PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

High Speed Liquid Impact

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A. THE PHYSICS OF IMPACT AND DEFORMATION: SINGLE IMPACT

I. High speed liquid impact

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[Plates 2 to 5]

A study has been made of the deformation at high strain rates of solids under the impact of liquids. A method is described for projecting a short liquid jet against a solid surface at speeds up to 1200 m/s. The flow of the liquid and the deformation of the solid during impact have been examined by high speed photographic methods. An attempt has been made to measure the magnitude and duration of the load by means of a piezoelectric pressure transducer. There is evidence that the liquid behaves initially on impact in a compressible manner. Part of the deformation of the solid is due to this compressible behaviour and part to the erosive shearing action of the liquid flowing at very high speeds out across the surface.

The mode of deformation in brittle and in plastically deforming materials has been investigated. The deformation patterns produced are shown to be characteristic of liquid impact. The predominating mechanism of deformation depends on the mechanical properties of the solid and on the velocity of impact.

When a drop of liquid moving at a high velocity strikes against a solid surface the impact pressure developed can be very high indeed. At impact velocities in the region of 1000 m/s a small water drop about the size of a raindrop, will permanently deform or fracture almost any high strength structural material. Even at more moderate velocities, in the region of say 100 m/s, the repeated impact of droplets will quickly erode the hardest surface.

Erosion damage due to drop impingement is now a problem of considerable technical importance. The basic situation which it presents—namely a liquid drop striking and deforming a solid surface—has also given rise to problems in physics and in materials science. The first experimental investigation of the physics of drop impact began with the famous experiments of Worthington (1908) who for the first time used high speed photography to study liquid impact. Since that time there have been other similar investigations, though in recent years the tendency has been to concentrate more on the damage produced by the drop than on the breakup of the drop itself. An excellent account of the early work can be found in a review by Engel (1957). More recent studies of the physics of impact have been of two kinds; in one the solid target is fired at a stationary suspended drop (Engel 1955, 1959; Jenkins & Booker 1960), and in the other a liquid drop in the form of a cylindrical jet is projected at a stationary target (Bowden & Brunton 1961; Bowden & Field 1964; DeCorso & Kothmann 1961). The information derived from both kinds of study is similar if allowance is made for the differences in geometry. In this paper a brief account will be given of the jet impact work.

Experimental

The experimental arrangement which was used is shown diagrammatically in figure 1. A small volume of liquid is contained in a stainless steel chamber. The chamber converges at one end to a fine orifice and the other end, which is open during filling, is sealed by a Neoprene disk. The liquid is extruded through the orifice as a cylindrical column by firing a flat nosed slug or bullet into the sealed end. The bore of the chamber was 0·53 cm, and the orifice diameters were usually in the range 1 to 3 mm. The inside of the chamber was polished and changes in cross sections were well rounded in order to minimize turbulence.

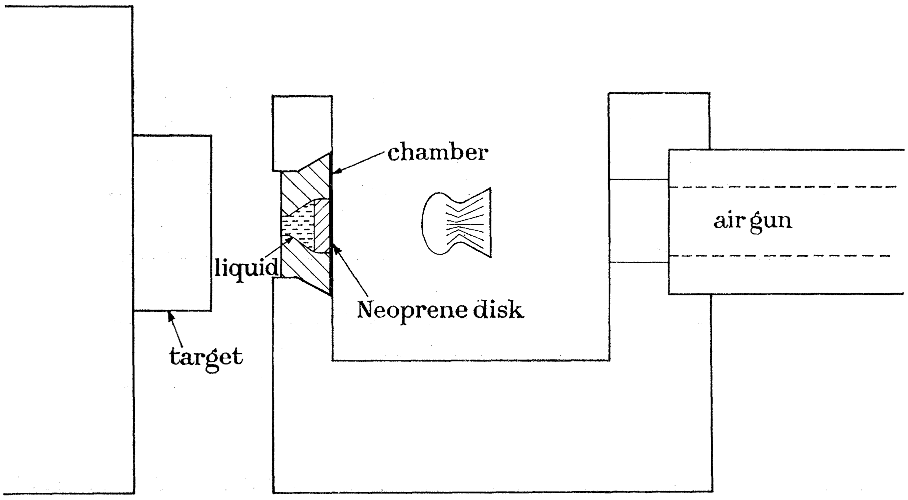

Figure 1. Diagram of the method used for producing a high velocity liquid jet.

The velocities of the drops produced in this way depended on the chamber dimensions and the bullet velocities. Velocities up to 1200 m/s were measured, and estimated velocities approaching 2000 m/s were possible. The upper limit was usually determined by the bursting strength of the chamber.

Measurements on the velocity and behaviour of the high speed drop were obtained with a Beckman and Whitley rotating mirror camera. Exposure times per frame of a fraction of a microsecond and framing rates of about 10^6/s were used.

Figure 2, plate 2, illustrates a typical sequence of photographs showing a cylindrical water jet produced by the apparatus striking a Perspex target. In this example the core diameter is 2·2 mm and the velocity 680 m/s. In order to produce a uniform jet the orifice section of the chamber must be clear of all liquid before firing. If there is liquid present in this section the head of the jet becomes enlarged and diffuse. Normally the jet will remain coherent for about 1 cm in air before it begins to break up. Various jet shapes have been produced with this method by slightly altering the design of the chamber.

The impact pressure

As long ago as 1928 Cook, in a paper on turbine blade erosion and cavitation erosion, pointed out that very high pressures can occur in liquid impact as a result of the

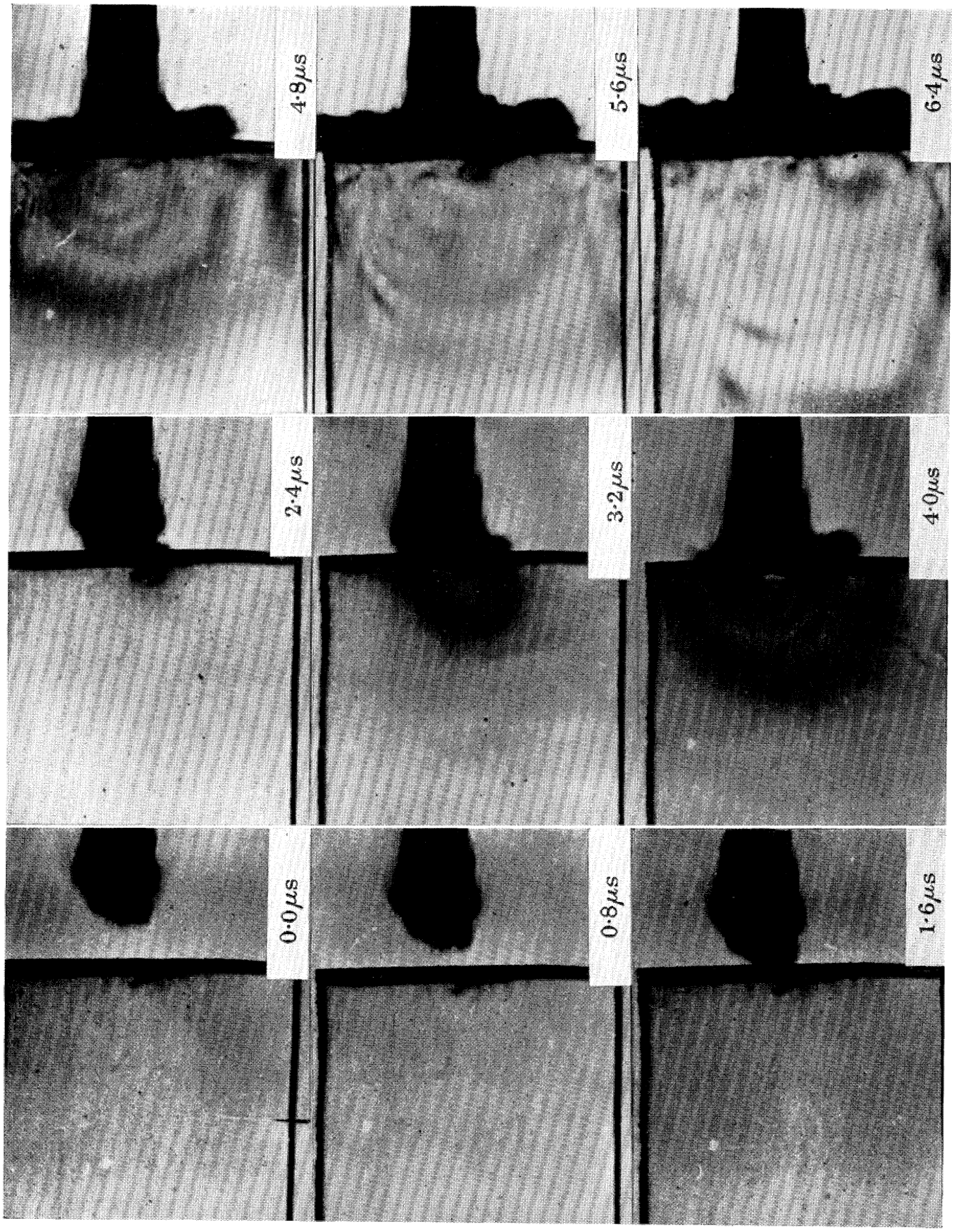

FIGURE 2. The impact of a 2 mm diameter water jet against a polymethylmethacrylate plate. Impact velocity 680 m/s. Framing interval 0·8 s.

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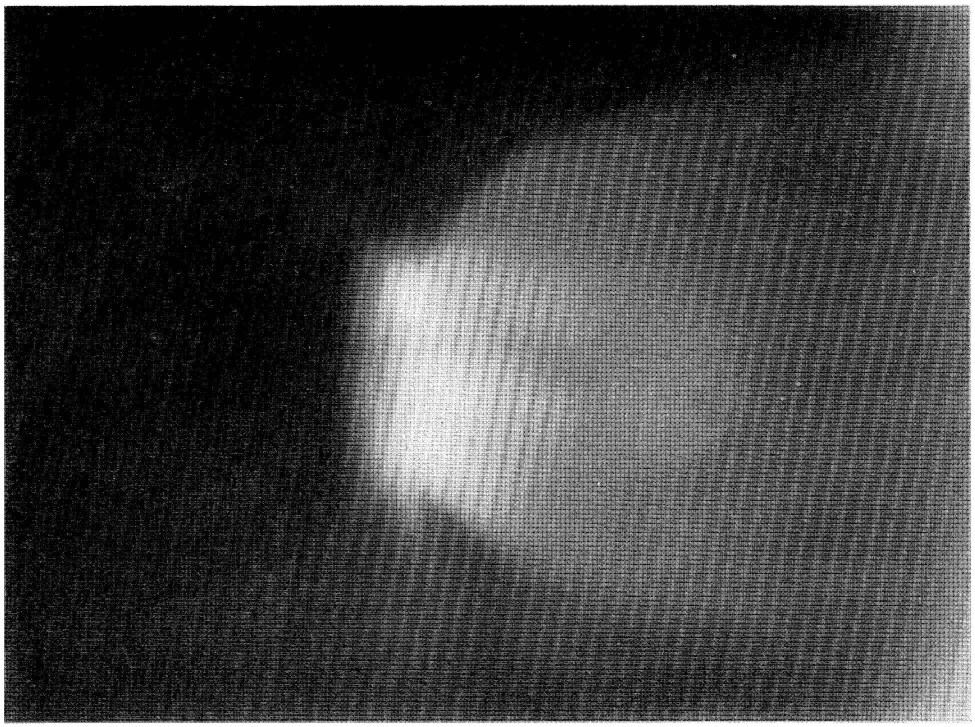

FIGURE 3. The light flash accompanying the impact of a water jet against a polymethylmethacrylate plate. Jet trajectory is horizontally across the figure from right to left.

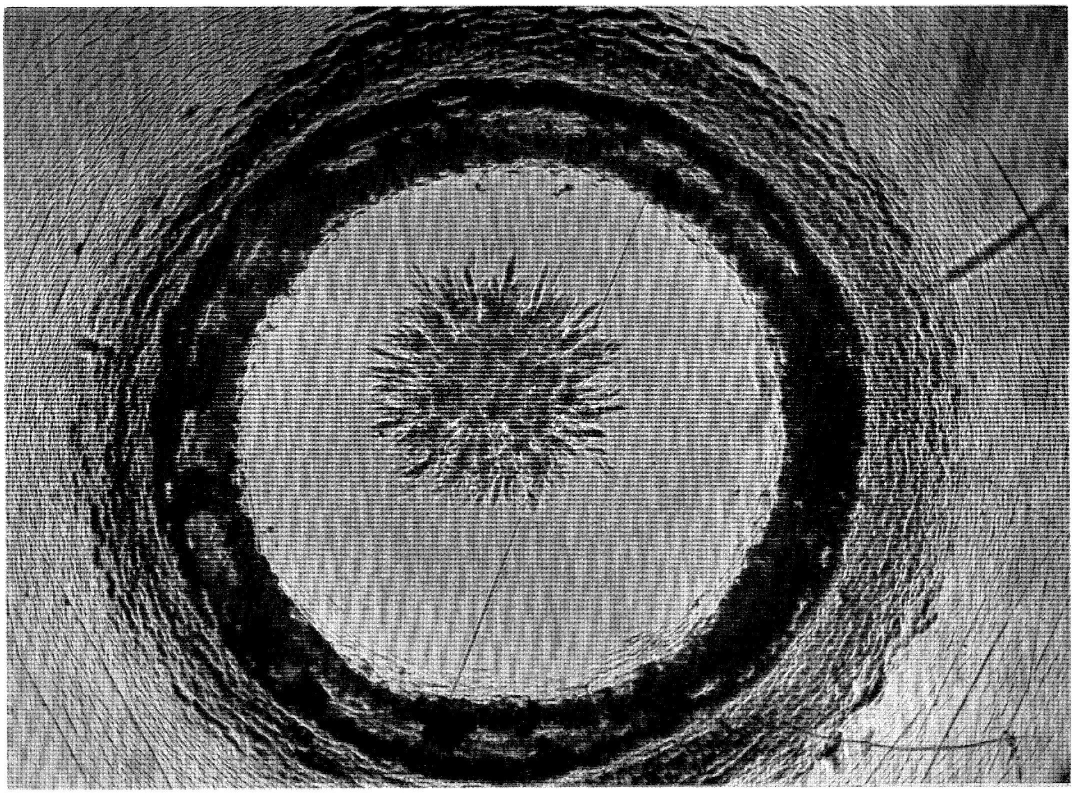

FIGURE 4. Ring deformation in polymethylmethacrylate due to the impact of a water jet at 950 m/s. The mean diameter of the ring deformation is 3 mm.

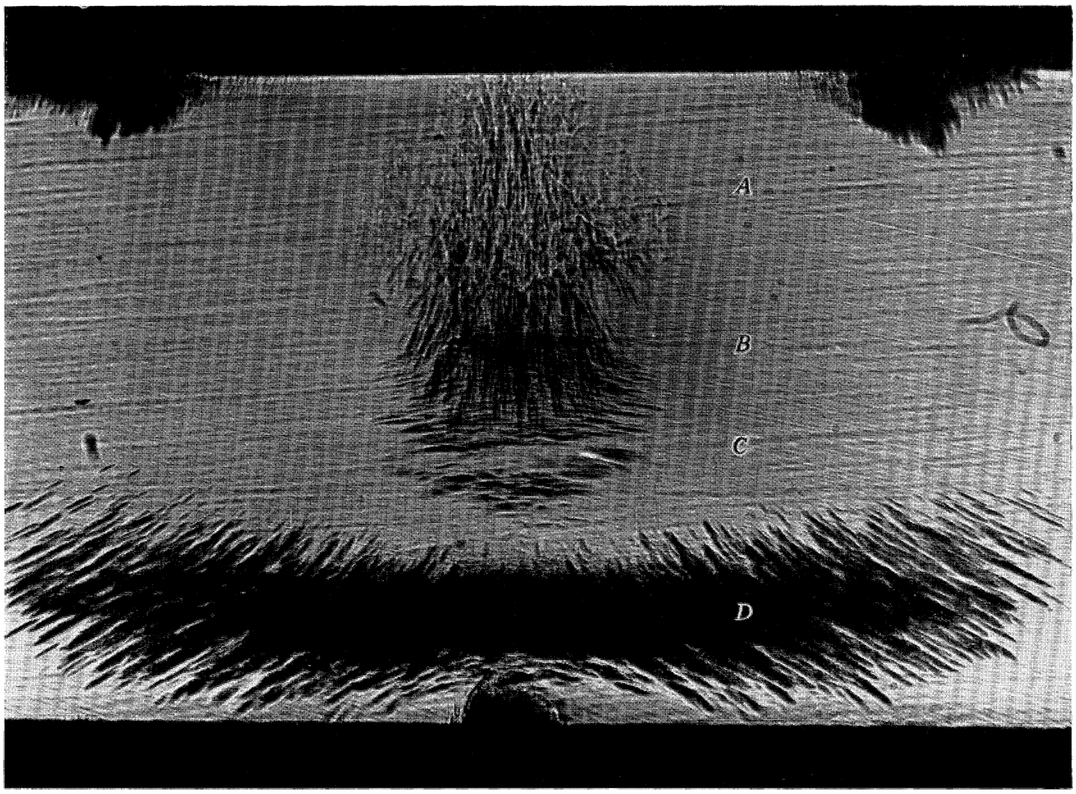

FIGURE 5. Cross section through a 3·5 mm thick polymethylmethacrylate plate. Fractures at *A* are shear fractures and lie along shear trajectories. Fractures at *B* are caused by the tangential tensile stresses across the front of the expanding dilatational wave. Fractures at *C* and *D* are the result of the reflexion and interference of the initial compression wave. Note that the scabbing fractures at *D* are more extensive than the ring fractures on the impact surface.

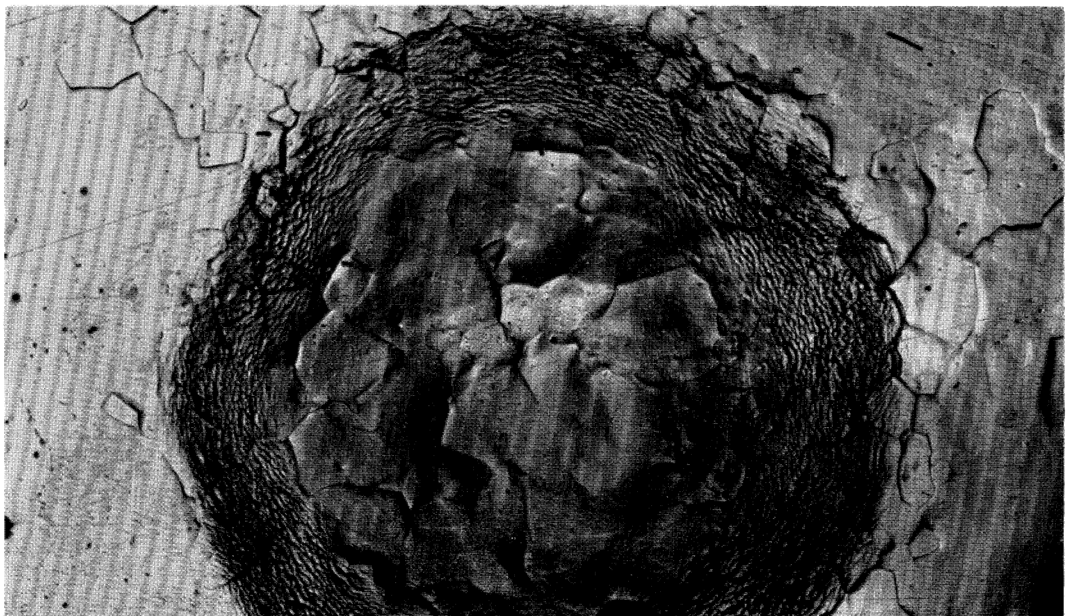

FIGURE 6. The deformation of aluminium caused by the impact of a water jet. The diameter of the depression is 3 mm. The wavy deformation around the rim of the depression is caused by the shearing action of the high speed liquid flow.

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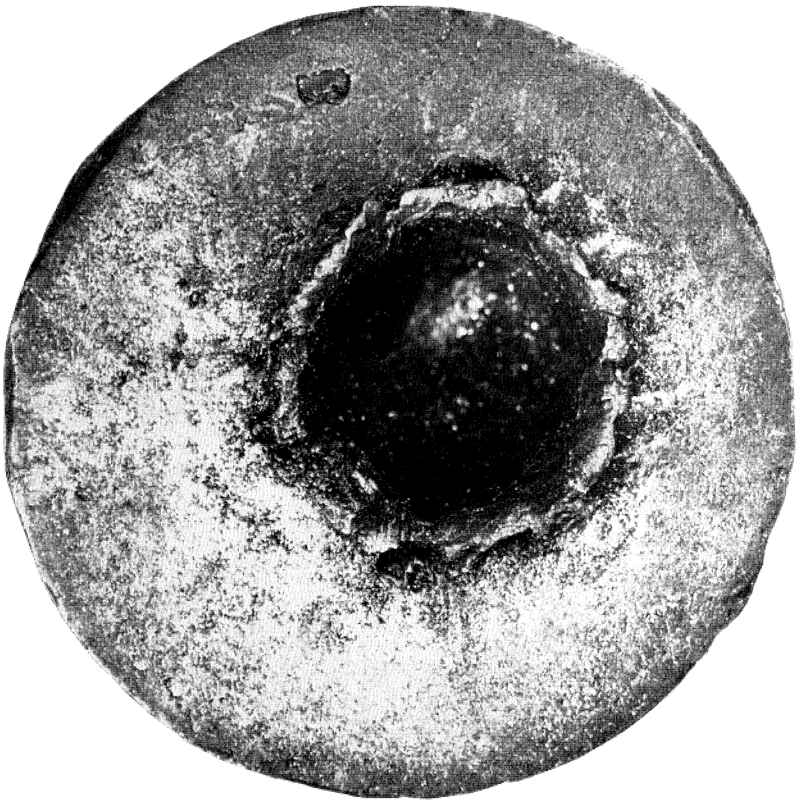

FIGURE 7. The deformation of a lead block caused by the impact of a 2 to 3 mm diameter water jet at a velocity in the range 1500 to 1800 m/s. Diameter of the depression 8 mm, depth 5 mm.

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water-hammer effect. The water-hammer pressure P for a liquid column striking a rigid surface is given by the well known equation

$$P = \rho CV, \tag{1}$$

where ρ is the density of the liquid and C the speed of compression waves in the liquid (at high impact pressures the compression wave propagates as a shock wave with speeds which are greater than the normal sound speed), and V the particle velocity or impact velocity of the liquid. Taking the elastic deformation of the solid into account, P is reduced and is given by

$$P = \frac{\rho_1 C_1 \rho_2 C_2 V}{\rho_1 C_1 + \rho_2 C_2}, \tag{2}$$

where ρ_1, ρ_2 and C_1, C_2 are the respective densities and sound speeds in the liquid and solid.

We have attempted to measure the impact load developed by a liquid jet by means of a barium titanate crystal embedded in the end of a steel pressure bar. The compression wave produced by the impact was displayed as a load time trace on an oscilloscope screen. In each case the trace showed that the load rose to a peak value within a microsecond and then immediately began to fall. The decay time was normally about 2 to 3 μs. The rapid decay is perhaps surprising in view of the fact that the jet impinges on the surface for at least 20 μs with approximately constant velocity. If, however, we consider the water-hammer effect, the peak load L will occur immediately and be given by

$$L = \rho CVA, \tag{3}$$

where A is the area of cross section of the jet head. This load will start to decay as soon as sideways flow begins—since the liquid is not constrained in any way along the sides of the jet. The decay time from peak load will be the time for release waves to move into the centre of impact from the boundary of the jet. For the 2 to 3 mm diameter jets used in this work the corresponding decay times would be 1 to 2 μs. The rather longer rise and fall times observed experimentally are probably due to the fact that the jet was unlikely to be perfectly flat ended and square with the solid surface.

The magnitude of the impact load of a water jet with a core diameter of 1·3 mm and a head diameter of 3 mm striking the pressure bar at 720 m/s was 620 Kg. There is no simple way of determining how this load is distributed and hence of obtaining the impact pressure. However, an average value of 95 Kg/mm^2 is obtained by dividing the load by the area of the jet head. The calculated value of the water-hammer pressure is 150 Kg/mm^2 (the value of C used here is that given in data by Cook, Keyes & Ursenbach (1962)). In either case the values are high, noticeably so when we compare them with the flow stress for say mild steel which is about 25 Kg/mm^2. It is hardly surprising that structural materials are damaged by liquid drops moving at these speeds.

An interesting phenomenological consequence of the high pressures is that the impact is accompanied by a light flash on the target surface. The flash is thought to be due to adiabatic compression of an air layer trapped between the liquid and the solid. DeCorso & Kothmann (1962), in a more extensive study of the flash, also arrived at this conclusion. An example of the impact flash is shown in figure 3, plate 3.

Other investigations have shown that the water-hammer effect occurs in the impact of spherical drops. Jenkins & Booker (1960) deduced impact pressures from measurements of the radial flow velocity from under a water drop during impact. They found agreement with values calculated from equation (1). Field (1962), Hancox (1962) and Bowden & Field (1964) have also concluded that for spherically shaped surfaces the maximum pressure is the water-hammer pressure. Engel (1955) used a modified form of equation (1). She finds P is given by

$$P = \tfrac{1}{2}\alpha\rho CV,$$

where α approaches unity for high impact velocities and the factor of $\frac{1}{2}$ is a consequence of the spherical shape of the drop.

Tangential flow

It has been observed that under certain conditions the flow velocity of the liquid along the surface, and away from the centre of impact, is greater than the impact velocity itself. Measured values showed the difference to be as much as two to three times the impact velocity. For a flat ended jet striking a rigid surface perpendicularly, the particle velocity along the surface should be the same as the particle velocity perpendicular to the surface. The velocity increase is thought to be connected with the shape of the head of the jet. It has been observed that an increase in velocity along the surface occurs only in cases where the jet head is inclined at an angle to the surface. In figure 2, for example, the flow velocity down the surface from the straight sided portion of the jet is equal to the impact velocity while the flow velocity up the surface from under the sloping face of the jet is 2·3 times the impact velocity. An explanation of this effect in terms of the 'jetting' action which occurs in the collapse of a metal wedge in a shaped charge (Birkhoff, MacDougall, Pugh & Taylor 1948) has been given by Bowden & Brunton (1961).

Since spherical drops always provide a sloping interface to a plane solid surface it might be expected that high radial velocities will occur on impact. Engel (1955) and Jenkins & Booker (1960) have reported radial velocities for spherical drop impacts which are as much as 5 times the impact velocity.

The deformation of a solid

The impact stresses which cause deformation may be classified as:

(1) Those associated with the short duration 'explosive' compression of the surface which arises from the water-hammer effect.

(2) Stresses caused by the erosive scouring action of the high speed radial flow. A few examples will be given here to illustrate these two effects.

The deformation of hard polymers

The deformation produced in a 3 mm thick plate of polymethylmethacrylate by the impact of a water jet is shown in figure 4, plate 3, and in section on a diameter in figure 5, plate 4. The failure pattern shown here is typical of most hard polymers and glasses.

The main feature of the deformation is an annular fracture separating a region of intense circumferential fracture from a central undamaged zone. The central star crack (figure 4) is seen to lie beneath the surface (figure 5). Measurements show that the diameter of the central area is equal to the diameter of the head of the jet.

The form of damage varied with the impact velocity. For velocities below about 450 m/s the ring fracture was replaced by an annular depression. Below the depression layer fractures could still be seen. These fractures cut the surface to form small hairline cracks. At higher impact velocities, in the region of 1000 m/s the ring fracture was replaced by a surface pit of approximately the same diameter. An examination of the outer fractured zone by multiple-beam interferometry showed that each fracture formed a small step in the surface. The average height of these fracture steps was only about 2000 Å. It was also noticed that the vertical surface of each step faced in towards the centre of impact. These small steps produced by the crazing fractures are important since they tend to obstruct the outward flow and as a result the surface is chipped along the line of the fractures. The deep annular pit in figure 4 is an example of a pit formed in this way.

It might be asked why the centre of the impact region is undamaged and why there are ring fractures surrounding it. The fracture process in a brittle material may be visualized thus: on impact the region under the jet is put into compression while the area immediately surrounding experiences radially acting tensile stresses. The latter will be most intense around the periphery of the compressed area and hence ring fractures will appear first along this boundary. Fracturing of the central area will be inhibited by the compressive stresses so that this region undergoes elastic deformation only. In materials which can deform plastically the shear stresses in the central region may cause the solid to yield in which case a permanent central depression would be observed.

Failure of the surface in a hard polymer is seen to consist of two processes, first the production of fractures by radial tensile stresses and secondly the removal of material from the fractured regions by the liquid flowing out at high speed over the surface.

The fractures below the surface (figure 5) have rather a complicated structure. The upper fracture (A) is the star pattern fracture visible in figure 4. These fracture planes lie on shear trajectories and open up under the rapidly applied shear stresses. In addition to shear stresses there are tensile components acting across the front of the expanding compression wave as it moves into the solid; these cause the fractures (B) lying perpendicular to the surface and below the main star crack. High speed photographs have shown this region forming and then closing up again, but not completely, when the wave has passed. Fracture regions (C) and (D) are related to the reflexion of stress waves in the lower surface. The main fracture zone (D) is caused by the large tensile stresses associated with the reflexion of the main compression wave. Fractures at (C) are probably formed as a result of the interference between this wave and the slower outgoing shear wave. In brittle materials fracturing due to stress wave effects is usually far greater than that in the impact area itself. High strength ceramic plates, for example, fail in this way by flaking and spalling of the rear surface. Under repeated impact the plates become thin and eventually perforate. This type of failure is of importance in connexion with the rain erosion of ceramic radomes.

The deformation of soft polymers

The two main features of the failure pattern in these materials are an outer ring of torn surface, and a narrow central penetration or 'piping'. The outer ring damage is not a fracture of the kind produced in hard polymers but a shearing or tearing of the surface caused by the outward liquid flow. The central penetration is a true fracture which occurs after the surface has been depressed several millimetres. This type of failure is found in natural rubber, Neoprene and polyethylene. In unplasticized polyvinylchloride (a relatively hard polymer) an outer Hertzian ring fracture similar to that found in the hard polymers, and a separate inner shear ring characteristic of a soft elastomer were both produced in the same impact area.

The deformation of metals

In metals large scale plastic flow occurs for impact velocities above about 600 m/s. The jet produces a shallow saucer-shaped depression which is equal in diameter to the jet head. An example showing a depression in aluminium caused by the impact of a water jet at 750 m/s is given in figure 6, plate 4. The surface of the depression is smooth near the centre (apart from some unevenness along the grain boundaries), but around the periphery the surface is sheared into a wavy series of elevations and depressions by the liquid flow. As in the case of polymers shear deformation of this kind was most intense where the surface underwent small sharp changes in contour. Slip lines, grain boundaries, twin boundaries and surface scratches were heavily deformed. In multiphase alloys it was generally the softer phase which was sheared. Hard intermetallic phases were often removed altogether from the surface around the rim of the depression.

For very high impact velocities in the region of 2000 m/s and with metals of relatively low yield strength such as lead and tin, the impact stresses are far greater than the yield stress. Under these circumstances the target itself flows hydrodynamically. The crater produced is approximately hemispherical in section with a pronounced lip giving the appearance of a frozen splash. An example of a high velocity crater in lead is shown in figure 7, plate 5.

The mechanism of deformation

From the account given above it can be seen that three general types of failure are possible in a solid struck by a liquid drop at high speed. The predominating form of failure in any particular case depends upon the mechanical properties of the solid.

The forms of failure are:

(1) Failure in the region of impact due to the rapid application of a large load over an area roughly equal to the cross sectional area of the drop. The actual area depends upon the shape of the drop. In hard polymers and brittle solids this causes circumferential fractures, ring cracks and sometimes, in materials which show some tendency to deform plastically, subsurface shear cracks. In metals, and in materials capable of deforming plastically at very high rates of strain, a simple surface depression is produced.

(2) Failure due to the shearing action of liquid flowing across the surface at high speed. This type of failure is localized at surface discontinuities. These may already exist in the surface as scratches, pits or inclusions, or they may be put in by the impact load and appear as cracks, sliplines and elevated grain boundaries. Surfaces which remain smooth during the impact are not affected by this shearing action. Failure of this kind is true erosion since it usually involves removal of material from the surface.

(3) Failure caused by the reflexion and interference of stress waves in the solid. This is found mainly in hard brittle solids. When it occurs it is often catastrophic and is more damaging than failure in the impact area. It is dependent on the shape and size of the solid target and is therefore to some extent controllable.

It seems that the deformation of a solid by a liquid drop can occur by several distinct mechanisms and that only in a qualitative way is it possible to single these out and study them separately. Generally, however, the failure process will be complicated and difficult to analyse, this will be especially true for conditions of repeated impact. From the practical point of view it may be possible to determine for a particular material and for specific conditions the predominating mode of failure and hence make some prediction about its useful life.

I wish to thank Professor F. P. Bowden, F.R.S., for his interest and advice in the work and the Armourers and Braziers' Company for a research fellowship.

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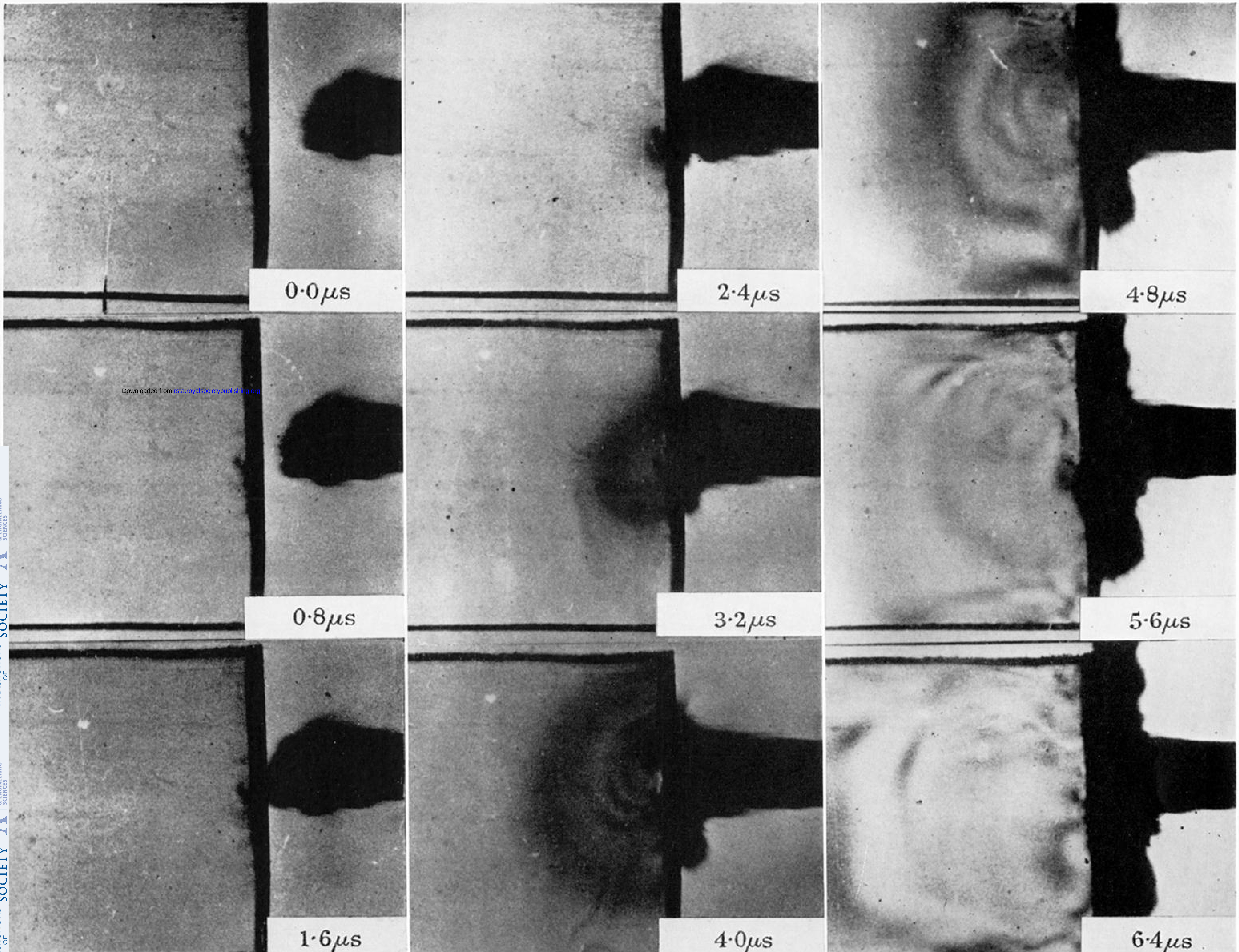
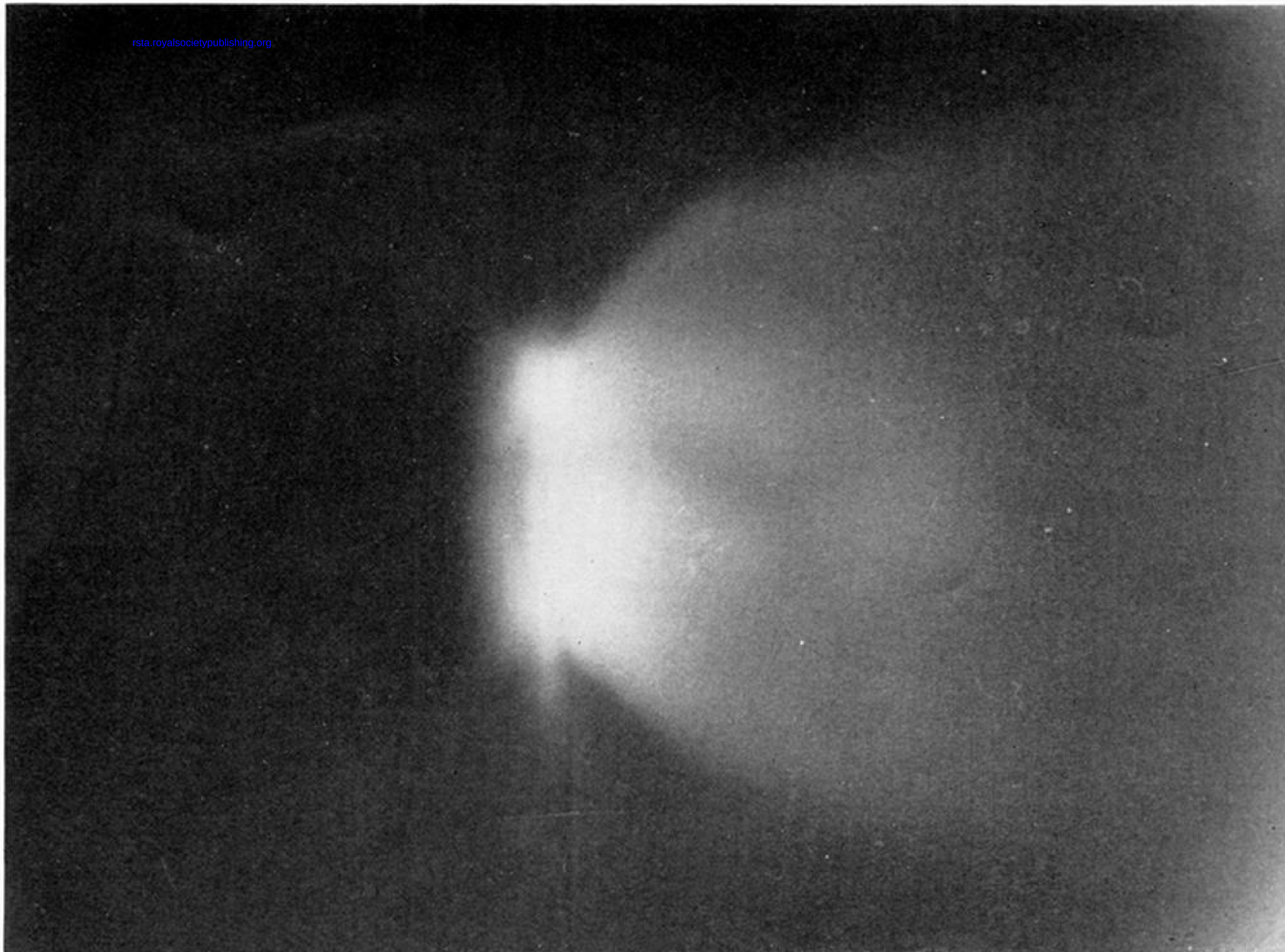


FIGURE 2. The impact of a 2 mm diameter water jet against a polymethylmethacrylate plate. Impact velocity 680 m/s. Framing interval 0·8 s.



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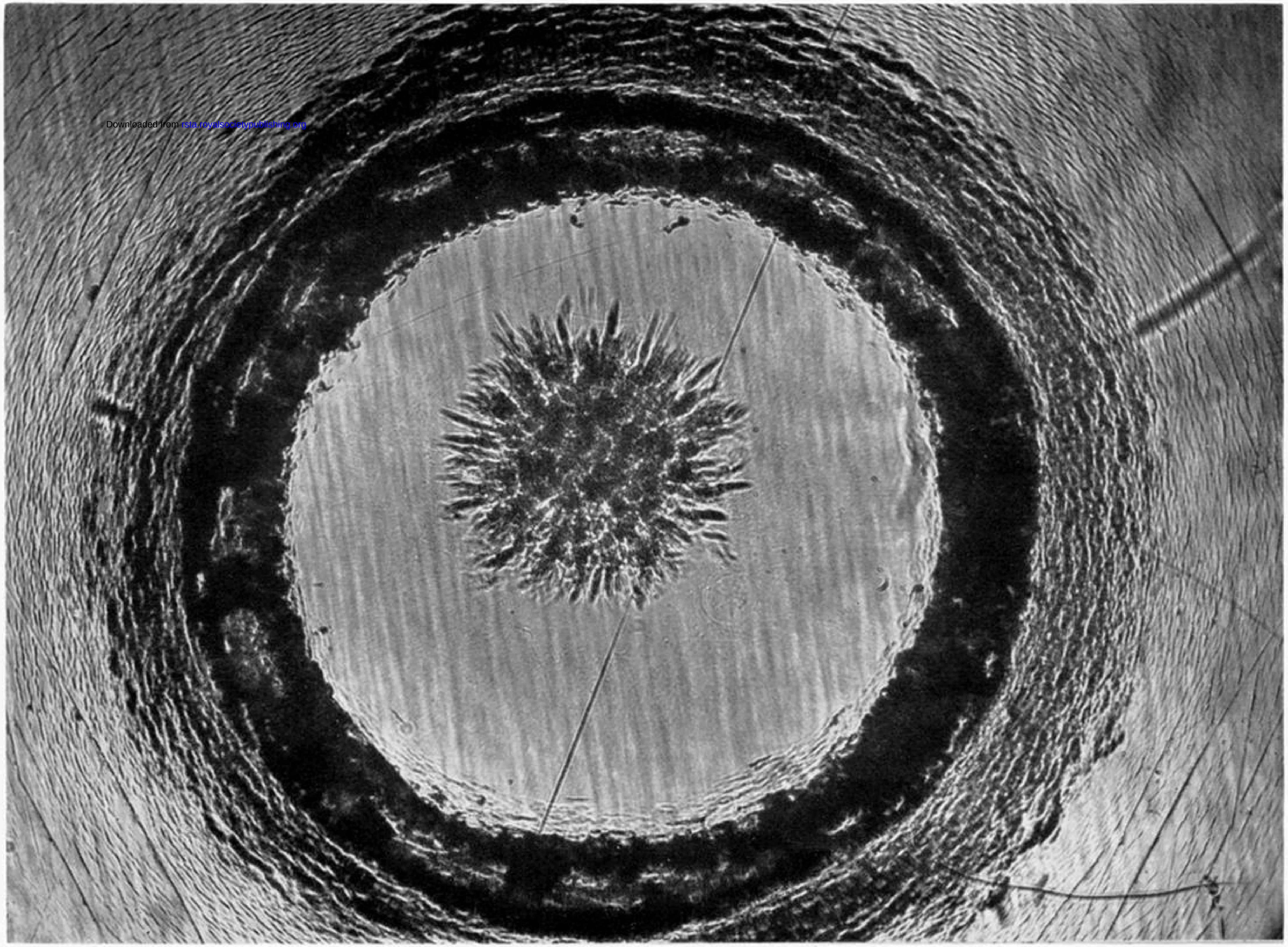

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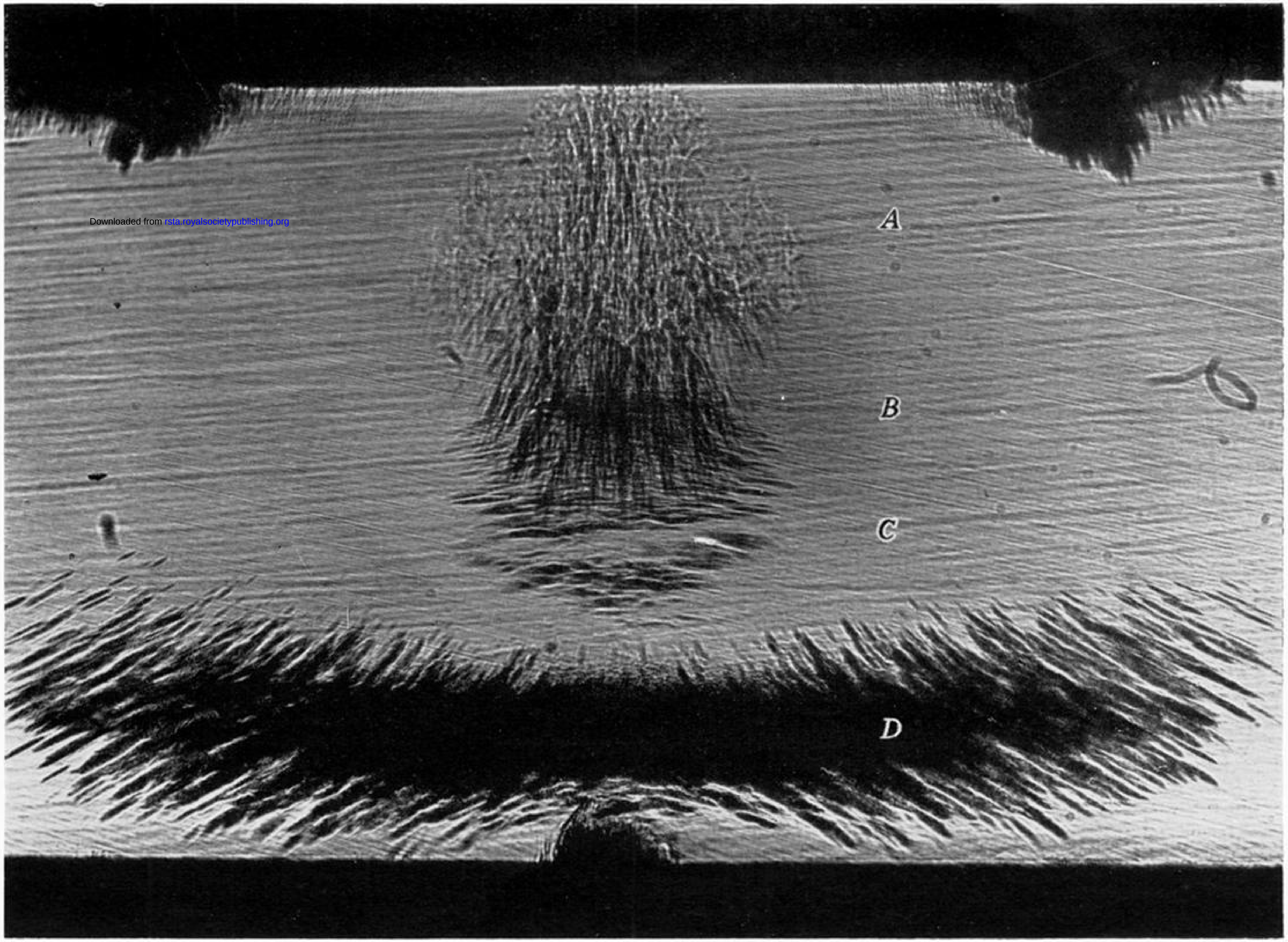

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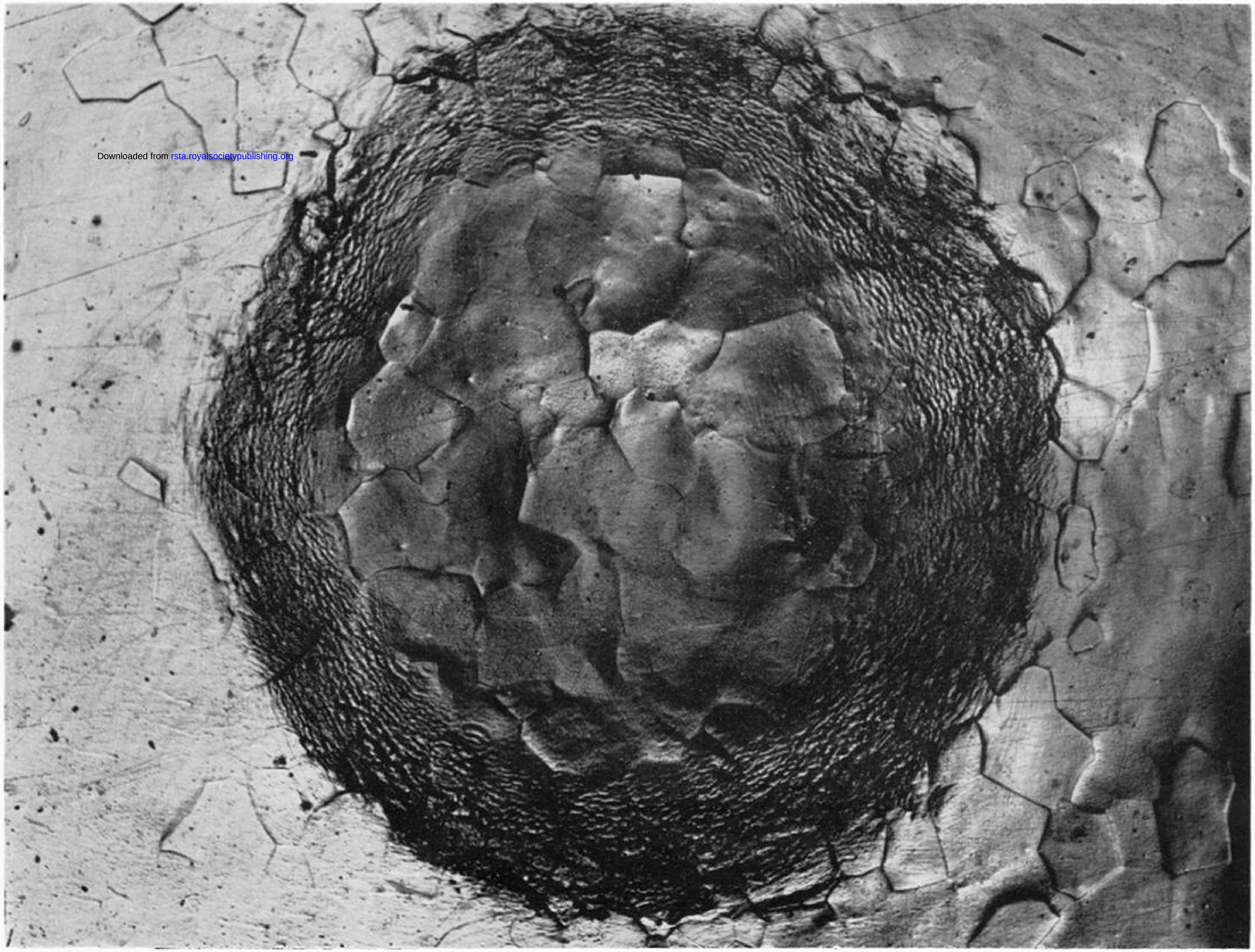

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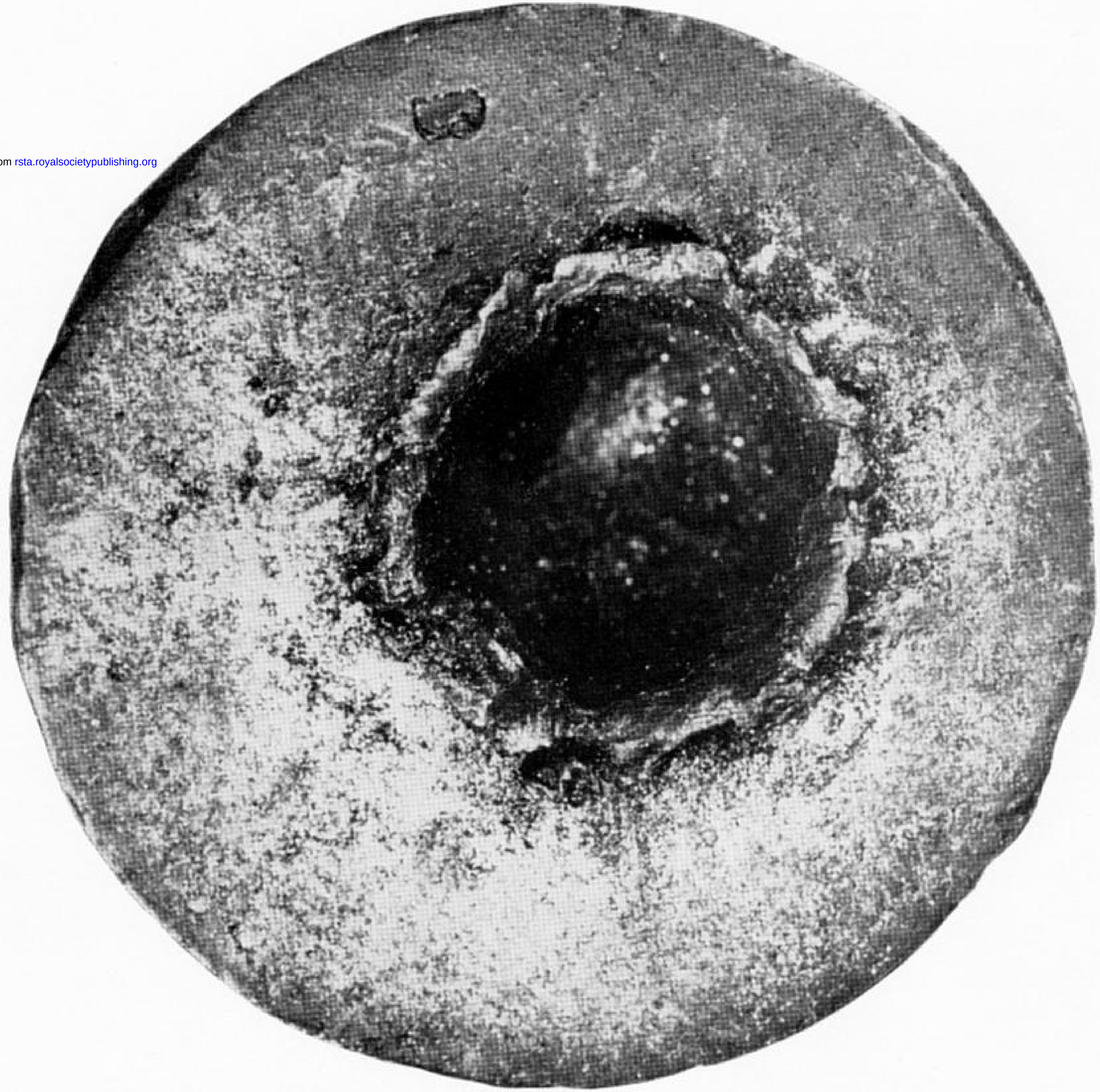
FIGURE 6. The deformation of aluminium caused by the impact of a water jet. The diameter of the depression is 3 mm. The wavy deformation around the rim of the depression is caused by the shearing action of the high speed liquid flow.



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