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

Stress Waves, Deformation and Fracture Caused by Liquid Impact

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II. Stress waves, deformation and fracture caused by liquid impact

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[Plates 6 to 9]

When a liquid mass strikes a solid surface, compressible behaviour, giving rise to a sharp peak of pressure, may occur in the initial stages of the impact. The duration of the peak depends on the dimensions and impact velocity of the liquid mass, and also on the compressional wave velocity for the liquid. There are similarities between this type of loading and that produced by the detonation of small quantities of explosive, since both give intense pressure peaks of only a few microseconds' duration.

The fracture and deformation of glasses, hard polymers, single crystal and ceramic materials by liquid impact at velocities up to 1000 m/s is described and briefly compared with that produced by solid/solid impact and explosive loading. The detailed development of fracture has been followed by high speed photography. In brittle solids the main characteristics of damage on the front surface is a ring fracture surrounding a largely undamaged area. The ring fracture forms at the edge of the loaded area where high tensile forces develop during impact. Outside this main ring of fracture short circumferential cracks occur; these are shown to be initiated by the Rayleigh surface wave at points where flaws existed. More complex fracture patterns which appear on the front surface of plates are due to the reinforcement of the surface wave with components of stress reflected from the back surface. Thin plate specimens often exhibit 'scabbing' fracture at the rear surface; in brittle materials of low attenuation this form of damage can be of prime importance.

Since the stress pulses producing fracture during liquid impact are short the fractures themselves remain short and discrete. By a combination of impact loading and etching it is possible to investigate the distribution and depth of flaws, their role in the fracture process, and the effect which etching has upon them.

Introduction

In earlier papers from this laboratory (Bowden & Brunton 1961; Bowden & Field 1964; to be referred to as papers I and II) the deformation produced in a solid by the impact of a liquid at high velocity was described. It was concluded that in such an impact the liquid behaves initially in a compressible manner, giving rise to pressures determined by the equation

$$P = \rho C V, \tag{1}$$

where P is the pressure, ρ the density of the liquid, C the compressional wave velocity for the liquid, and V the impact velocity. The duration of this high pressure was shown to depend upon the shape and size of the impacting liquid mass. In the case of an impacting liquid cylinder, for example, the duration depends upon the time taken for the release waves from the sides of the cylinder, travelling at velocity C, to reach the centre of the cylinder. Figure 1 illustrates this behaviour. The shaded areas denote liquid still under compression. After the release waves reach the centre, this takes a time r/C, where r is the radius of the cylinder, the pressures quickly fall to the lower values given by incompressible flow conditions. Since C for water is about 1500 m/s it means that for a 3 mm diameter liquid cylinder impacting at 1000 m/s the peak pressures should reach $1{\cdot}5 \times 10^{10}$ dyn/cm^2

and last approximately 1 μs. (In fact for such a high velocity impact the value for C is more correctly replaced by a shock-wave velocity. The appropriate values can be found from curves given by Cook, Keyes & Ursenbach (1962). If this correction is made the pressures for an impact velocity of 1000 /ms are about $3{\cdot}7 \times 10^{10}$ dyn/cm^2.)

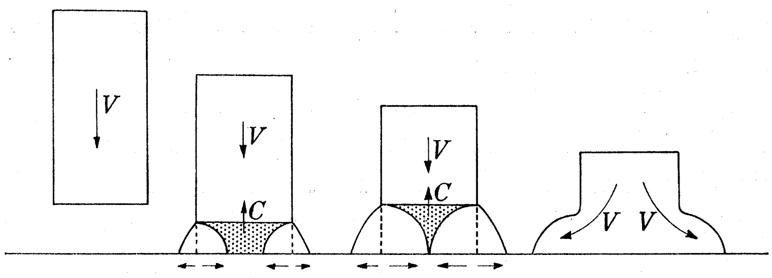

FIGURE 1. Impact of a liquid cylinder.

The high pressures in the case of the cylinder result basically from the fact that although the whole area of the head of the cylinder impacts against the solid only the liquid at the edges is free to flow initially and the liquid at the centre remains compressed until reached by the release waves. It might be thought that this compressible behaviour would not occur during the impact of a liquid mass with curved profile. However, this situation has been considered in paper II where it was demonstrated that there is a region around the point of impact where flow is prevented in the initial stages of impact. For a spherical drop the radius of this region x_0 is given by

$$x_0 = rV/C, \tag{2}$$

where r is the drop radius, and V and C are as before. It was also shown that the pressures on the surface in this area of radius x_0 were uniformly equal to ρCV. Equation (2) shows that the region where compressible behaviour occurs depends on both the radius of the drop and the impact velocity. Clearly for very low values of V this area is vanishingly small. Outside this region incompressible flow is possible and lower pressures result.

It is interesting to compare the duration of the high pressures reached in the impact of liquid masses with the corresponding duration for solid bodies. The general conclusion is that the duration is usually longer, and often very much longer, in the solid impact situation. In the case of a solid cylinder, for example, the pressures are still given by equation (1) (St Venant 1867), but the duration now depends on the time taken for the stress wave to travel twice the length of the cylinder. For a solid sphere the duration of high pressure may approach 100 μs, whereas the corresponding sized liquid sphere would give compressible behaviour for 1 μs or less.

Further differences are apparent if the pressures and energies of impact are considered; taking as examples water ($\rho_1 P_1 V_1 C_1$) and steel ($\rho_2 P_2 V_2 C_2$), since ρ_2/ρ_1 and C_2/C_1 are approximately 8 and 3 respectively, the ratio of the pressures P_2/P_1 for equal impact velocities is 24. Conversely, for there to be equal pressures the ratio of the velocities V_2/V_1 has to be 1/24. In this latter case there is the additional point that although the stresses may build up to the same stress level the rise time for the solid/solid impact, because of the lower impact velocity, is longer. These various factors are all important in explaining the many differences observed when the fracture damage resulting from a solid/solid impact is compared with that from a liquid/solid impact.

Fracture experiments

Figure 2, plate 7, shows the result of the impact of a cylinder of liquid at 650 m/s on commercial plate glass. The jet, of head diameter 3 mm, was produced by the apparatus described in paper I, and its velocity was measured by means of high speed photography. The size of the head of the jet corresponded closely to the diameter of the large ring fracture. The main ring fracture and undamaged central area resemble the pattern of failure produced by the static indentation of glass by a solid sphere or cylinder except that the ring fracture is composed of many small fractures rather than one continuous crack. The additional features caused by the impulsive loading are the circumferential fractures outside the main ring crack. These cracks are short and discrete because the stress pulse producing them was of such short duration (about 1 μs). The initiation of the cracks is consistent with there being a surface distribution of flaws on the surface of the solid; the flaws growing when a tensile stress of sufficient magnitude was applied by one of the stress waves.

The formation of the short fractures around the loaded area has been studied with a Beckman and Whitley high speed camera capable of framing rates in excess of 10^6 frames/s. Figure 3, plate 6, shows six frames from a sequence in which a lead slug impacts against the top edge of a 3 in. × 3 in. × $\frac{1}{4}$ in. glass specimen at an impact velocity of about 210 m/s. The time interval between frames was 1·94 μs. It can be seen that in the final stages the lead flows as a liquid. However, compressible behaviour in the initial stages of impact does give rise to a peak of pressure (for the reasons discussed in the preceding section), and it is this peak of stress which causes the initiation of the cracks as it passes out across the surface from the impact area. The point at which fresh fractures appear moves out at a velocity which was measured as 3000 ± 300 m/s. Since the velocity of the Rayleigh surface wave for the glass used was about 3100 m/s it is reasonable to relate the initiation of the short circumferential cracks which surround the main ring fracture with this wave. Further evidence for this has been provided in sequences taken using polarized light so that the position of the stress waves in relation to the fractures can be observed (paper II).

If a solid sphere impacts a glass surface at a velocity sufficient to cause a ring fracture the short circumferential fractures outside the ring crack do not form. This is because this impact gives a pulse with a much longer rise time and duration (see preceding section). In contrast explosive loading, which like the liquid produces a short intense pulse, again gives the circumferential cracks (Christie & Kolsky 1952; Kolsky 1953).

It is interesting to note that glasses do not exhibit the region of subsurface damage found in hard plastics (see the preceding paper by J. H. Brunton, and paper I). The reason for this is that the defects in glass occur mainly at the surface, while in hard polymers such as Perspex the defects are located almost equally throughout the bulk as at the surface.

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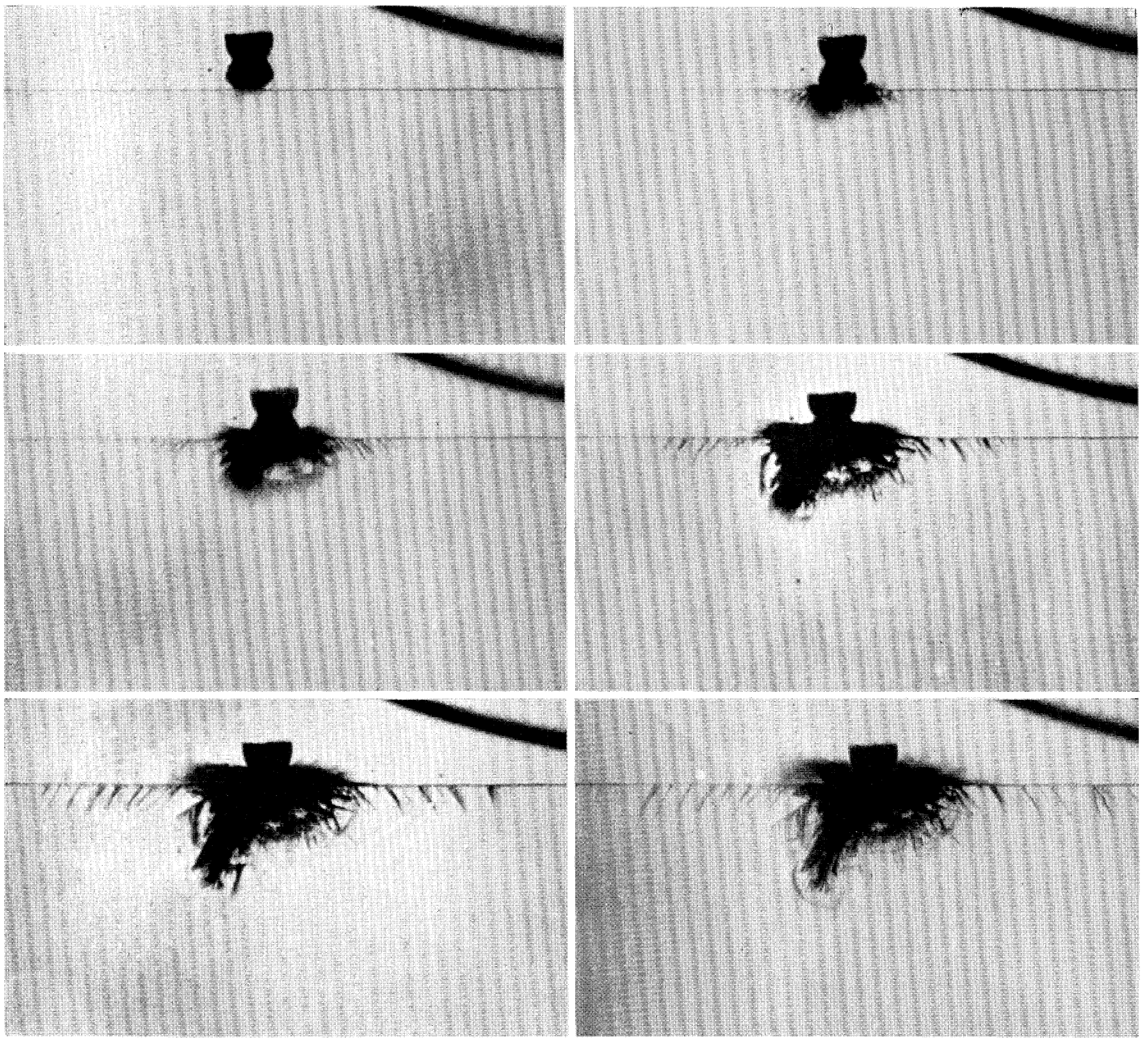

(i) (ii) (iii) (iv) (v) (vi)

FIGURE 3. The initiation of fractures along the top edge of a 3 in. × 3 in. × $\frac{1}{4}$ in. glass plate by the surface wave. Internal between frames 1·94 μs. (Magn. × 1·2.)

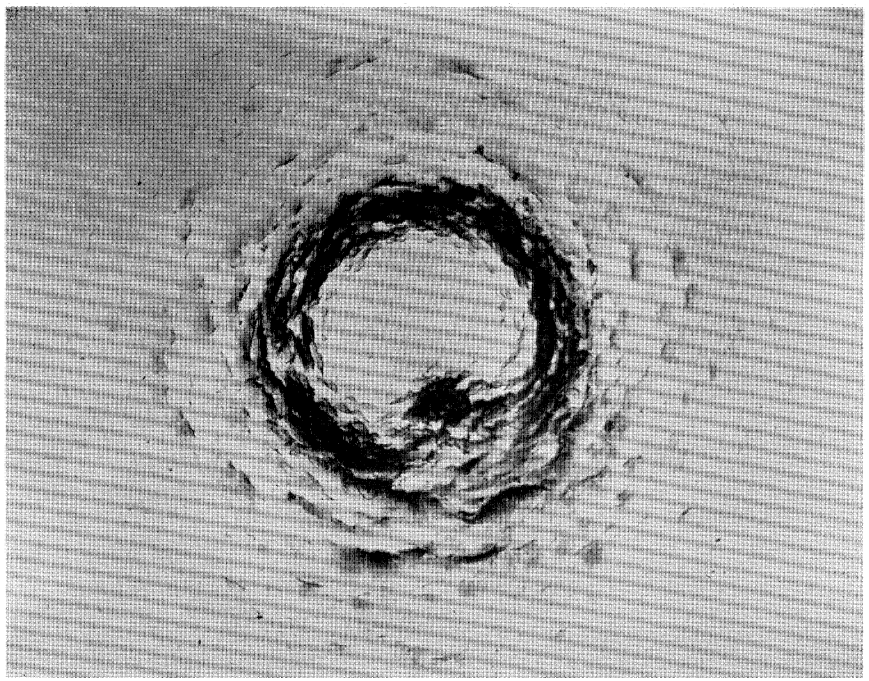

FIGURE 2

FIGURE 2. Fractures produced in plate glass by the impact of a 3 mm diameter liquid jet at 650 m/s impact velocity. (Magn. × 9·3.)

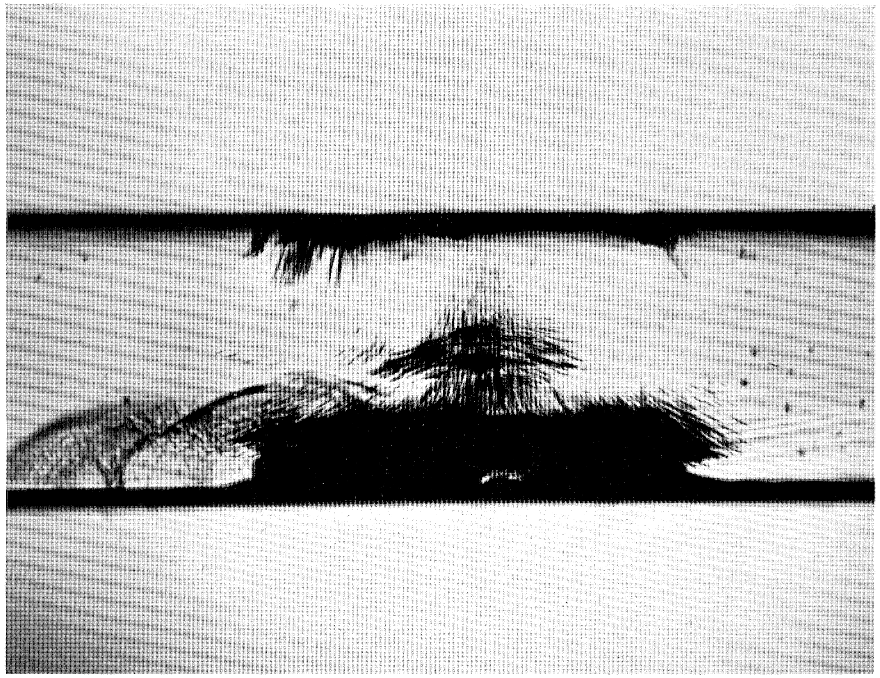

FIGURE 4

FIGURE 4. Cross section through a $\frac{1}{8}$ in. thick Perspex plate. The ring fracture can be seen on the upper surface and the more severe scabbing failure at the lower surface and in the body of the specimen. (Brunton.)

DESCRIPTION OF PLATE 8 (*facing*)

FIGURE 6. Fracture and erosion of a glass ceramic caused by the impact of a liquid jet at a velocity of 720 m/s. (Magn. × 19.)

FIGURE 7. The result of five impacts at a velocity of 720 m/s. The fractured region has been eroded away by the outward flow of liquid. The region subjected to compressive stresses during impact remains as an island of undamaged material. (Magn. × 16.)

FIGURE 8. Fractures produced on a 1 in. diameter block of sapphire by the impact of a liquid at 720 m/s. The top surface of the specimen was the (0001) plane. (Magn. × 12.)

FIGURE 9. Fractures produced on a 1 in. diameter cylindrical block of sapphire by the impact of a liquid at 720 m/s. The top surface of the specimen was the $(10\bar{1}0)$ plane. Preferential fracture occurs on the two $(10\bar{1}0)$ planes which intersect the loaded surface. (Magn. × 10.)

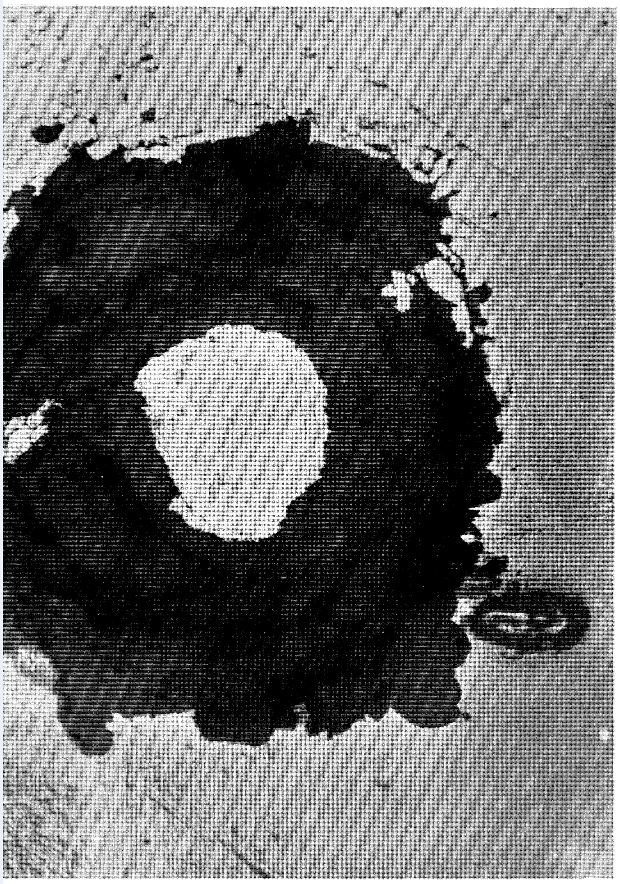

Figure 7

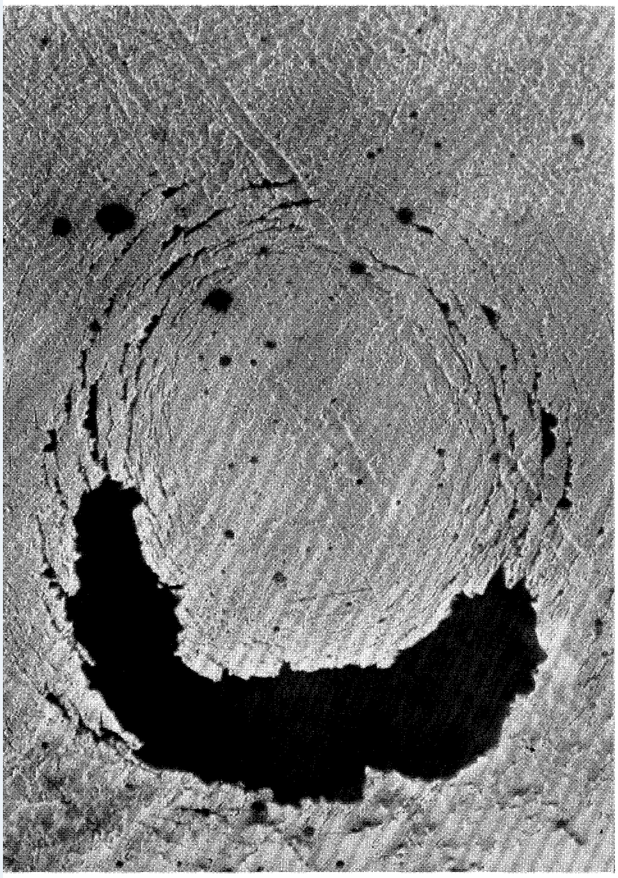

Figure 6

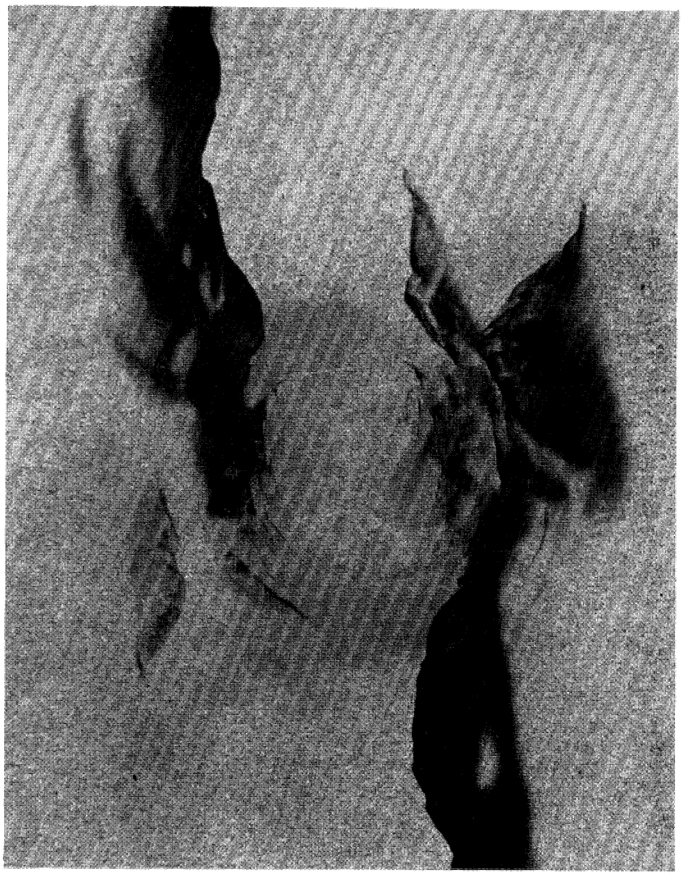

Figure 9

Figure 8

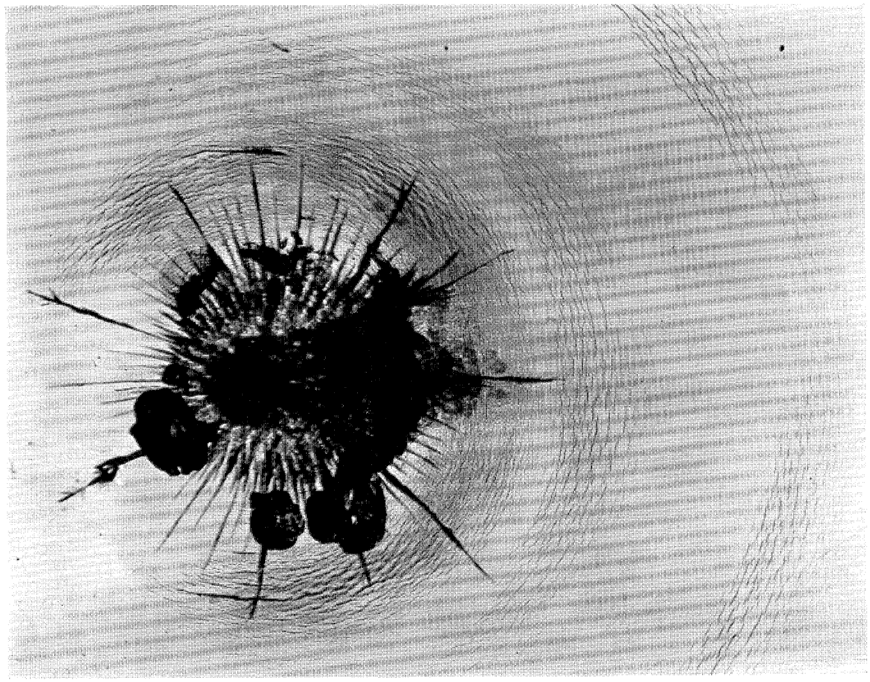

FIGURE 5. The fracture of a $\frac{3}{16}$ in. thick Perspex plate by the impact of a liquid at 720 m/s. Localized bands of fracture occur on the top surface. (Magn. ×7·5.)

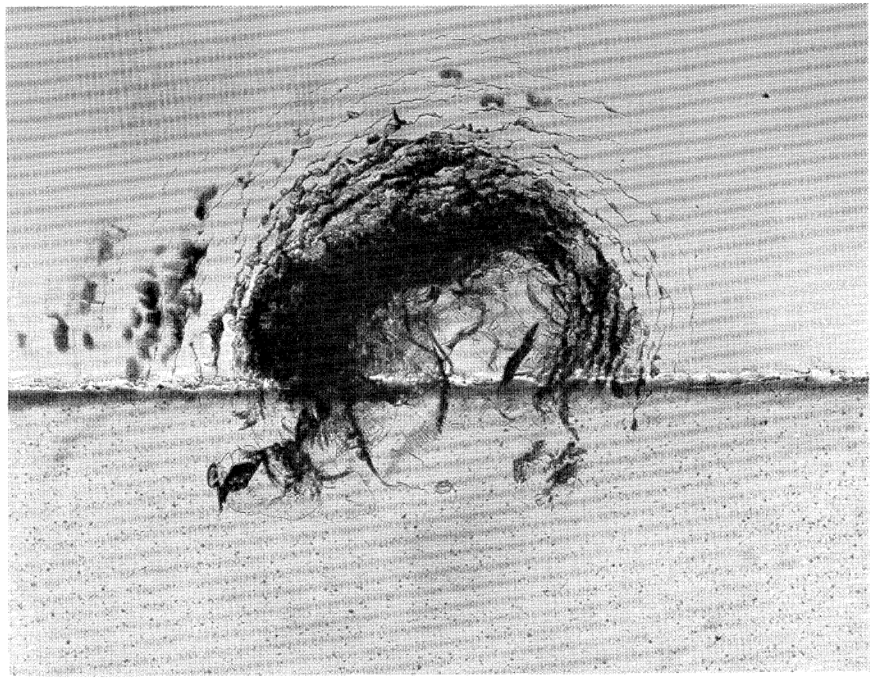

FIGURE 10. An increase in strength occurs when surface layers are removed. The lower half of this glass specimen was etched in a 10 % hydrofluoric acid with the removal of a layer of 8 μm before impact on the dividing line between the treated and untreated regions. (Magn. ×16.)

Fracture of thin plates

The interaction between the primary stress waves and stress components reflected from the boundaries of the solid becomes important for targets of finite size. Clearly there will be situations when these waves reinforce, and this reinforcement may cause failure of the solid. Each particular situation depends very much upon the geometry of the solid, but one general point emerges and that is that damage may occur at large distances from the loaded area.

When a liquid drop strikes a thin plate of brittle material at high velocity 'scabbing' (spalling) may occur at the rear surface. An example is illustrated in figure 4, plate 7, which shows in cross section the result of the impact of a high speed jet on a $\frac{1}{8}$ in. thick sheet of Perspex. Near the top surface can be seen the ring crack and subsurface damage. At the rear surface a large 'scab' of material has been detached, while above it a secondary scab is visible (in this example coincident with the subsurface damage). The conditions for scabbing arise when the dilatational compression pulse set up by the impact reflects at the rear surface forming a pulse of tension. A little way in from the rear surface the resultant stress becomes tensile and may build up sufficiently to cause failure of the material. Once the main scab has become detached the remainder of the pulse reflects at the new back surface and a secondary scab may form.

The fact that liquid impact can cause this form of failure is further confirmation of the intense 'explosive' nature of the stress pulse produced in such an impact. From the position of the scabbing fractures and a knowledge of the strength properties of the solid it is possible to estimate roughly the size and shape of the stress pulse involved.

If the front surface of a thin plate specimen is examined after impact it may show localized 'bands' of fracture surrounding the loaded area. An example of this form of fracture is shown in figure 5, plate 9, for a $\frac{3}{16}$ in. thick sheet of Perspex that was impacted at 720 m/s by a liquid jet. The unfocused central region is the back scabbing occurring at the far surface of the specimen. The radial fractures also started at the rear surface which accounts for the first part of their path length being out of focus. After the circumferential cracking adjacent to the loaded area, there are two fairly distinct 'bands' of fracture separated by undamaged material. Glass shows similar bands (paper II), but with different spacings. An additional point with glasses is that the second band is often more intense than the first. With high velocity impacts more than two bands may form. For a $\frac{1}{2}$ in. thick glass specimen impacted at a velocity of about 1200 m/s by a 3 mm diameter water jet the fracture bands have been observed out to a radius of about 1·5 in.

These bands of fracture on the top surface of specimens can be explained by considering the reinforcement of the Rayleigh wave propagating along the top surface with components of stress reflected at the rear surface. The first wave to return to the top surface is the reflected dilatational wave, and since this is now a wave of tension it reinforces the surface wave causing fracture at a radius y_1, given by

$$y_1 = \frac{2x}{\{(C_1/C_R)^2-1\}^{\frac{1}{2}}}, \tag{3}$$

where x is the thickness of the specimen and C_1 and C_R are the dilatational and Rayleigh wave velocities respectively. The observed band is of finite width because the load is applied over an area rather than at a point and the stress pulses themselves are of finite duration.

In calculating the position of further bands allowance has to be made for the fact that when a dilatational wave reflects at a boundary it produces not only a dilatational wave of opposite phase but also a distortional wave. Further, the relative intensities of these reflected waves depends partly upon the angles involved and partly upon the Poisson's ratio of the solid. A calculation of the possible reinforcement positions on the top surface and the energies involved for materials of different Poisson's ratio has been made in paper II, which shows that the position and intensity of the fracture bands found in practice is in good agreement with the predicted picture.

Ceramic materials

Ceramic materials of both the alumina and devitrified glass types have been found to exhibit a similar form of failure to that found in glasses and brittle plastics. The result of a single impact at a velocity of 720 m/s on a devitrified glass ceramic is shown in figure 6, plate 8. Many small circumferential cracks can be seen surrounding the loaded area. The high speed outward flow has also been important in eroding material from the outer edges of these cracks. On the one side of the damage mark a large amount of material has been eroded away from the cracked region. This was because the impacting jet was not perfectly symmetric in this case and the flow occurred preferentially in one direction.

If further impacts are made on the same area the cracking increases in severity, and the outward flow erodes more material. The result after five impacts when the eroded 'channel' is complete is shown in figure 7, plate 8. It is interesting to note that the material which was directly beneath the impacting jet, and which was subjected to large compression forces, still exists as an island of undamaged material.

In further experiments on this ceramic the jet was fired at the same impact velocity of 720 m/s, but at different angles to the surface. As the angle α to the normal increased the pattern of damage became unsymmetric, although up to about α equal to 20° the total amount of damage remained essentially the same. This is not too surprising when it is remembered that the deformation is caused partly by the impact stresses and partly by the high speed outward flow of liquid. As the angle varies the component of impact pressure normal to the surface falls off as the cosine of the angle. However, when the drop impacts at an angle the flow of liquid is increased in the direction of impact, there may also be a further increase in velocity as a result of jetting if the geometry is suitable; considerable local failure will then occur so that the 'total' amount of damage remains high.

With thin plates of ceramic scabbing was frequently the main form of damage. Repeated impact on a thin plate lead eventually to complete penetration of the plate as the material was eroded from the front surface and scabbed from the rear. Scabbing was greatly reduced in severity when the specimen was impacted at an angle; this was because the path length of the dilatational wave was effectively increased. A small but definite improvement was also found when ceramics with greater acoustic attenuations were used.

Crystalline solids

If definite cleavage planes are present in the impacted solid the fracture pattern is modified. An example is given in paper I of a diamond loaded on a (111) surface; the ring crack was replaced by a hexagonal pattern made up of cleavage cracks on other {111} planes. In figure 8, plate 8, the impact mark produced on a single crystal sapphire specimen is shown. The specimen was in the form of a 1 in. diameter cylindrical block with its top surface the basal plane (0001). Although sapphire is not usually regarded as having a well defined cleavage plane there is clear indication in this figure of hexagonal symmetry. The planes exhibiting preferential fracture are the $\{10\bar{1}0\}$. The outer circumferential cracks are in general longer than those nearer the loaded area; this is because the dilatational wave caused by the impact has reflected from the sides of the specimen forming a tension which has enlarged the outer cracks as it passed back over them. In this example the reflected wave was not by itself sufficient to cause scabbing fractures near the edges of the specimen. Figure 9, plate 8, shows the result of an impact on another 1 in. diameter cylindrical block, but this time with a $(10\bar{1}0)$ plane as the top surface. In this orientation of the sapphire only two of the other $\{10\bar{1}0\}$ planes intersect the top surface; both of these are horizontal in the figure as shown. It is clear that most of the fracture energy has gone into opening up these planes. The fractures that do form are intense because of the limited number of possible fracture planes and the fact that the weak planes which are present are here inclined to receive a large component of the main tensile stress.

Removal of surface defects

Glasses, unlike most other solids, have their major defects located almost entirely at the surface. This means that glasses are very susceptible to surface treatments. If, for example, the surface layers are removed by etching with hydrofluoric acid the strength of the material increases. This is illustrated in figure 10, plate 9, which shows the effect of etching the lower half of the specimen (in an agitated 10% solution of hydrofluoric acid for 4 min) before impact at 720 m/s on the dividing line between the regions. The advantage of this method is that comparison of the two halves of the specimen, which were equally stressed, indicates the degree of strengthening since the number of short stress wave cracks is a measure of the flaws present. It is clear that only a small number of cracks occur in the etched region of the specimen in figure 10, and that most of these can be traced to origins in the untreated part. The tensile strength of the treated glass was estimated from the impact velocity and separate indentation experiments to be in excess of $3{\cdot}5 \times 10^9$ dyn/cm^2 (approximately 50000 Lb./in.^{2}), while that of the untreated glass was about $5{\cdot}5 \times 10^8$ dyn/cm^2 (8000 Lb./in.^{2}). The thickness of layer removed in this example was 8 μm. Similar experiments have been performed on series of other specimens varying the impact velocity (i.e. the applied stresses) and the amount of etching before impact. This has given results on the improvement in strength of glasses in terms of thickness of surface layer removed.

The very marked improvement in strength caused by a surface treatment shows the importance of defects located at the surface. The weakening by defects is usually attributed to the presence of microcracks which act as stress raisers (Griffith 1920). These microcracks are too small to be directly visible but it has been suggested by Hillig (1962) that the etch pits produced by hydrofluoric treatment grow from Griffith-type flaws. (Microcracks have also been investigated by 'decoration' techniques using either sodium or lithium vapour (Andrade & Tsien 1937; Gordon, Marsh & Parratt 1958; Argon 1959; Ernsberger 1960).) The dotted appearance in the acid treated area of figure 10 is due to the presence of small etch pits. As etching progresses these pits develop in size but do not grow in numbers, thus supporting the idea that the pits are located at defects. This view is further supported by the results of impact experiments on very lightly etched glass specimens for it was found that the stress-wave fractures were always located at the same point as an etch pit (paper II).

Inglis (1913) has treated the case of a crack of length l and tip radius a in an elastic solid and found that the stress concentration is given by the formula

$$S/S_1 = 1+2\sqrt{(l/a)}, \tag{4}$$

where S_1 is the applied stress and S is the concentrated stress at the crack tip. Clearly if cracks do exist on glass the acid treatment can reduce the stress concentration either by decreasing the crack length, or by rounding off the crack tip and increasing a. Both Proctor (1962) and Hillig (1962) have considered various simple models for the etching of cracks. One model assumes that the acid does not penetrate the crack but only removes the surface, thus shortening the crack, while a second assumes that the acid can penetrate the crack and etch equally in all directions. An important consequence if this second case is that the depth of an etch pit remains equal throughout to its initial flaw depth, while its radius increases parabolically (Wilkinson & Proctor 1962).

The results of the present experiments confirm those of Proctor (1962) in showing that the first model is unsuitable. However, a much better agreement is found with the model which allows acid to enter the flaw (paper II).

It is important to note that the etching process needs to be controlled carefully, otherwise it will eventually weaken the surface. The reason for this is that on some glasses insoluble reaction products form on the surface and this can quickly lead to preferential etching. This can be largely avoided if weak, well agitated, solutions of hydrofluoric acid are used with a little sulphuric acid added to help dissolve any products which start forming on the surface.

Conclusion

The impact of a liquid mass at high speed has been shown to produce a short sharp pulse, comparable in many respects to that produced by the detonation of a small explosive charge against a surface. This behaviour, it is suggested, is a direct consequence of the inability of the liquid to flow in the early stages of the impact, thus giving rise to compressible behaviour. This result has important practical applications to aircraft passing through rain and to the erosion of turbine blades moving at high velocity through wet steam.

The fracture behaviour of glass when loaded by an intense pulse of short duration is very different from that at lower rates of loading; this is readily apparent when the circumferential fractures described above are compared with the long radial fractures that are commonly seen in, for example, fractured window glass. With a solid impact the stress to produce fracture occurs at a much lower impact velocity than with a liquid and the rise time of the stress is correspondingly greater. This combined with a longer duration (of impact of the order of 100 μs compared to the 1 to 2 μs of high speed liquid impact) explains the difference in fracture behaviour. The fracture pattern for a solid impact of moderate velocity resembles more closely that produced by static loading, and the fracture energy is dissipated in forming a ring crack and in developing a relatively small number of radial cracks. The circumferential fracture found with high speed liquid impact and explosive loading it is suggested are the result of the interaction of the Rayleigh stress wave with flaws. Since the circumferential fractures are short and discrete the fracture pattern on one specimen gives essentially the result of many tensile experiments.

When a liquid strikes a thin plate of brittle solid at a high velocity 'scabbing' may occur at the rear surface. In terms of weight loss this is often the most serious form of damage. If the front surface of a thin plate specimen is examined localized bands of fracture are found; they are explained by considering the interaction of reflected stress waves from the rear surface with the Rayleigh wave at the front surface. The attenuation coefficient is an important factor in determining the extent of the fracture damage in thin plates.

In crystallographic solids the pattern and extent of fracture depends on the available cleavage planes. For these materials, therefore, the amount of damage can be minimized by careful choice of orientation.

By combining the impact method with etching experiments it is possible to investigate both the etching process and also measure the depth of flaws on the surface of glasses. It was found that the removal of thicknesses of only a few microns increased the strength many fold. The improvement of strength with thickness removed is consistent with the idea of submicroscopic flaws on the surface, and with the acid entering the flaw during etching.

I thank Professor F. P. Bowden, F.R.S., and Dr J. H. Brunton for helpful discussions, Du Pont de Nemours Company for a grant to the laboratory, and Owen-Illinois Glass Co. (U.S.A.) for a research fellowship.

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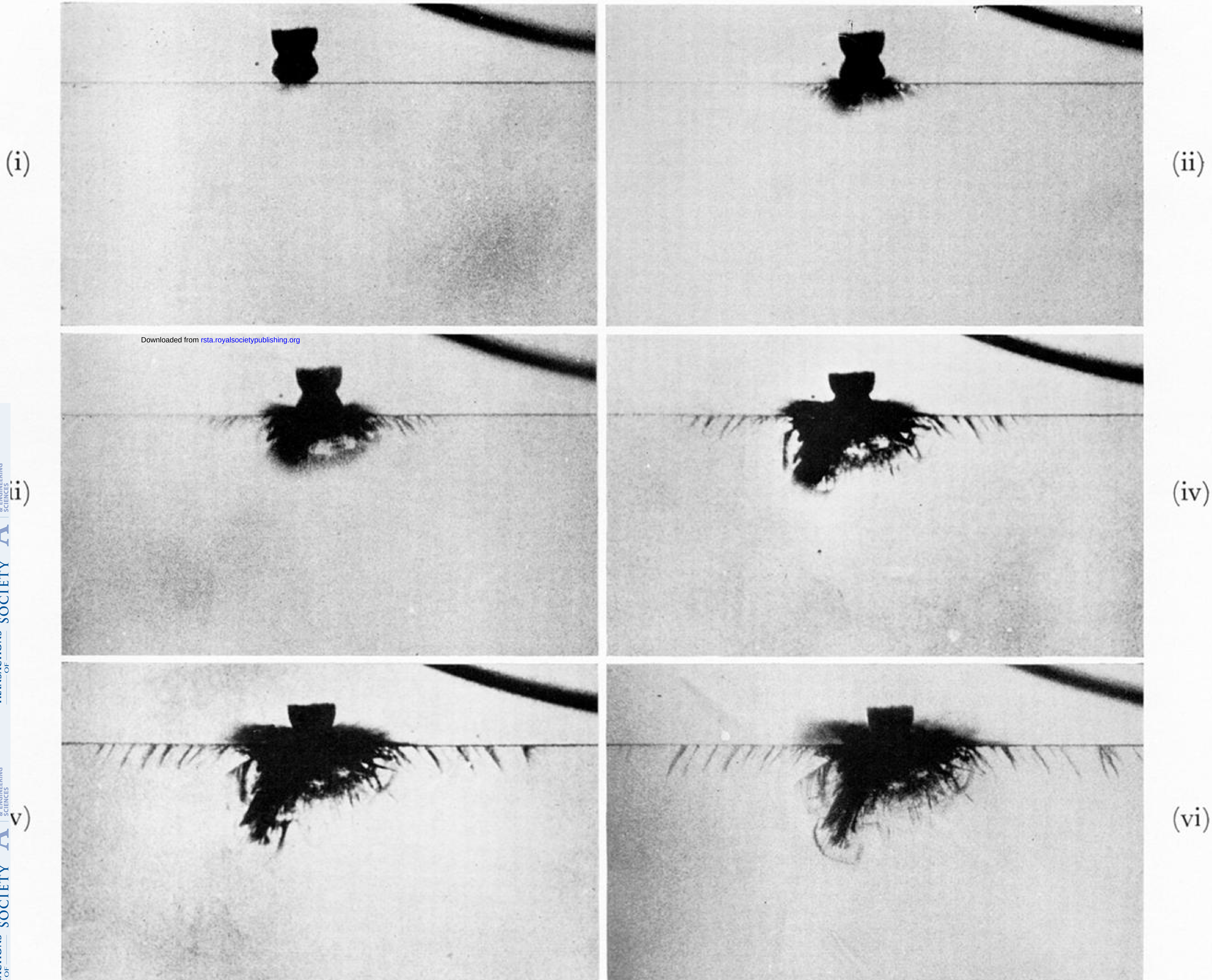

Figure 3. The initiation of fractures along the top edge of a 3 in. × 3 in. × $\frac{1}{4}$ in. glass plate by the surface wave. Internal between frames 1·94 μs. (Magn. × 1·2.)

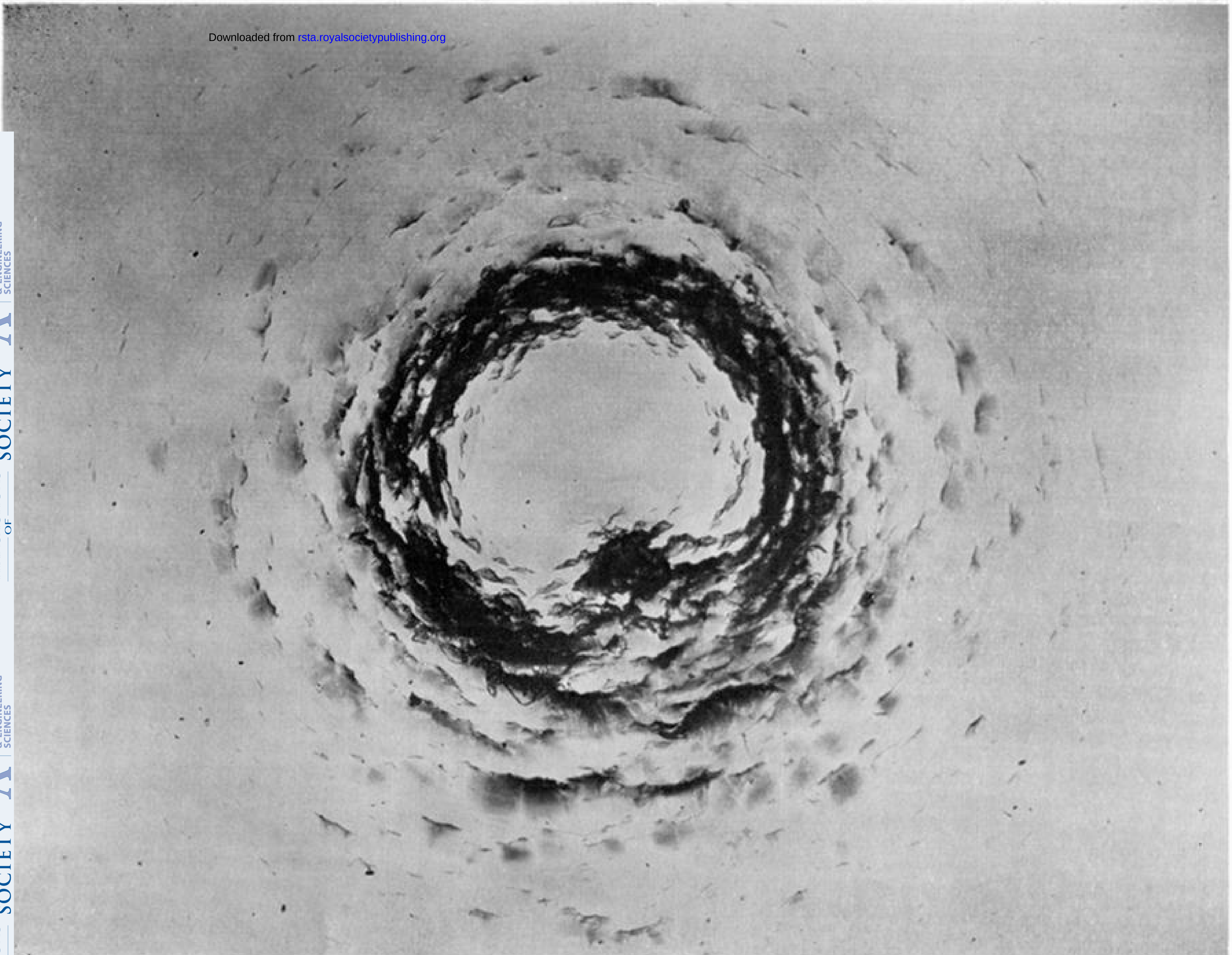

FIGURE 2

IGURE 2. Fractures produced in plate glass by the impact of a 3 mm diameter liquid jet at 650 m/s impact velocity. (Magn. $\times 9{\cdot}3$.)

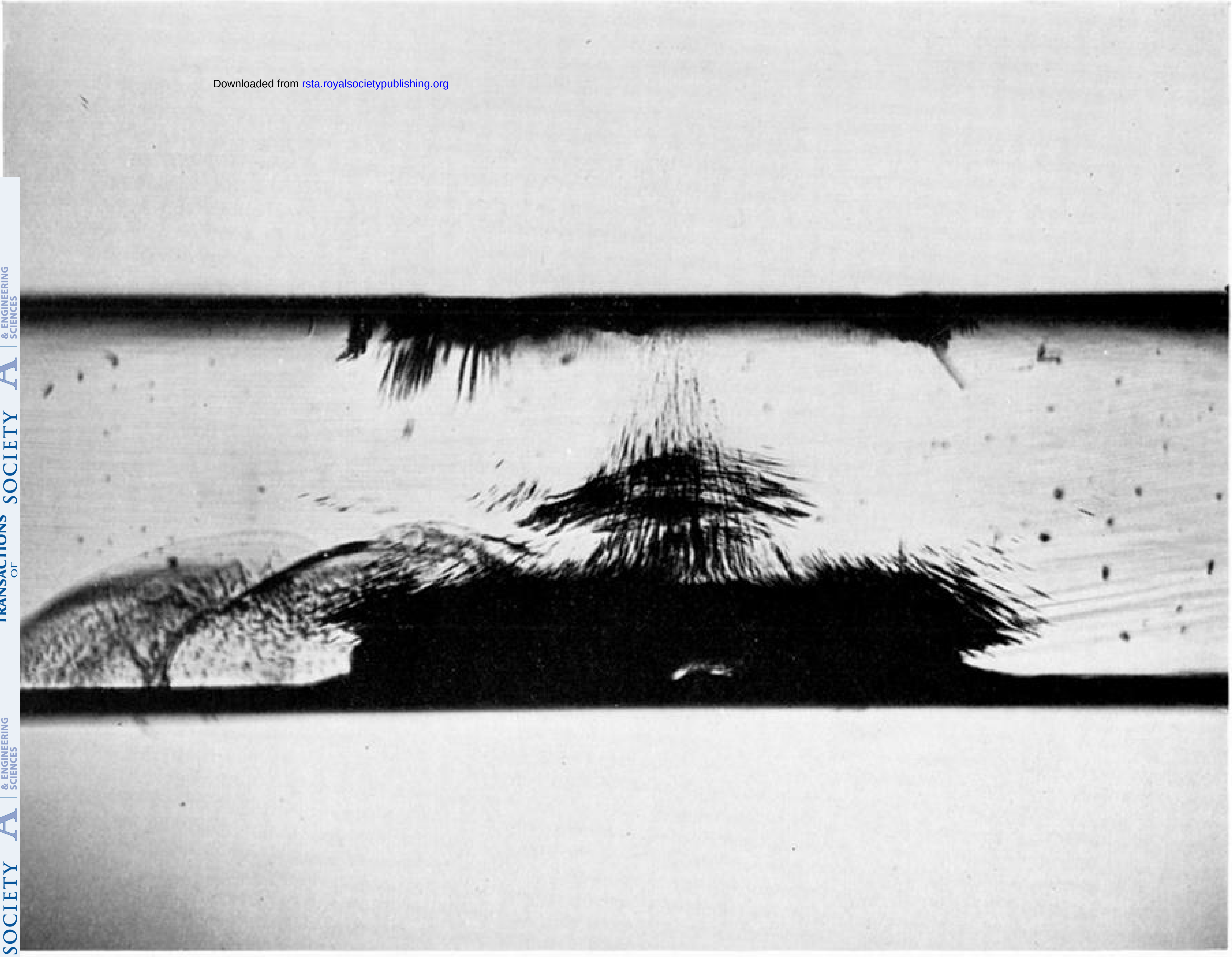

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FIGURE 4

FIGURE 4. Cross section through a $\frac{1}{8}$ in. thick Perspex plate. The ring fracture can be seen on the upper surface and the more severe scabbing failure at the lower surface and in the body of the specimen. (Brunton.)

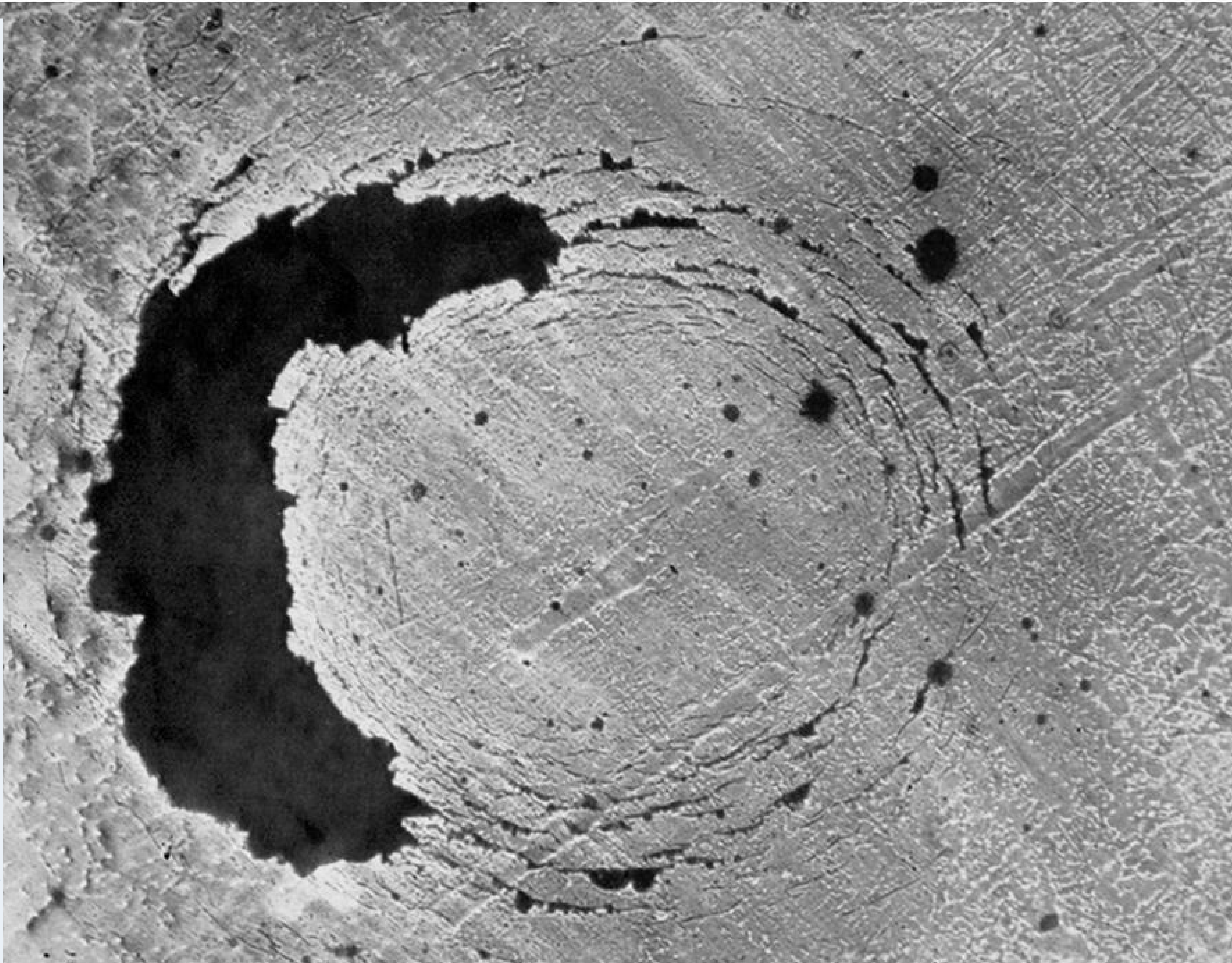


FIGURE 6

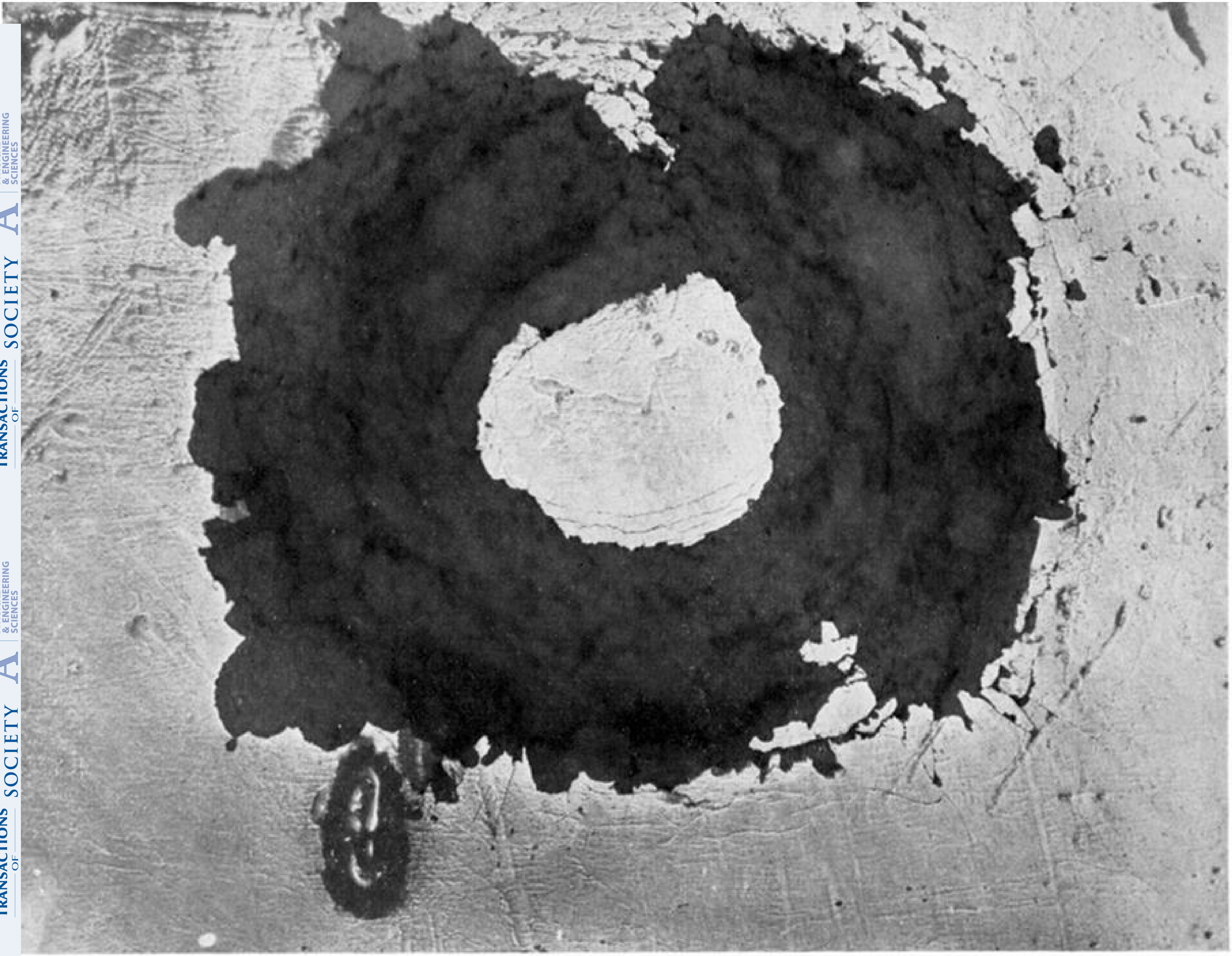


FIGURE 7

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

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

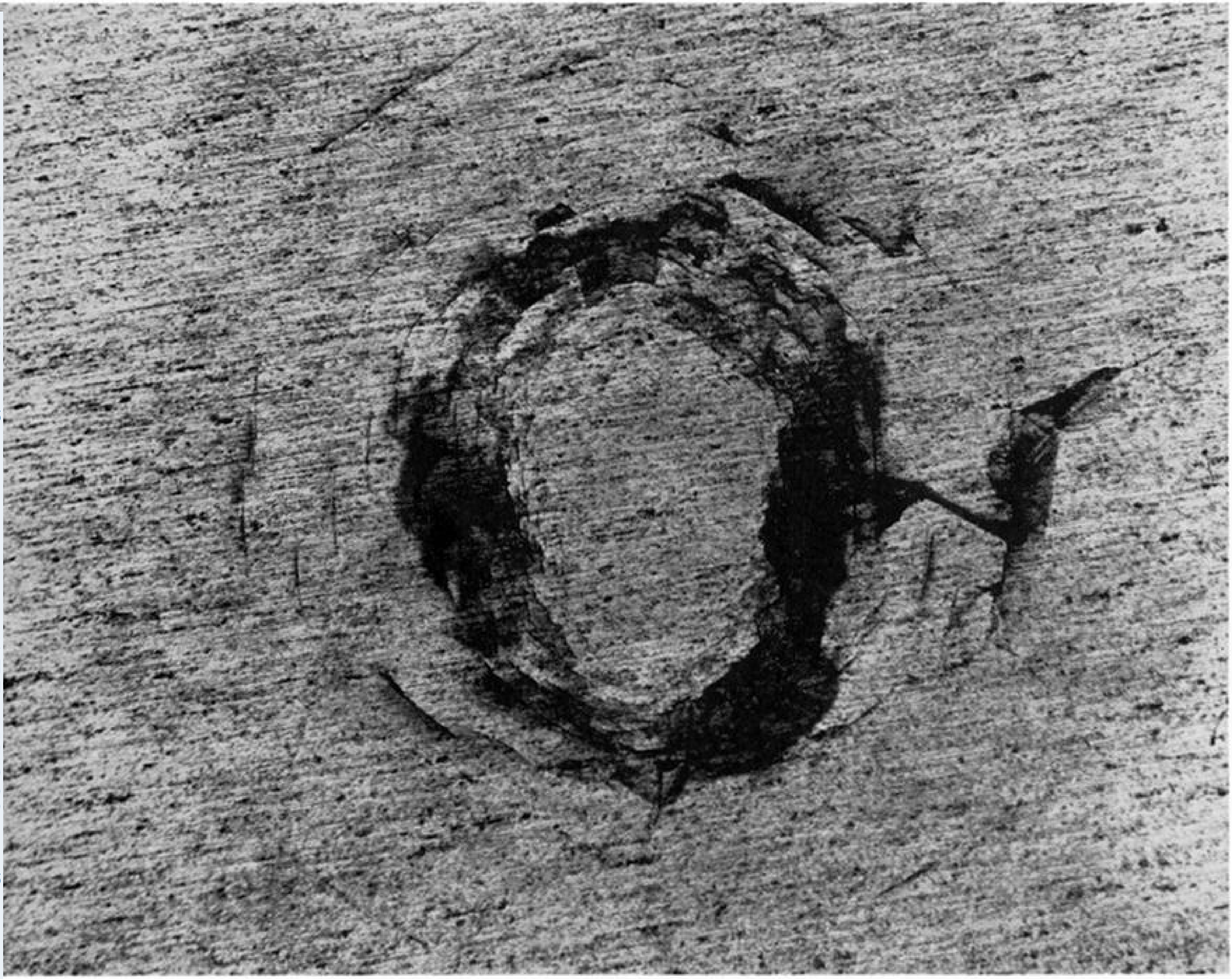


FIGURE 8

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

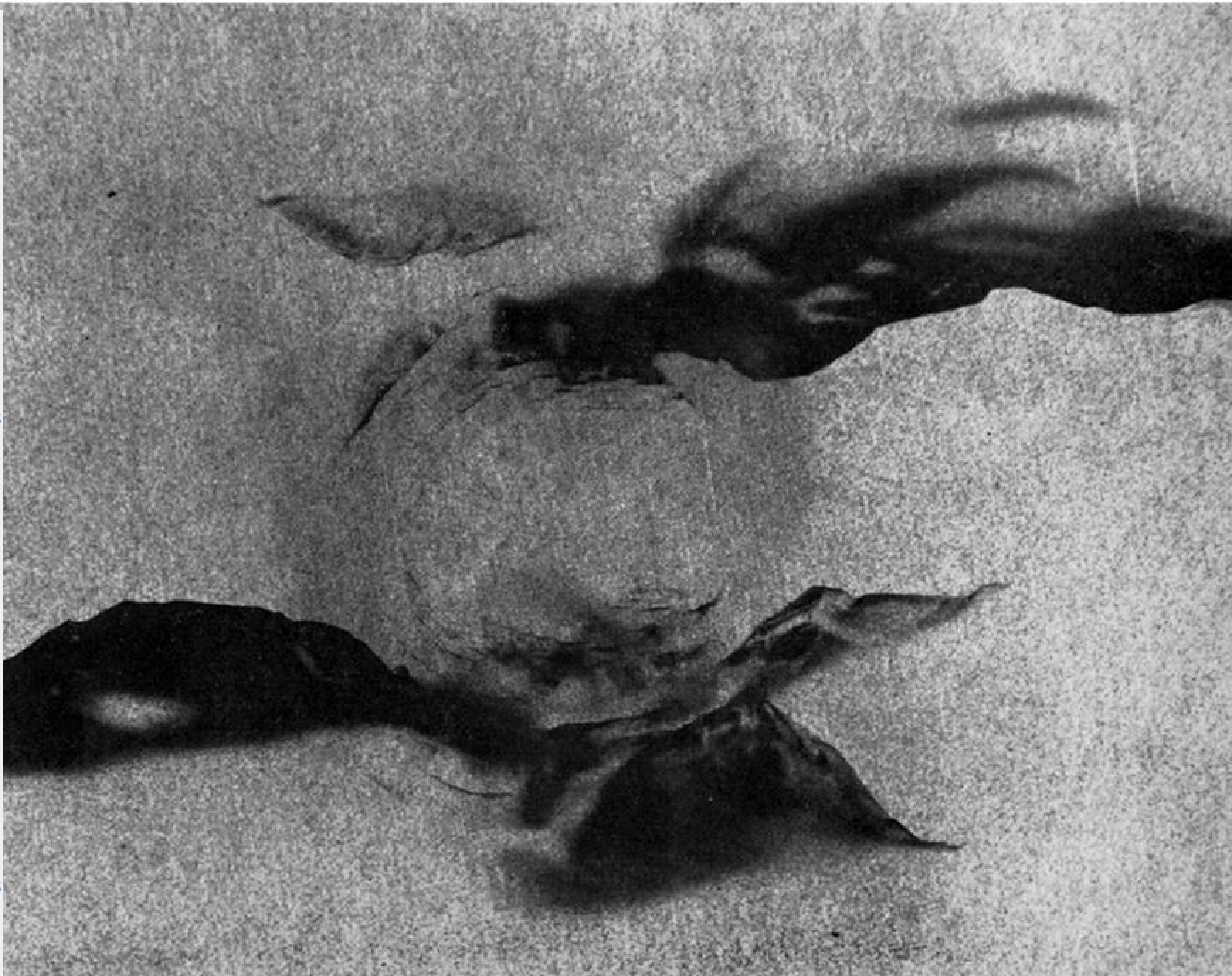
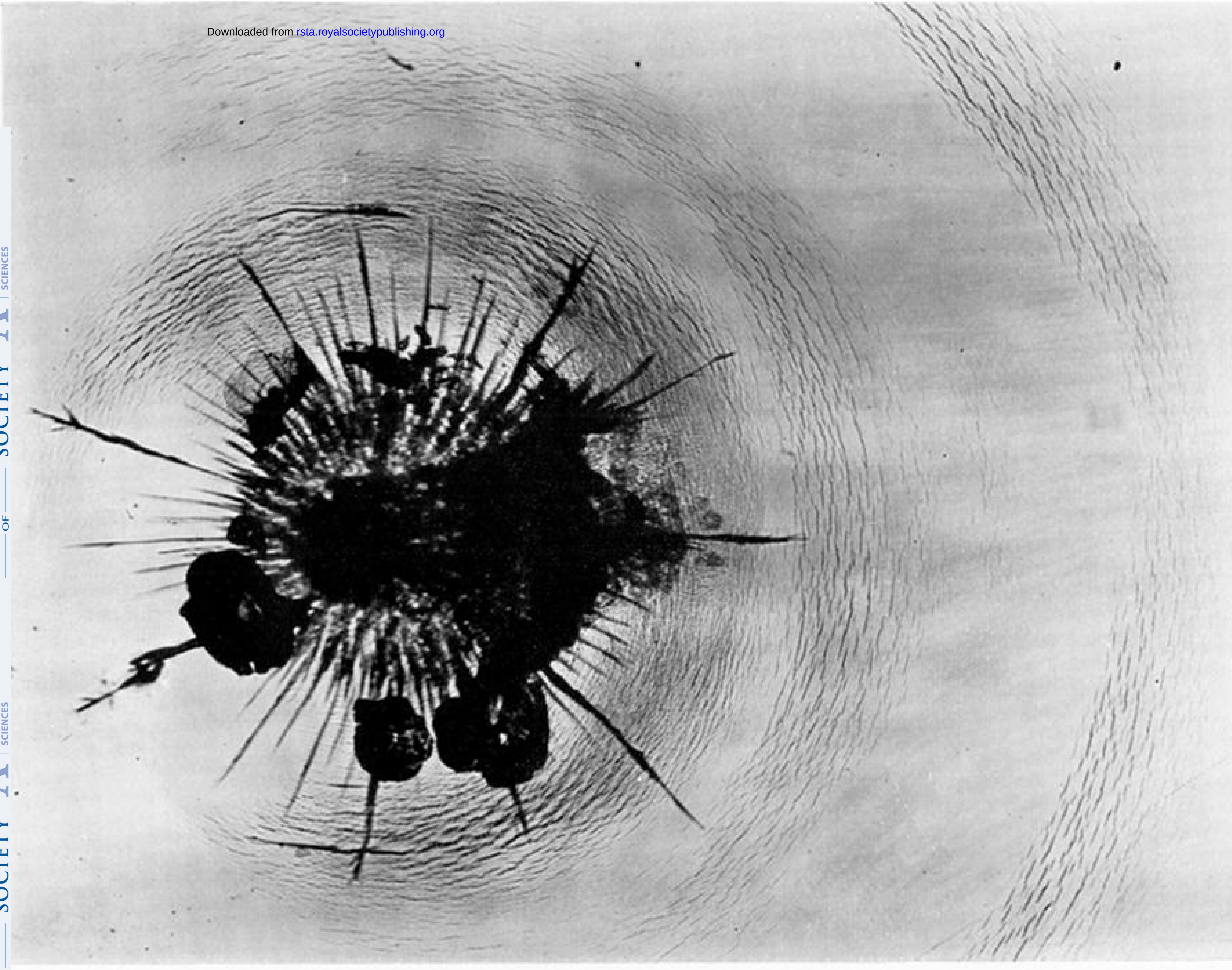


FIGURE 9



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

FIGURE 5. The fracture of a $\frac{3}{16}$ in. thick Perspex plate by the impact of a liquid at 720 m/s. Localized bands of fracture occur on the top surface. (Magn. × 7·5.)

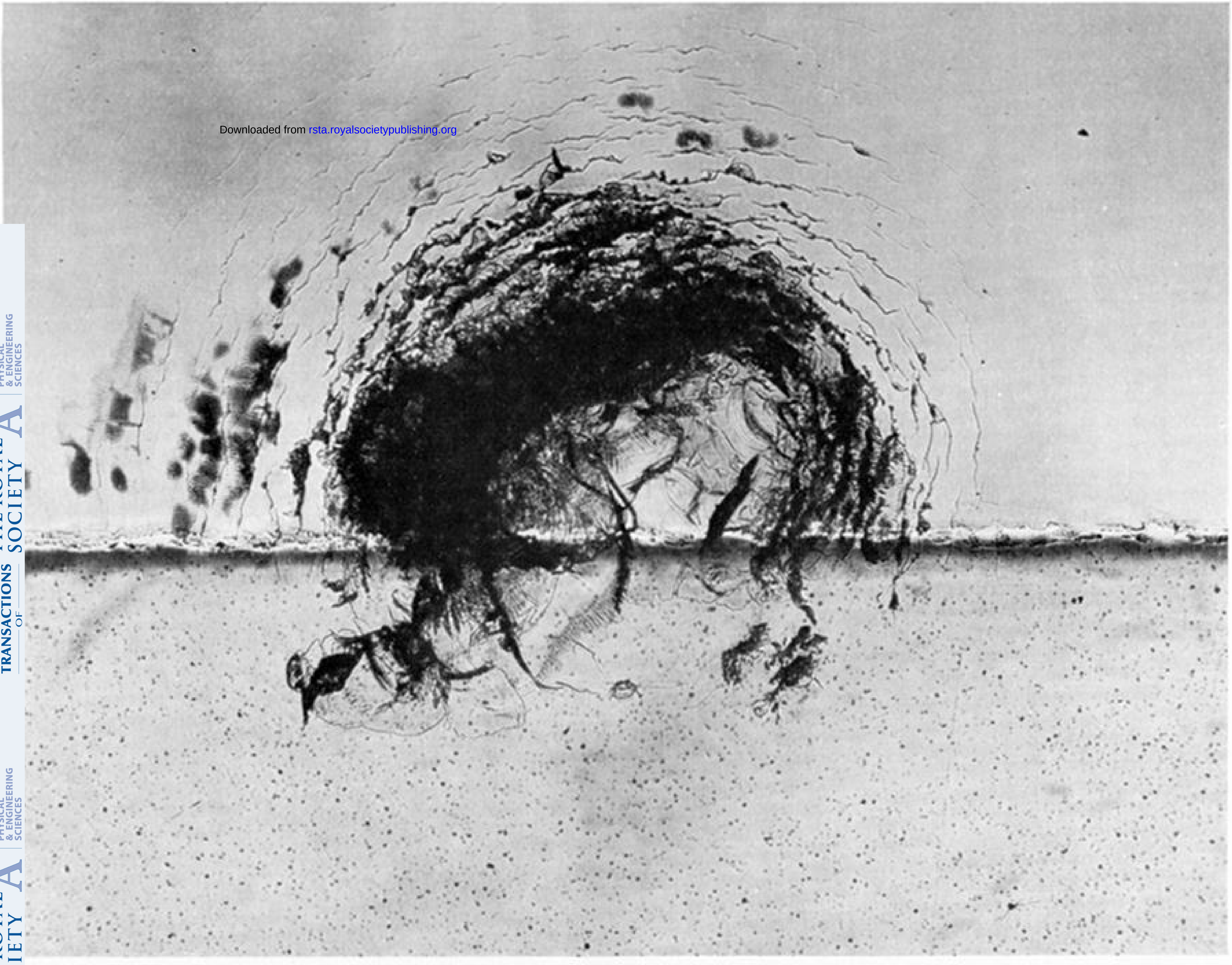


FIGURE 10. An increase in strength occurs when surface layers are removed. The lower half of this glass specimen was etched in a 10 % hydrofluoric acid with the removal of a layer of 8 μm before impact on the dividing line between the treated and untreated regions. (Magn. × 16.)

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