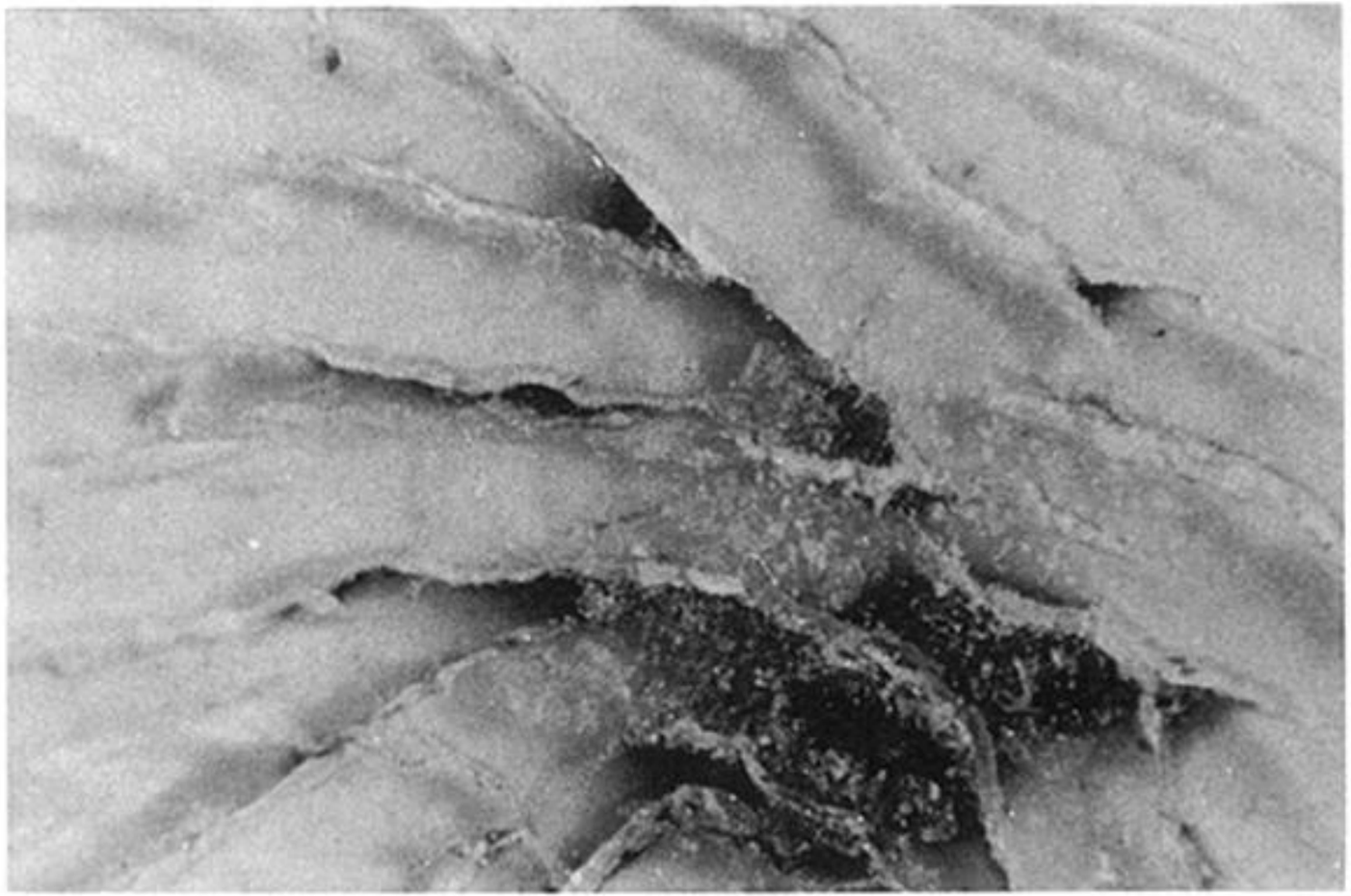


Figure 3. Heat sensitive film recovered after impact of HMX showing branching of the shear bands and discolouration where branching occurs. Original in colour. Width of figure 6 mm.

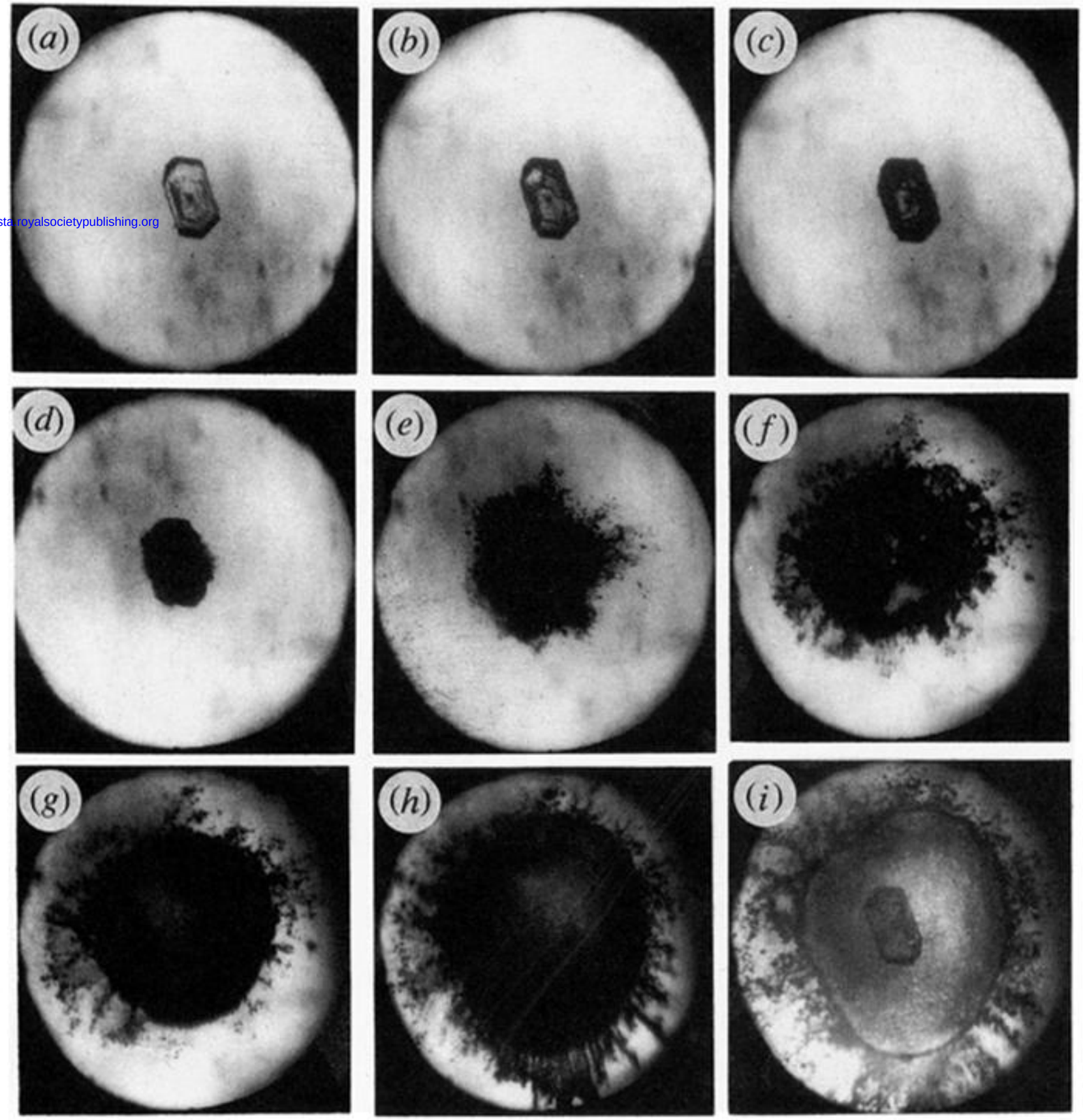


Figure 4. Selected frames from a high-speed photographic sequence of the rapid deformation of a crystal of PETN. Times of each frame: (*a*) 0, (*b*) 7 μs, (*c*) 14 μs, (*d*) 28 μs, (*e*) 175 μs, (*f*) 315 μs, (*g*) 350 μs, (*h*) 385 μs, (*i*) 441 μs.

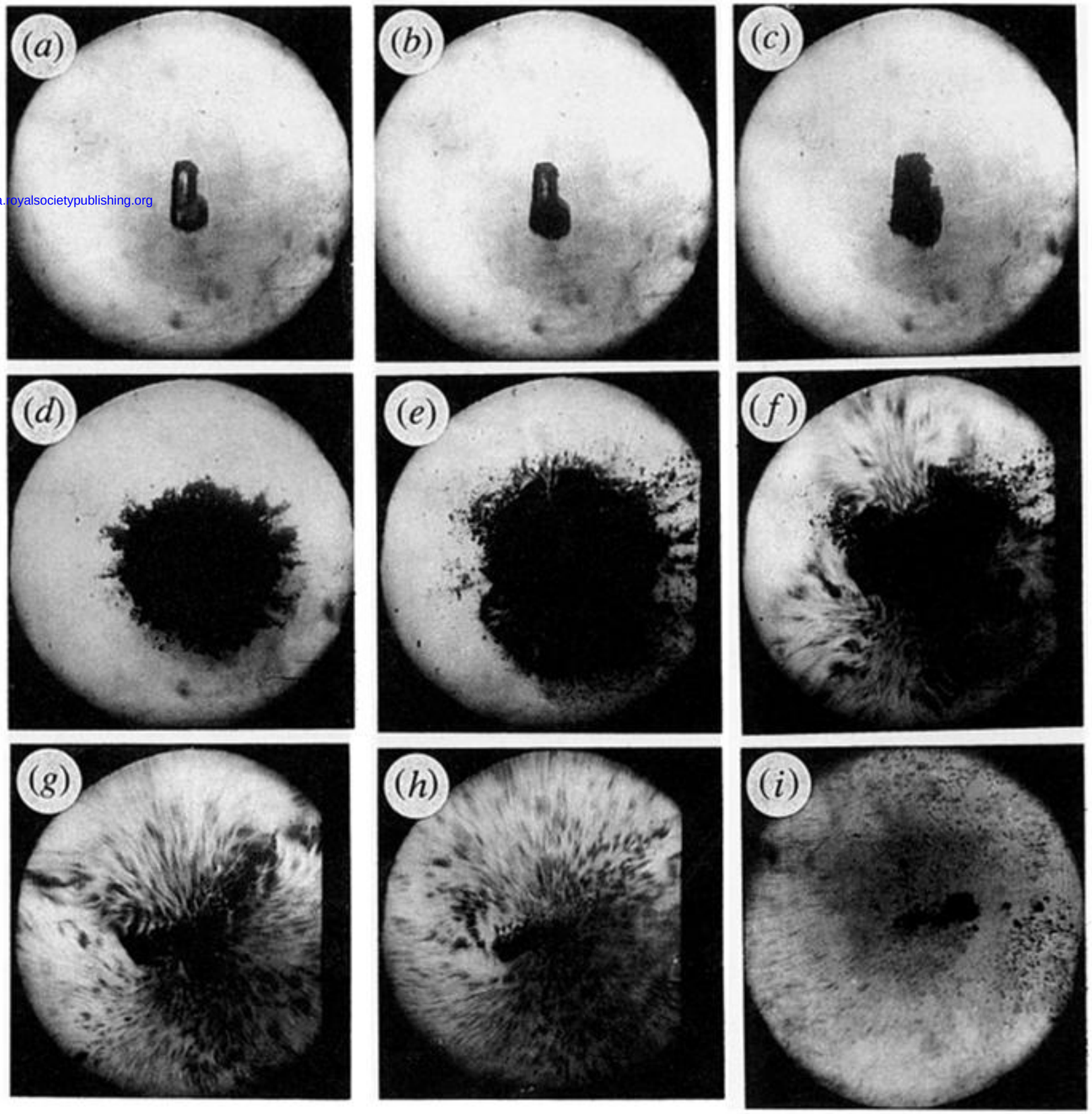
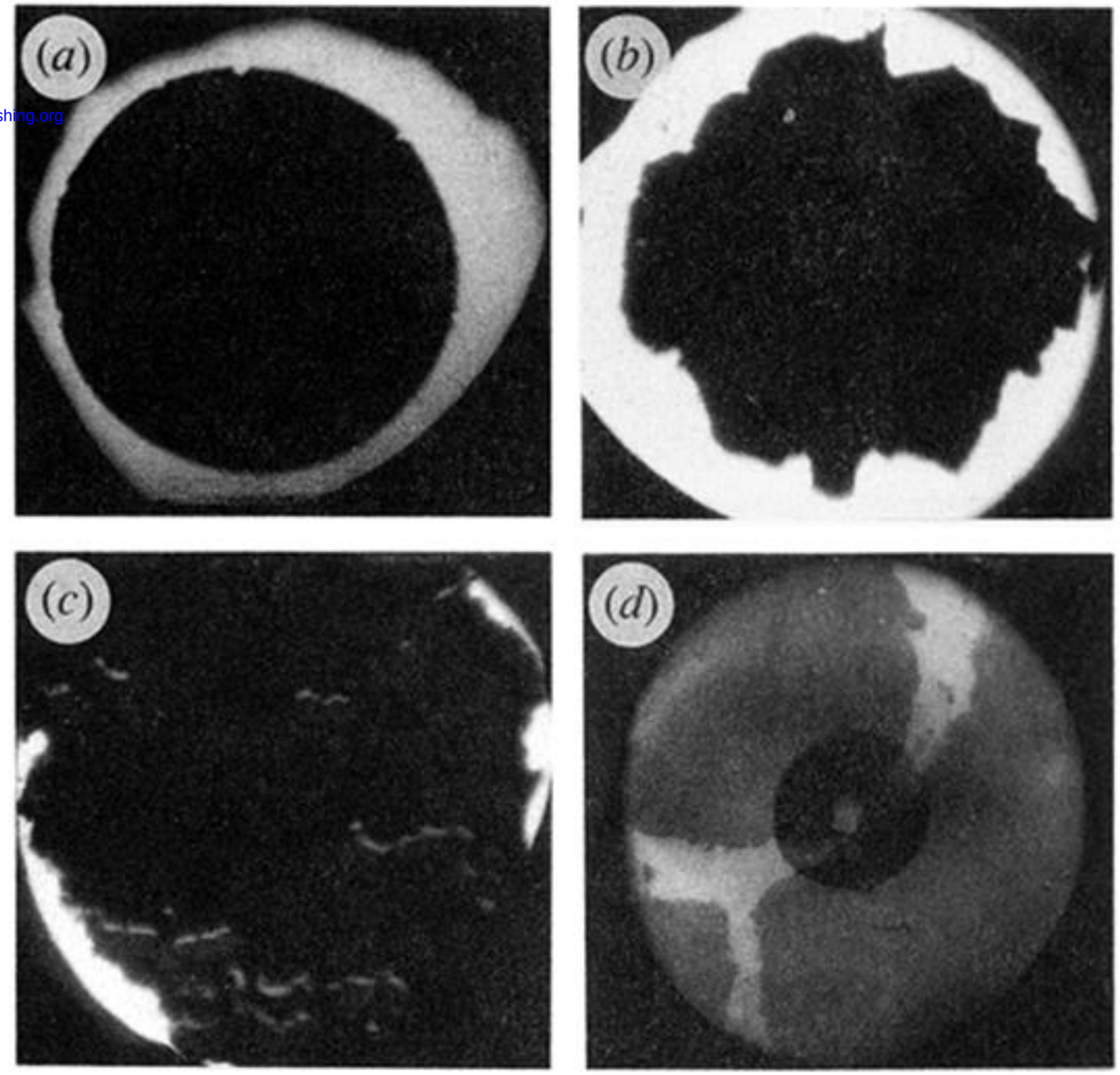
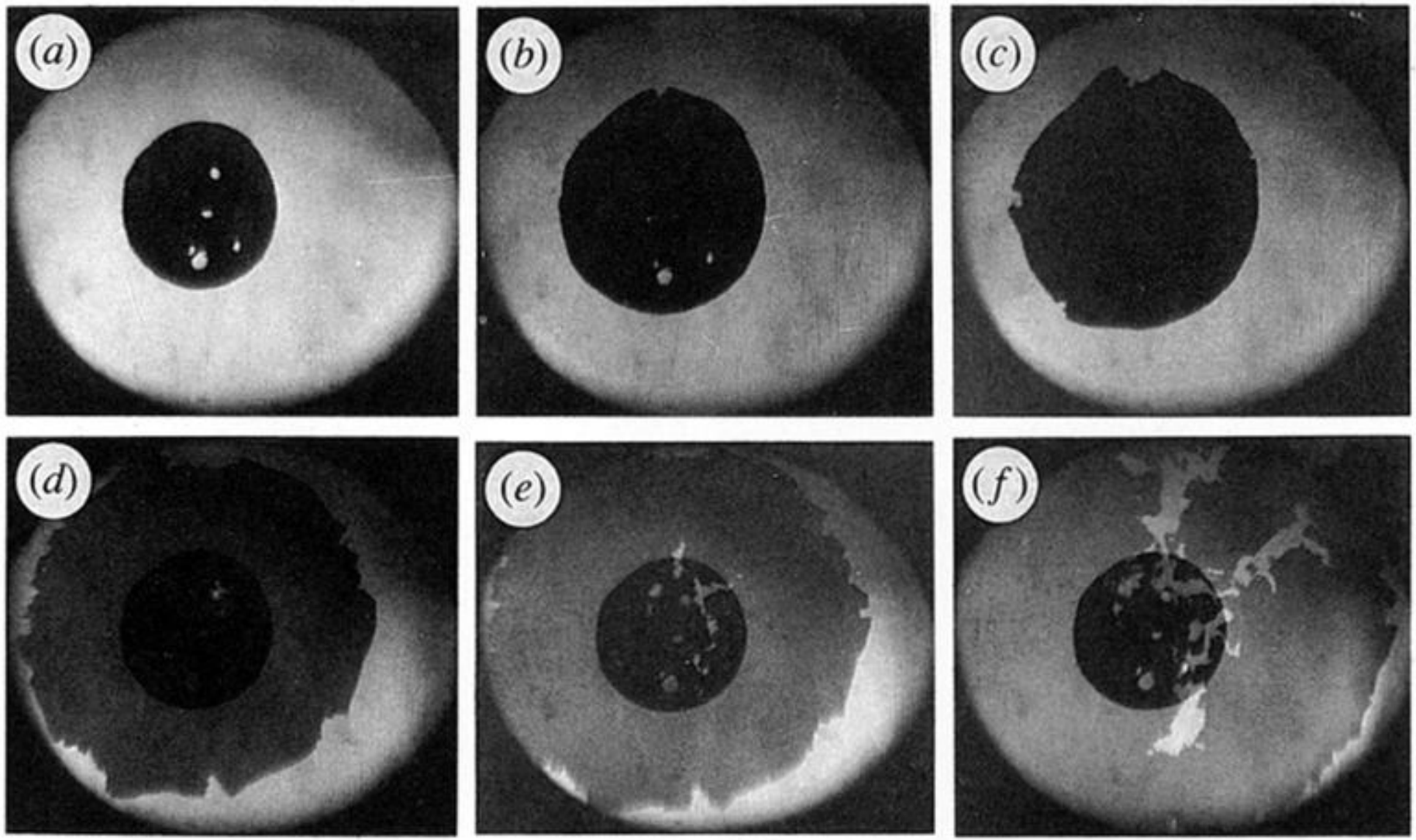


Figure 5. Selected frames from a high-speed photographic sequence of the rapid deformation of a crystal of β-HMX. Times of each frame: (a) 0, (b) 49 μs, (c) 105 μs, (d) 350 μs, (e) 448 μs, (f) 455 μs, (g) 462 μs, (h) 469 μs, (i) 490 μs.



igure 6. Single frames selected from the high-speed photographic sequences of the rapid eformation of 5 mm diameter, 2 mm thick discs of various EMCDBs to show the sorts of behaviour bserved. Times given are measured from the start of deformation. Each frame is exposed for *i*. 2 μs. (*a*) Smooth flow (700 μs); (*b*) jagged periphery (490 μs); (*c*) debonding (560 μs); (*d*) ensitization caused by punching a hole in the middle. This frame exhibits overwriting enabling the nitial state (the dark annulus) to be compared with the final state (the grey area with channels ormed by the deflagration event). Note that the channels begin at the site of the original hole.



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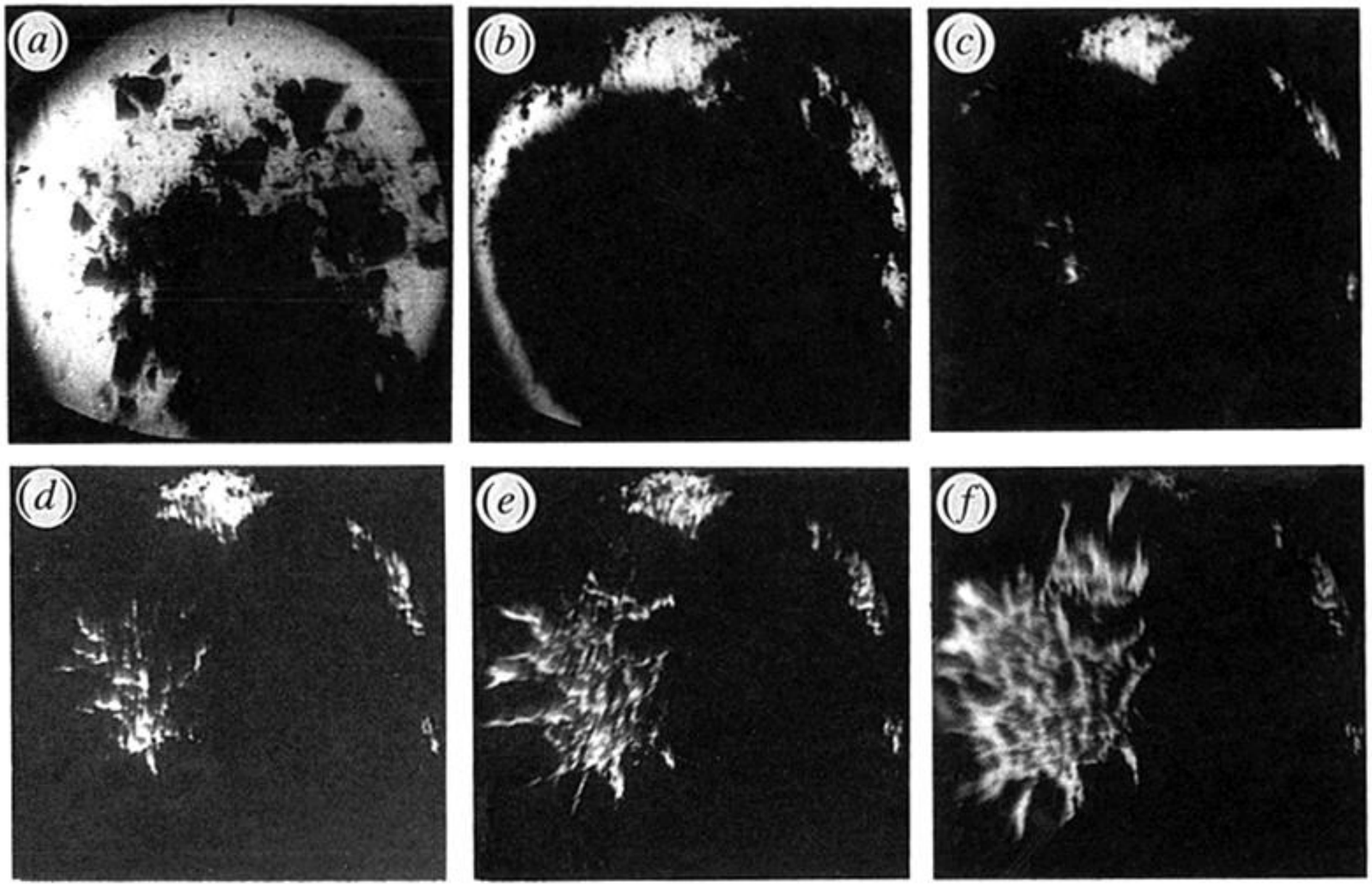

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