The Application of Dislocation Etching Techniques to the Study of Liquid Impacts [and Discussion]

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V. The application of dislocation etching techniques to the study of liquid impacts

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[Plates 13 and 14]

Erosion damage is very often the cumulative result of a series of liquid droplet impacts which individually do not produce any deformation visible under the optical microscope. Such collisions do, however, produce dislocations in the crystalline structure surrounding the area of impact, and in suitable materials these dislocations can be revealed by chemical etch pitting.

The technique is particularly easy to apply to freshly cleaved lithium fluoride crystals, and it has been used to study several types of impact. The impact of solid balls produces symmetrical rosettes of dislocations lying on {110} planes, and the dimensions of the rosettes can be related to the area of contact and stress distribution calculated from the theory of the collision of elastic/plastic bodies. Similar, but less symmetrical, rosettes are produced by liquid impacts and, by comparison of the extent and distribution of the dislocation loops in the two cases, it has been possible to make an estimate of the pressure and effective area of contact for liquid drops of various sizes, quantities which are otherwise difficult to measure. The behaviour of liquids other than water has also been investigated.

1. Introduction

When considering the problem of the pressure developed by a liquid impacting on a solid surface, it is necessary to take into account the compressibility of the liquid. It has been shown by Ackeret (1932) that for a cylindrical liquid jet moving with a velocity V the pressure is given by the expression

$$p = \rho_l C_l V\left(1+\frac{\rho_l C_l}{\rho_s C_s}\right)^{-1}, \qquad (1)$$

where ρ is the density of the material and C the corresponding velocity of elastic compressive waves, the subscripts l and s referring respectively to the liquid and the solid. For most metals the value of $\rho_s C_s$ is an order of magnitude greater than $\rho_l C_l$ for water, so that to a sufficient approximation

$$p = \rho_l C_l V, \qquad (2)$$

the so-called 'water-hammer' pressure. Although it has been suggested by Engel (1955) that this equation can be applied to the impact of a spherical drop by the inclusion of a factor α which does not differ greatly from 0·5, it seems probable that the shape of the liquid surface will have a much more profound effect on the extent and duration of the pressure pulse.

For typical impact velocities encountered in modern steam turbines (up to 600 m/s) Ackeret's formula gives maximum pressures which are of the same order of magnitude as the tensile strengths of the constructional materials. Nevertheless, a large number of impacts are needed to produce appreciable loss of material and it seems probable that the damage is the cumulative effect of a succession of small increments of lattice damage, taking the form of the nucleation and expansion of dislocation loops, which later interact to form cracks and eventually lead to a fatigue type of failure. The observation of the internal structural damage produced by individual impacts is rendered difficult by the fact that it is confined to a small volume of the same order of magnitude as the droplet size, which in the low pressure stage of a steam turbine is typically much less than 1 mm in diameter. It has, however, proved possible to detect these small amounts of damage by employing an etch pitting technique, as described in detail by Newkirk & Wernick (1962). This technique is based on the observation that for many materials chemical etchants can be found which will selectively attack points on the close packed crystal planes where the structure is imperfect, forming large pyramidal pits. By choosing a material which has a low background density of dislocations, it is possible to detect the additional damage produced by droplet impacts, and hence gain some information about the stresses involved.

2. Calibration of crystals

For the present studies lithium fluoride offered a number of advantages as a target material. It is readily available in the form of single crystals of a high degree of purity, which can easily be cleaved to a suitable size, and it has a convenient value of yield stress and a small plastic strain range. The main disadvantage is that it is slightly soluble in water. Suitable polishing and etching solutions for the {100} (cleavage) planes have been described by Gilman & Johnston (1956).

The material used in these experiments was obtained from air-grown X-ray quality crystals, which were annealed for 16 h at 800 °C before use. The initial dislocation density varied between 10^4 and 10^6 cm^{-2}, apart from those dislocations which were arranged in low angle subboundaries, and it was thought necessary to determine the stress sensitivity for each melt. This was done by means of standard ball and diamond hardness indentations. After etching, the hardness impressions are found to be surrounded by very characteristic rosettes of etch pits, and the sizes of these dislocation rosettes are a measure of the hardness of the crystal (Whapham 1958; Vaughan & Davisson 1958). Since the diameters of the rosettes are several times larger than the permanent impressions, and the etch pit contrast can be made much higher, it is possible to extend the calibration procedure to much lower loads than are normally encountered in conventional hardness tests. In the present instance loads as small as 2 g were used with both ball and diamond indenters, and the consistency of the calibration is shown in figure 1. The size of the rosettes has been taken as the mean overall length of the arms lying parallel to the cube edges (or ⟨100⟩ directions) of the crystal (see figure 3, plate 13).

3. Distribution of dislocations within the rosettes

In spite of the occurrence of small amounts of plastic deformation, the distribution of dislocation loops can be accounted for by consideration of the elastic stress field for a ball in contact with a plane, as first set out in the classic work of Hertz (1881). He assumed a normal stress distribution of the parabolic form

$$p = p_{\text{max.}}\left[1-\frac{x^2+y^2}{r^2}\right]^{\frac{1}{2}}, \tag{3}$$

with the maximum stress $p_{\text{max.}}$ occurring at the centre of the circle of contact of radius r.

By employing suitable mathematical techniques the Hertzian elastic stress/strain relations can be integrated to obtain the internal stress field (Morton & Close 1922; Davies 1949). As a consequence of the axial symmetry of the problem both the Tresca and von Mises yield criteria lead to the conclusion that yielding should be initiated at a point within the body, at a small distance below the centre of contact. The present experimental results confirm the prediction (Sneddon 1948) that in feebly work-hardening material the occurrence of appreciable local plastic deformation does not distort the long-range elastic stress distribution. When the region of plastic flow covers the whole area of contact the surface stress can be found from plastic strain field theory, by integrating along the contours of maximum shear stress, and Ishlinsky (1944) has shown that in the case of a spherical indenter this leads to a mean stress $\bar{p} = 2{\cdot}66Y$, where Y is the uniaxial yield stress.

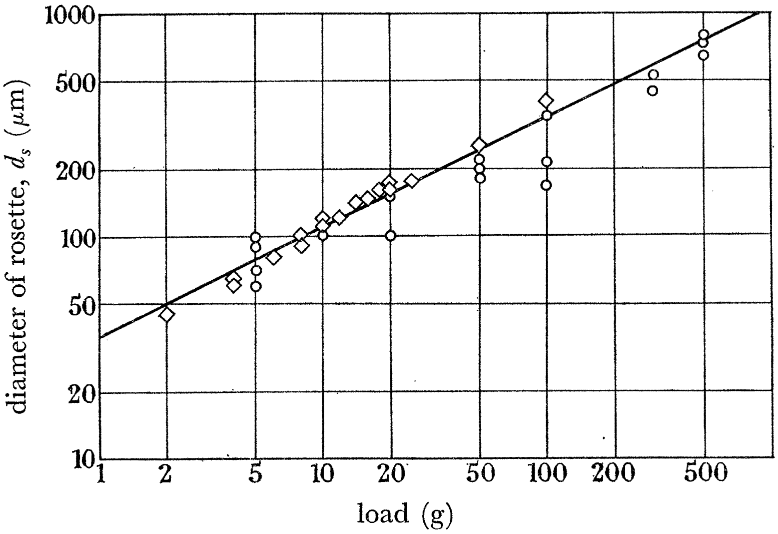

FIGURE 1. Calibration curve: rosette diameter as a function of static load. ◇, Diamond; ○, ball indenter.

If the semi-infinite plane represents the cleavage face of a lithium fluoride crystal, we have the further restriction that, because of the ionic structure of the crystal, the dislocation loops contributing to the deformation must have their Burgers vectors in a ⟨110⟩ direction, and can only move within {110} planes. The positions of the maximum shear stress components on these planes, in relation to the circle of contact, are shown in the form of contour lines in figure 2. One would expect the planes passing through the areas of maximum shear stress, represented by the groups of parallel lines in figure 2, to have the highest density of dislocation loops, and this is confirmed by comparison with a typical dislocation rosette, as shown in figure 3, plate 13.

From consideration of the geometry of the system it can be seen that the rosette arms lying parallel to the cube edges (in the ⟨100⟩ directions), and shown as continuous lines in figure 2, correspond to dislocation loops lying on the {110} planes inclined at 45° to the surface, hereinafter denoted by the symbol $\{110\}_{45}$. The segments of these loops which intersect the surface are screw components, and they define sections of the crystal which are being pushed downwards and outwards by the compressive stresses under the area of contact. In a similar manner the oblique arms of the rosette, which lie parallel to the surface $\langle 110\rangle$ directions, and are represented by dashed lines in figure 2, are traces of edge dislocations moving on $\{110\}$ planes which are perpendicular to the surface (denoted by $\{110\}_{90}$), and which correspond to sections of crystal being displaced radially outward by the surface stress components. The longest arms pass through the edge of the area of permanent deformation, and thus provide a convenient measure of the area of contact.

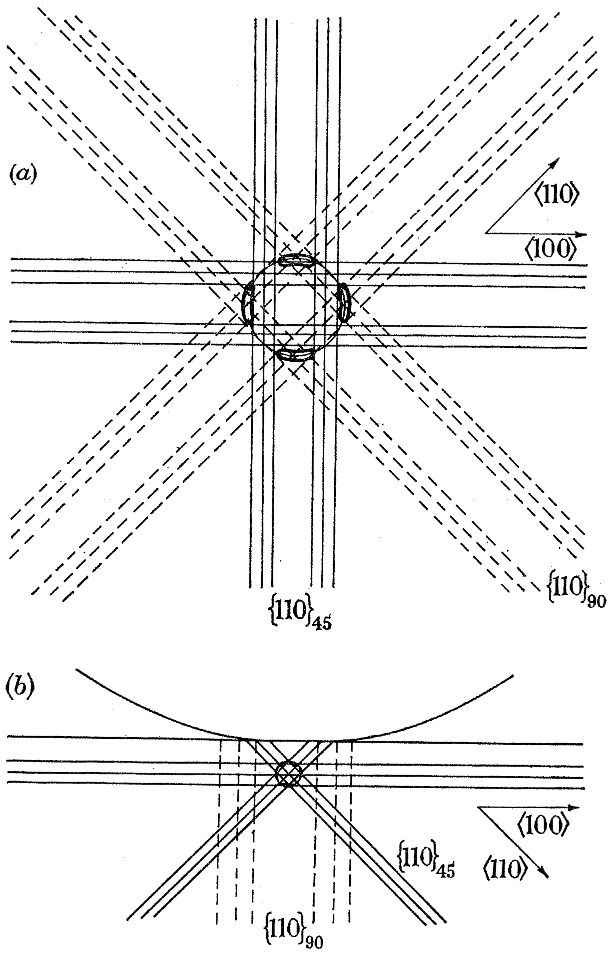

FIGURE 2. (*a*) Surface slip line traces passing through the circle of contact. (*b*) Vertical section through centre of circle of contact, showing position of stress maximum below surface.

4. SOLID BALL IMPACTS

The validity of using a static calibration procedure for the measurement of dynamic stresses has been established by demonstrating that acceptable values are obtained for the stresses involved in the impact of solid balls at moderate speeds.

A number of steel and bronze balls were allowed to fall on to freshly cleaved lithium fluoride crystals, and after the standard etching treatment had been applied the corresponding dislocation rosettes (figure 4, plate 13) were identified, and the appropriate measurements carried out. If the rosettes were asymmetrical or otherwise malformed, the length of the longest arm was recorded, so that the calculated stresses should be regarded as maximum values.

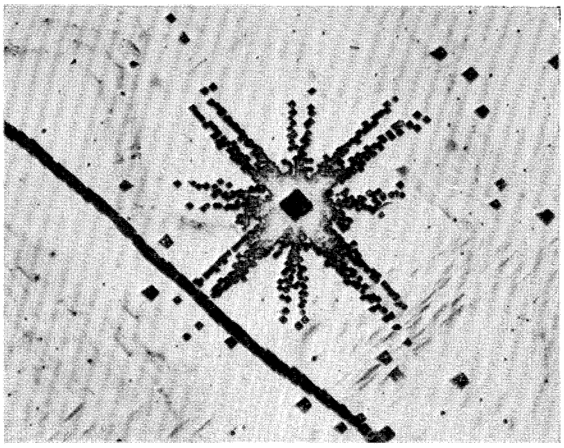

FIGURE 3. Dislocation rosette surrounding diamond impression. Load = 16 g. (Magn. × 200.) Crystal orientation corresponds with figure 2(*a*).

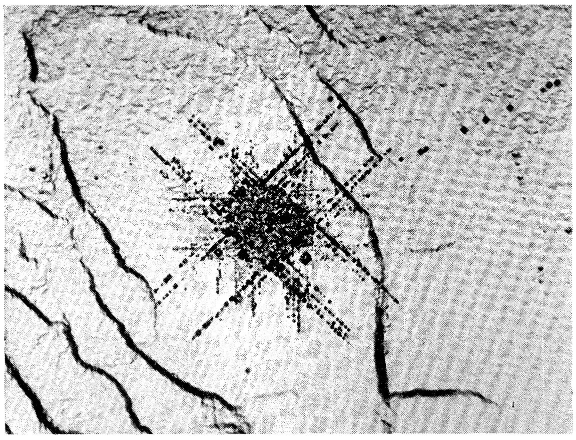

FIGURE 4. Rosette produced by the impact of a 1 mm steel ball. Velocity, 165 cm/s. (Magn. × 200.)

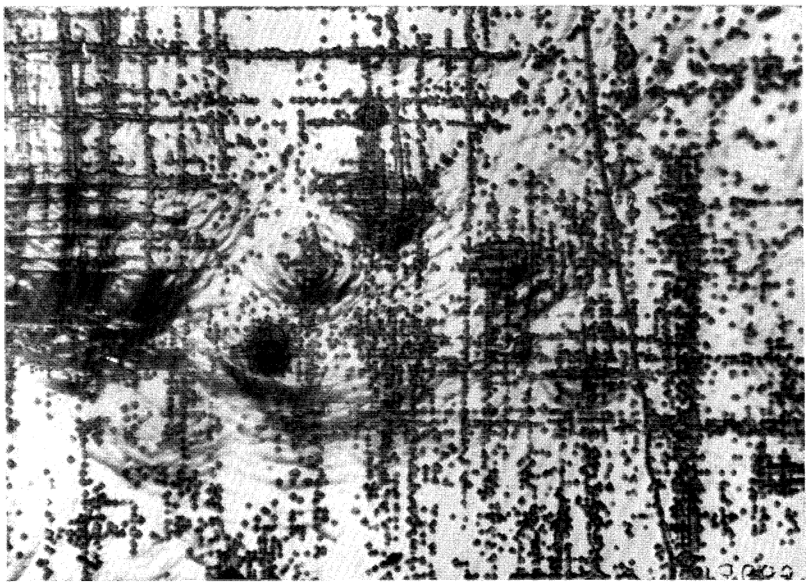

FIGURE 9. Development of slip lines after 100 000 impacts with methanol drops. (Magn. × 300.)

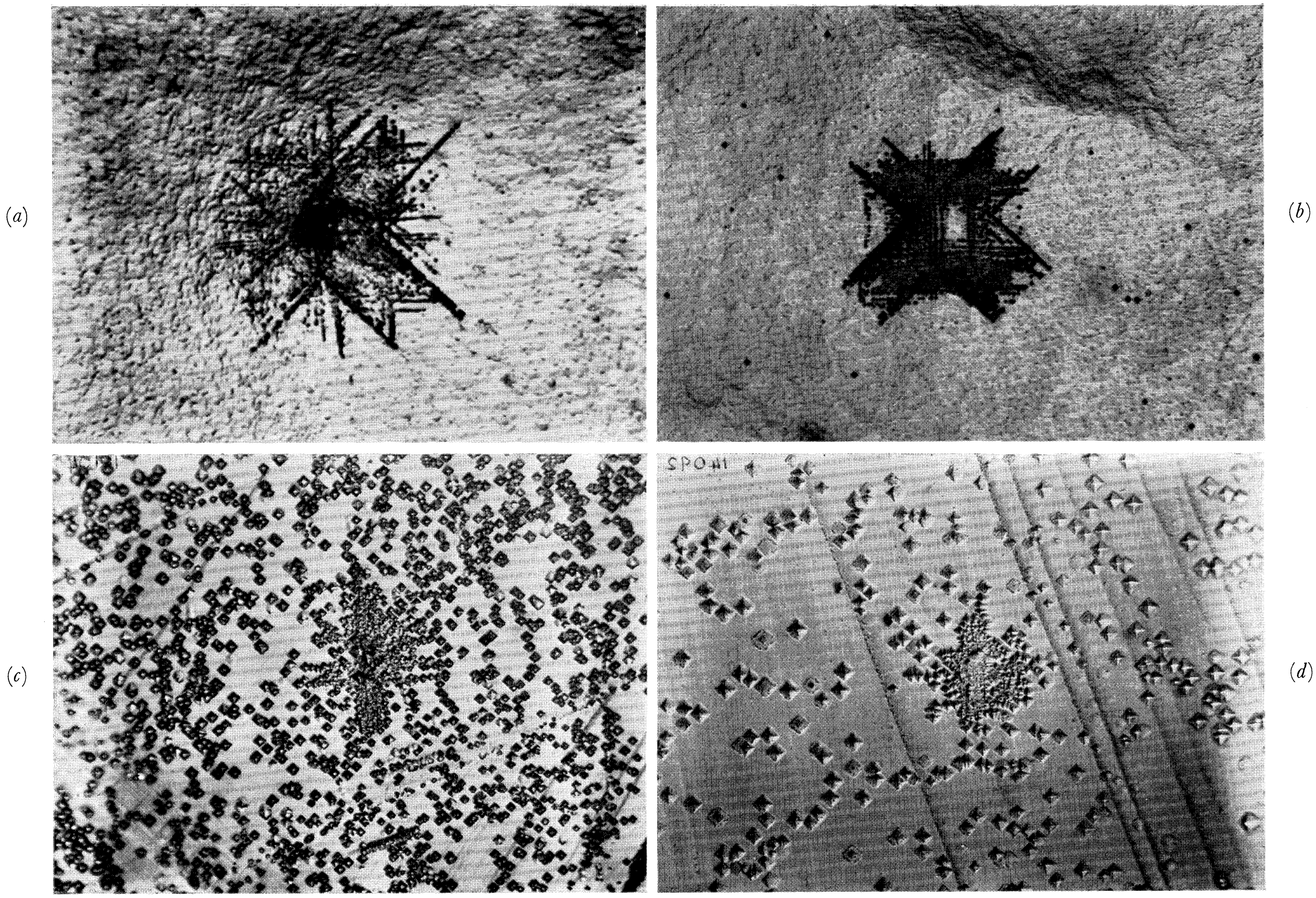

FIGURE 7. Rosettes produced by liquid impacts. (*a*) 1·5 mm water drop, 15 m/s. (Magn. × 400.) (*b*) 2·5 mm water drop, 26 m/s. (Magn. × 400.) (*c*) 3 mm methanol drop, 65 m/s. (Magn. × 500.) (*d*) 3 mm mineral oil drop, 65 m/s. (Magn. × 500.)

If we accept Ishlinsky's (1944) estimate of the stress required to produce 'fully plastic' deformation, and treat dynamic impact as a quasi-static process, the equation of motion of an impinging sphere of radius R and mass M will be

$$2{\cdot}66\pi Y_d R/\alpha = -M\mathrm{d}^2\alpha/\mathrm{d}t^2, \tag{4}$$

where $\alpha = r^2/R$ is the approach distance and Y_d is the dynamic yield stress. After integration and insertion of the appropriate boundary conditions it is found that the radius $r_{\max.}$ of the area of contact is given by

$$r_{\max.}{}^2 = \left[\frac{MV^2R}{2{\cdot}66\pi Y_d}\right]^{\frac{1}{2}} = \left[\frac{\rho}{2Y_d}\right]^{\frac{1}{2}} VR^2. \tag{5}$$

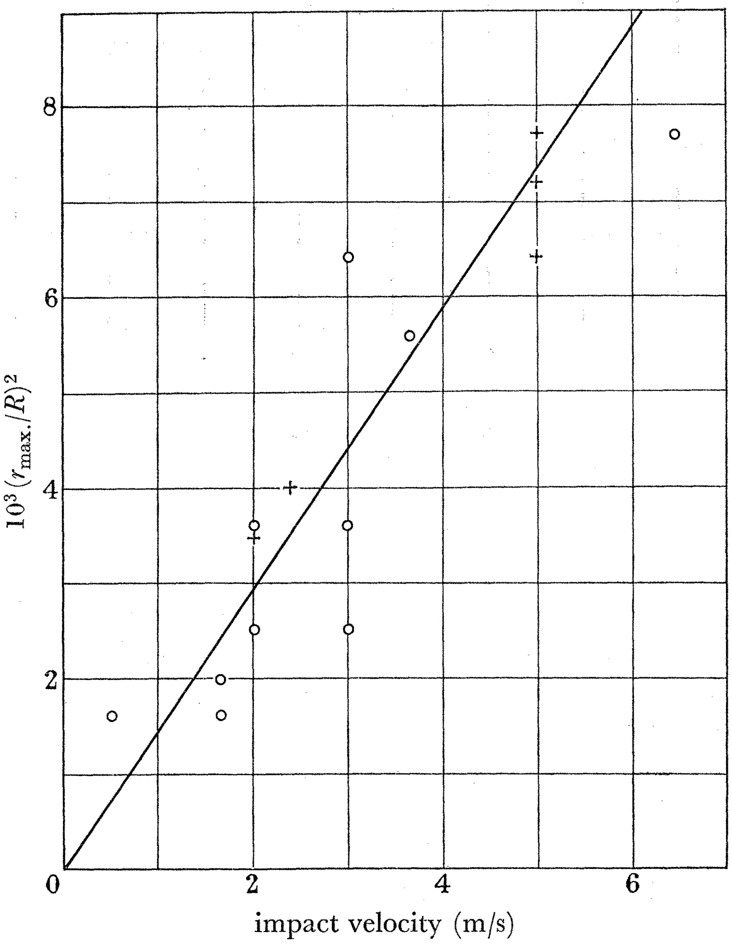

FIGURE 5. Variation of $(r/R)^2$ with impact velocity.

The linear variation of area of contact with velocity was confirmed experimentally (figure 5), and from the slope of the graph a value of $6{\cdot}2 \times 10^9$ dyn/cm² was obtained for the dynamic yield stress. This is some 30% greater than the static yield stress determined in a similar manner.

The value of the dynamic yield stress was then used to calculate the maximum force involved in the individual impacts, and hence to express the loads as a function of velocity. In order to correlate the results obtained with balls of differing sizes, it is convenient to normalize the loads by dividing by L_y, the static load required to initiate yielding with the ball in question. The resulting experimental values, as shown in figure 6, tend to fall a little below the straight lines calculated from the theoretical formula and the appropriate value of the yield stress. Thus the rosettes tend to underestimate the stresses involved.

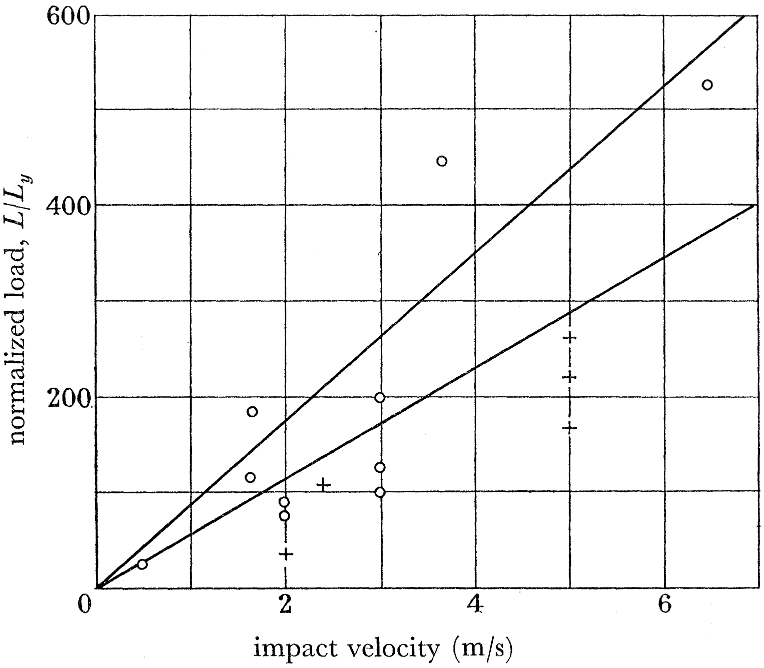

Figure 6. Normalized loads as a function of velocity. ○, Steel balls; +, bronze balls. The solid lines represent theoretical values.

5. Liquid impacts

Estimates of the impact stresses have also been obtained from measurements made on the dislocation configurations resulting from liquid impacts. Because of the much higher velocities required to produce comparable stresses, freely falling drops cannot conveniently be used, and the initial experiments were conducted with droplets projected from the periphery of a rapidly rotating disk. Unfortunately the speed and direction of these drops was insufficiently controllable, and in all the subsequent experiments the impacts have taken the form of a specimen moving at high speed and colliding with a relatively slowly moving stream of drops—a situation which is closely analogous to that prevailing in a steam turbine. The specimens were mounted on a rotor arm enclosed in an evacuated chamber and rotated at shaft speeds up to 6000 rev/min, while a stream of droplets was introduced into the path of the specimens from a vibrating hypodermic needle, similar to that described by Ryley & Wood (1963).

Lithium fluoride crystals which had been exposed for short times under these conditions produced a small number of rosettes which were sufficiently well isolated from the general background for meaningful measurements to be made on them. Only a small percentage of the incident drops produced well formed rosettes, such as those shown in figure 7, plate 14. If these are compared with the rosettes produced by solid balls of similar diameter (figure 4), it will be noticed that there is a marked tendency for the dislocation loops to form on the $\{110\}_{45}$ rather than the $\{110\}_{90}$ planes, and this has been confirmed by cleavage sections taken through the impacted area. However, it has been assumed that the calibration curve is still valid, since the mobility of the dislocations should be high enough to permit the loops to develop fully during the few microseconds lifetime of the pressure pulse.

Permanent indentations are not normally observed at the centres of the rosettes (indeed in a few cases the central area is relatively free of damage) so that it is difficult to determine the effective diameter of contact, and in most cases it has been taken as the mean overall width W of the best defined arms of the rosette. The values of r/R were of the order of magnitude V/c, as predicted by the analysis given by Bowden & Field (1964), but the individual results showed a large scatter, with a surprising tendency for the smaller contact areas to occur at the higher velocities. However, the unusually large contact areas were almost invariably associated with large rosettes, and hence with above average loads, so that the impact stresses showed much less scatter.

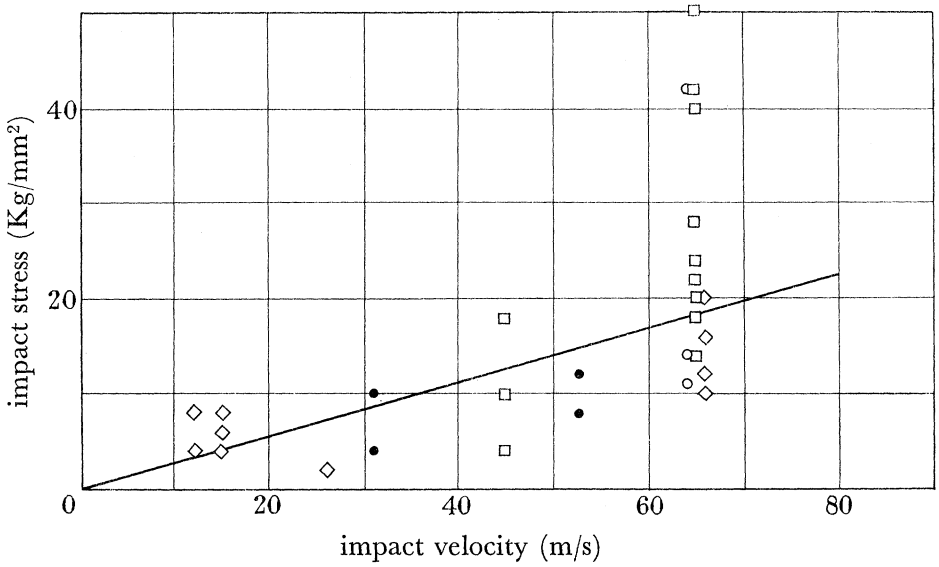

Figure 8. Impact stress as a function of liquid impact velocity. ◇, Water; ○, oil; ●, mercury; □, methanol.

Experiments were carried out with drops of water, methanol, mineral oil, and mercury, and the impact pressures all fell within a common scatter band (figure 8). The first three liquids have similar values of ρ and c, and the impact pressures could be tolerably well represented by the expression $p = 2\rho c V$, using the values of the constants which are appropriate to water. The velocity of compressional waves in mercury is also similar to that for the other three liquids, but its density is much greater, and in this instance substitution in the formula $2\rho c V$ leads to pressures which are much larger than the experimentally observed values.

6. Discussion

It is evident that the dislocation rosettes produced by liquid drops impacting under apparently identical experimental conditions can vary greatly in size and shape. This may be due to either (*a*) chance variations in the distribution of lattice imperfections able to act as stress raisers for the nucleation of dislocation loops within the target crystals, or (*b*) appreciable deviations from the ideal geometry of impact, due to peculiarities of the droplet shape. The first alternative seems unlikely since the background dislocation density was seldom so low that no pre-existing dislocations were present in the area of impact, and also the solid ball impacts produced rosettes which were satisfactorily reproducible. The second explanation is much more probable, as the rotor arm inevitably produces a slip-stream effect in the residual air in the test chamber, and this will tend to distort the droplets, particularly at the higher velocities. The relatively low pressures produced by the mercury drops are possibly a consequence of the great difficulty of producing stable drops.

The preponderance of $\{110\}_{45}$ dislocation loops in the liquid impact rosettes and the absence of appreciable permanent depressions shows that there is little tendency for the target material to be displaced sideways during the impact. Also there is no evidence that the subsequent surface flow of liquid produced any deformation near small surface imperfections, such as cleavage steps, at least for the impact velocities used in these experiments.

The development of the damage under repeated impacts takes the form of an extension of the dislocation loops to form slip bands on the $\{110\}_{45}$ planes (figure 9), but the tests have not yet been continued for sufficient time to lead to cracking and appreciable loss of material.

7. Conclusion

The size of the effective area of contact, as deduced from measurements made on the most clearly defined rosettes, is not incompatible with the theory of liquid impact put forward by Bowden & Field (1964), but the peak pressures sometimes considerably exceed the water-hammer pressure $p = \rho CV$. For a large steam turbine with a final stage tip speed of 500 m/s this implies impact pressures much larger than 70 Kg/mm^2 (45 tons/in.^{2}), which would be sufficient to initiate slip in the commonly used shield materials, and probably lead to fatigue failure under repeated impacts.

The author wishes to thank Dr T. Broom for many helpful discussions. The paper is published by permission of the Central Electricity Generating Board.

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VI. Discussion

F. J. Heymann (Westinghouse Electric Corporation)

In response to Dr Bowden's invitation to comment, I should like to make some brief reference to the work recently done by DeCorso in the Westinghouse Research Laboratories, at the request of the Westinghouse Steam Division, with which I am associated. DeCorso's experimental approach owes much to Dr Brunton, who visited us during the early stages of the programme and gave us the benefit of his experience. The single-jet impact apparatus is similar in principle to that used by Brunton, though different in design particulars. The details of the apparatus and some early results were reported by DeCorso & Kothman (1961). The subsequent emphasis was on developing a technique for quantitative measurement and characterization of the damage pits produced, and on relating the damage pit measurements to jet size and jet impact velocity for various materials of interest in the context of steam turbine blade erosion. A method of ranking the materials for erosion resistance was used which depends on an upper tolerance limit of the pit depth measurements in relation to impact velocity, and also uses a 'visible damage velocity threshold' to establish a 'low'-velocity point where no actual measurement of pit depth could be made. These results are reported by DeCorso (1965).

One conclusion stated therein is that, given an equal amount of fluid impacting for the higher velocities well above the damage threshold, drop size does not affect the damage, but that at velocities near the threshold, damage increases with drop size.

DeCorso does not make any generalizations concerning the relation between damage and velocity, and indeed since his plots of pit depth against velocity are presented as straight lines on arithmetic scales, they do not readily lend themselves to the determination of an exponential relationship. However, if data points are taken from his Fig. 14 at the two velocities of 1500 ft./s and 3000 ft./s, it is found that the pit depths at the higher speed range from about 3 to 4 times those at the lower speed. For geometrically similar pits, this corresponds to a proportionality between pit volume and the 5th to 6th power of velocity, within the specified velocity interval. This is a higher exponent than that found by many other investigators. If one considers not absolute velocity but impact velocity minus threshold velocity then pit volume is proportional to the 3·2 power of the latter for most materials tested.

To investigate the possible effects of surface work hardening due to the mechanical polishing given to specimens, a number of comparison tests were made with mechanically and electropolished specimens of the same material, at several impact velocities. While DeCorso states that he found no significant effect of the polishing method on damage, yet in the results he presents in his Fig. 4 this is true only for Stellite, whereas for 12% Cr steel the crater volume in electropolished surfaces is consistently greater, by a factor of 2 to 3, than the crater volume in the mechanically polished surface. This seems consistent with the fact that electropolishing reduces the endurance limit of 12% Cr steel by 15%, whereas Stellite is less affected.

DeCorso observed the same light flash on impact as is reported by Brunton, and arrived at essentially the same explanation for this phenomenon after conducting a number of experiments which ruled out various alternative explanations which had been proposed. A report on this investigation is to be published.

One may ask whether a single impact type of apparatus is at all suitable for material evaluation, since the fatigue mechanism, which undoubtedly plays a role in actual service environments with repetitive impacts, is here lacking. It is of interest, therefore, to compare the ranking of several materials taken from DeCorso's results, with that from the erosion test apparatus at the Westinghouse Steam Division (a supersonic nozzle directing a steam and water jet against a stationary specimen in a vacuum corresponding to that of a low pressure turbine), and with other results from Westinghouse records and from the literature, using various types of test apparatus. Such a table is presented below (table 1), and one may note that there is good general agreement between the different tests, although certain inconsistencies also manifest themselves (for example, 18-8 steel against 12% Cr steel). One must recognize, of course, that because of differences in material preparation, heat treatment, etc., direct comparisons are not completely valid.

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R. A. Scriven (Central Electricity Research Laboratories)

It appears from the papers by Dr Brunton and Dr Field that the two dominating processes producing surface damage are (*a*) the shearing effect of liquid moving across the surface, and (*b*) Rayleigh waves. Both of these effects will always be present, especially (*b*), with (*a*) varying according to the state of the surface. Is there any evidence which points to either (*a*) or (*b*) predominating in given circumstances and is it possible for (*b*) to always act as the trigger mechanism for (*a*)?

J. H. Brunton and J. E. Field

The importance of the stress waves is mainly confined to brittle materials where they initiate fractures which can subsequently act as sights for preferential erosion.

In ductile materials the surface damage is mainly confined to the impact area itself and the surface stress wave does not produce detectable damage. However, the shear stresses in the impact area are sufficient to cause grain tilting and the formation of slip lines and twin boundaries, etc. These features are then eroded.

T. Broom (Central Electricity Generating Board)

Is the role of surface protuberances to be ascribed simply to their shear under the rapidly moving surface film? Could cavitation *behind* the protuberance be important?

Table I. Comparison of erosion data from various test methods

De Corso (1965)	Heymann & Stahl (1956–63)	Hengstenberg (1931–33)	Rathbone (1930–31)	Leith & McIlquham (1961) †	Rheingans (1958) †	Plesset & Ellis (1955) †	Mousson (1937) †
	(Westinghouse unpublished work)						
single jet impact	steam + drops impingement	rot'g specimen rep'd impact	in turbine field tests	vibratory cavitation	vibratory cavitation	resonant cavity	venturi cavitation
pit depth at 3000 ft./s (μm)	rate of weight loss (mg/h)	rate of volume loss parameter	visual rating after 76 weeks	'relative erosion'	weight loss after 2 hr (mg)	rate of mean penetration (μm/h)	volume loss after 16 h (mm^3)
titanium C-130 heat tr'd, 5·5	titanium C-130 AM heat tr'd, 0·23	tool steel hardened, 1·2	stellite, 'very light'	chrome plate hard, 1	stellite, 0·6	titanium alloy, 13	stellite, 0·9
titanium RS-140 annealed, 11·0	stellite 6 rolled, 0·33	stellite, 1·3	nitralloy, 'light'	titanium 150A rolled, 1	12 Cr steel hardened, 9·0	stellite, 15	12 Cr steel hardened, 3·5
stellite 6 rolled, 16·0	chrome-plate hardened, 0·40	12 Cr steel hardened, 2·2	chrome plate, 'medium'	stellite 6 weld, 2	18–8 steel cast, 13·0	colmonoy, 16	18–8 steel rolled, 3·5
12 Cr steel rolled, 24·0	titanium RS-140 annealed, 0·70	chrome plate, 6·5	12 Cr steel, 'heavy'	tool steel M50 rolled, 2	12 Cr steel cast, 20·0	18–8 steel, 26	12 Cr steel rolled, 46·7
18–8 steel, 35·0	18–8 steel flame-sprayed, 1·00	nickel, 6·5	18–8 steel, 'very heavy'	colmonoy 6 weld, 6	aluminium, 124·0	nickel, 70	18–8 steel flame-sprayed, 207
—	colmonoy 6 strip, 1·20	12 Cr steel, 9·1	nickel, 'very heavy'	nickel plate hard, 17	—	aluminium, 3500	aluminium no. 214, 1810
—	12 Cr steel hardened, 1·45	—	—	18–8 steel cast, 19	—	—	—
—	12 Cr steel rolled, 11·0	—	—	12 Cr steel cast, 25	—	—	—
—	18–8 steel rolled, 21·0	—	—	aluminium soft, 200	—	—	—
—	nickel, 54·0	—	—	—	—	—	—
—	aluminium soft, 150·0	—	—	—	—	—	—

† The listed data have been selected and adapted from the original results, to obtain comparative rankings for materials similar to those listed in the other columns.

J. H. Brunton and J. E. Field

In theory the flow of liquid over a protuberance could give rise to cavitation damage. In our experiments the deformation of a protuberance suggests that is has been sheared along its length rather than locally deformed by collapsing cavities. This behaviour may be due to the very small step heights (approximately 2000 Å) which prevent the development of an effective cavitation zone.

G. Langbein (Dornier System, Germany)

Does the presence of a water film on the surface smooth out roughening due to slip lines and grain boundaries?

J. H. Brunton and J. E. Field

Yes, a liquid film on a surface very effectively reduces shear damage, and to a lesser extent reduces the impact pressure.

A. Smith (C. A. Parsons and Co. Ltd.)

Tungsten chrome tool steel with an ultimate tensile strength of 170 tons/in.^{2} at zero mean stress, can be eroded by the repeated impact of water droplets of 100 μm Sauter mean diameter $\Sigma d^3/\Sigma d^2$ travelling at 1700 ft./s. The impact pressure calculated from the expression $P = \rho CV$, however, if considered as a fluctuating stress of ± 25 tons/in.^{2} at a mean stress level of 25 tons/in.^{2}, is within the fatigue limit of this material and suggests that the actual pressures are higher. Could neglect of the influence of surface tension on very small droplets, in the derivation of the equation for impact pressures, be the reason for the discrepancy?

J. H. Brunton and J. E. Field

The peak pressure for an impact velocity of 1700 ft./s is calculated to be about 50 tons/in.^{2} when the sound speed is taken as 4700 ft./s. However, at these high impact velocities the sound speed should be replaced by the speed of shockwaves; the appropriate value for C is then about 9400 ft./s, which corresponds to an impact pressure of 100 tons/in.^{2}. This pressure may well be sufficient to cause fatigue failure. However, it is perhaps unwise to correlate erosion damage and fatigue failure in this way, as there are several mechanisms of deformation operative in the erosion process and fatigue is only one of these. Stress-concentration effects could also raise the stress over localized areas to values above the 100 tons/in.^{2} calculated above.

T. B. Benjamin (Department of Applied Mathematics, Cambridge University)

To estimate the pressure arising from the initial impact of a liquid jet which approaches a solid boundary with velocity V, use has been made of the well known formula $P = \rho CV$ from elementary water-hammer theory. Presumably, in keeping with the usual simple approximation, the density ρ and sound velocity C were assigned the values for the liquid at atmospheric pressure. It should be remembered, however, that this formula derives from the assumption that only a weak shock wave is generated in the liquid, implying that

V is very much smaller than C. The very high jet velocities achieved in the present experiments are in fact comparable with the velocity of sound (e.g. about 1500 m/s for water), and so the simple estimate of P may be rather inaccurate.

On the other hand, a good deal of information is available about strong shock waves in liquids, having mainly been obtained in connexion with underwater explosions and I wonder whether this might be useful in the present connexion as the basis for improved estimates of the impact pressure?

J. H. Brunton and J. E. Field

This is, of course, an important point, and in our calculations of the water-hammer pressure we have in fact used for the values of C the shockwave data published by Cook, M. A., Keyes, R. T. & Ursenbach, W. O. (1962 *J. Appl. Phys.* **33**, 3413).

A. G. Atkins (Cavendish Laboratory)

If successively higher rates of strain tend to produce more-brittle behaviour in materials, why does one get the very plastic 'splashing' in hypervelocity impacts? Would not one expect a more 'rigid' behaviour?

J. H. Brunton and J. E. Field

There are two points here. The sensitivity to strain rate varies with the material; polymers, for example, are very sensitive to strain rate and fail in a brittle manner when loaded impulsively, while copper and aluminium are less dependent on the strain rate and flow plastically. The other point is that in the region of impact, and only in this region, the very intense compressive stresses tend to prevent brittle fracture.

S. K. Carpenter (Hawker Siddeley Dynamics, Ltd.)

Some missile structural problems may be best solved by employing erosion resistant coatings over the basic structural material.

As the more complex fracture patterns on the front surface of an impacted specimen are due to reinforcements of the surface wave with components of stress reflected from the back surface, will the presence of an interface between coating and solid modify the present results? Is work on coated structures contemplated in the future?

J. E. Field

An interface is very important in determining the transmission and reflexion of stress waves. The exact behaviour will depend on the acoustic matching, that is upon the relative values of the product ρC for the two materials. For example, for a compressive wave moving from a material with a high ρC into a material of a low ρC there will be a large tensile component reflected back into the material. For perfect matching (the products ρC equal) the wave passes through the interface without reflexion.

R. G. Popple (English Electric Co., Ltd., Nelson Research Laboratories, Stafford)

In Dr Brunton's and Dr Field's description of the damage due to impact there appears to be no explicit mention of the effect of the internal stress of the solids on the extent of the damage.

Since many materials show a higher ultimate strength in compression than in tension (Nielson, L. E. *Mechanical properties of polymers*, Reinhold, 1962, p. 102) it would be expected that in materials with no internal stress, the first fracture to appear would be tensile in origin. However, if the material has an internal compressive stress the applied tensile stress required to cause fracture would be correspondingly larger, and an optimum value of internal stress can be imagined at which the probabilities of tensile or compressive fracture are equal, and thus the fracture if the substance is subjected to both tensile and compressive stresses will be a minimum.

Extending the work of Carr (U.S. Pat. 2842487), it has been shown in the N.R.L. that nickel electrodeposits at least 0·060 in. thick can be prepared with hardness values in the region 650–838 V.H. 10, having an internal stress which is tensile or compressive according to the conditions of deposition. It is hoped that Dr Marriott will have an opportunity to test such deposits.

J. H. Brunton and J. E. Field

In our experiments we have not, as yet, studied the effect of the target specimen being in a state of stress, except in the case of thermally toughened glass specimens where the thin outer layer of compression and the high internal tensile stresses affect both the initiation and propagation of fracture.

Since in practical situations the material subjected to liquid impact may well be stressed then the effect of these stresses on the development of damage is clearly very important.

D. C. Jenkins (R.A.E., Farnborough)

I have measured the radial flows from drops impacting on a steel surface over the speed range 300 to 3750 ft./s and throughout this speed range I find that if a Bernouilli pressure $\frac{1}{2}\rho w^2$ is calculated, where w is the measured radial speed, then this pressure agrees very closely with the corresponding hammer-blow pressure ρCV where V is the impact speed and C is the speed of propagation of the shockwave in the water. Can Dr Brunton offer any explanation for the agreement found between these two pressures? I accept that as the impact flow is not steady then allowance should be made for this by including a time-dependent term in the calculation of the Bernouilli pressure but perhaps this is zero in this case. My results are given in *Aerodynamic capture of particles* (Pergamon Press, 1960).

J. H. Brunton

I am, of course, aware of the experiments referred to by Mr Jenkins. In our work, however, we have found that if a liquid drop has its front surface parallel to the target surface then the flow velocity from under the drop is the same as the impact velocity. If, on the other hand, under the same conditions, the front surface of the drop is inclined to the target surface the outward flow velocity from under the wedge exceeds the impact velocity. This is an experimental fact which we have tried to explain on the basis of the shaped charge theory of Birkhoff, MacDougall, Pugh & Taylor (1948, *J. Appl. Phys.* **19**, 563). It is possible to apply this idea to a spherical drop. In this case the wedge angle is the angle formed between the curved drop surface and the target surface at the edge of the region of compressible behaviour. Since the extent of this region depends upon the impact velocity and drop radius the appropriate wedge angle varies with impact velocity. Calculations show that the experimental curve of radial flow velocity versus impact velocity found by Mr Jenkins can be satisfactorily explained by using this approach (Field 1962, Ph.D. Thesis, University of Cambridge).

K. K. Shal'nev (Institute of Mechanics, Moscow) [Plate 15]

The analysis of the phenomenon of the secondary effect of the wave-acoustical cavitation in connexion with the experimental and theoretical investigations of Bowden & Brunton (1961) and Bowden & Field (1964), which have shown that the deformation of solids by the impact of liquids can be due to the interaction of stress waves, would be of some interest. We obtained the results communicated here in the course of experiments connected with the development of a method of testing the resistance of different materials to cavitation erosion by means of treatment by sound waves (Shal'nev 1949, 1952).

When the sound wave treatment method is used the specimen is kept stationary, but in the vibration method it oscillates together with the cavitation exciter.

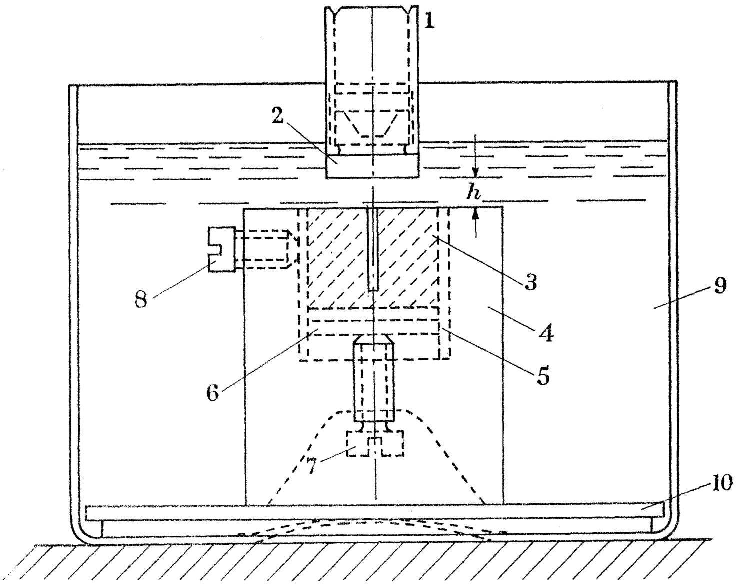

FIGURE 1. The diagram of tests on cavitation erosion by the method of treatment with sound waves.

In our experiments for a wave cavitation exciter a magnetostrictional vibrator with a nickel pipe of 20 mm diam., oscillation frequency of 8000 Hz and an amplitude of 0·066 mm was used. One end of the pipe (1, figure 1) was plugged by a steel plug, 2. The tested specimens were fixed in an immovable clamp with the help of a split cylindrical ring, 5, steel washers, 6, and steel thrust screws, 7 and 8.

The clamp with the specimens of 1 kg weight was placed in a glass vessel, 9, on rubber pads.

In the experiments with lead specimens additional gaskets of Whatman paper were placed between the specimen and the steel gasket, to ensure a uniform distribution of the pressure of the screw, 7. The distance *h* between the specimens and the plug could be regulated by placing additional gaskets under the vessel. The tested specimens of materials had the form of round cylinders of 30 mm diam., and 4 to 30 mm in height. The height or the depth of lead specimens was about 4 to 5 mm.

The photographs (figures 2 and 3, plate 15) of different enlargement show the erosion of the front surface of specimens, that is, of the surface facing the plug and directly subjected to the cavitation force, and of the rear surface of the same specimen. The rear surface of the specimen is in contact with the paper washer, as mentioned above.

Specimen 1 (2) was tested at $h = 2{\cdot}7$ mm, and specimen 2 (4) at $h = 1{\cdot}0$ mm. In both experiments the duration of test was 15 min, but as the pipe was observed to vibrate irregularly it affected the intensity of erosion. The front surface of the specimen 1 (2) is covered with multiple crater-like pittings with sharp edges, slightly raised above the initial surface of the specimen.

The front surface of specimen 2 (4) is covered with isolated pits occupying a larger area than on specimen 1 (2). On the rear surface of the specimen 1 (2) small pits are observed surrounding a relatively large hole in the specimen centre. On the rear surface of specimen 2 (4) a local pit of ring form is seen, as if reflecting one of the front surface pits.

Let us examine the possible causes of the origin of pits on the rear surface of specimens.

If the cause is assumed to be cavitation on the rear surface of specimens, the question arises, can such a cavitation appear in the above-mentioned design of the device?

Cavitation on the rear surface of a specimen could be induced only by the vibration of the specimen itself. However, simple consideration shows that a lead specimen, rigidly clamped in a heavy device cannot be excited by the pressure waves going out of the vibrator pipe and cavitation zone to oscillations of such extent that cavitation should occur. It is necessary to keep in mind that a paper and a metal gasket are tightly pressed to the rear surface of the specimen. It would be more plausible to suppose that it is an effect of the stresses, appearing in the specimen at the formation of pits on its front surface.

For the present the origin of forces creating the erosion of the front surface is not yet known to us. However, if they are able to give rise to local damage of the metal, they can also excite the stress waves in the specimen. Being reflected from the front and rear surface of the specimen they form standing waves with an initial period of about 8 m/s.

Unlike the impact of liquid drops moving with a velocity of several hundred metres per second, the rate of the movement of the vibrator nickel pipe end or the rate of the vibrating bubbles surface movement does not in the tests described exceed some tens of metres per second. However, the acceleration of the moving liquid particles reach values of several hundreds and even thousands of the acceleration due to gravity. The erosion intensity dependence on the acceleration was noted by Haller (1940).

The cavitation nature of erosion should be confirmed by further investigations of the secondary effect of the wave cavitation erosion and a comparison of the results with those of the investigation of deformations caused by a direct impact of liquid drops.

References (Shal'nev)

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Bowden, F. P. & Field, J. E. 1964 *Proc. Roy. Soc.* A, **282**, 331.
Haller, P. 1940 *Schweizer Archiv. Angew. Wiss. Tech.* **6**, 61.
Shal'nev, K. K. 1949 *Dokl. Acad. Nauk, SSSR*, **57**, no. 1, 33.
Shal'nev, K. K. 1952 *Inzh. Sb.* **12**, 195.

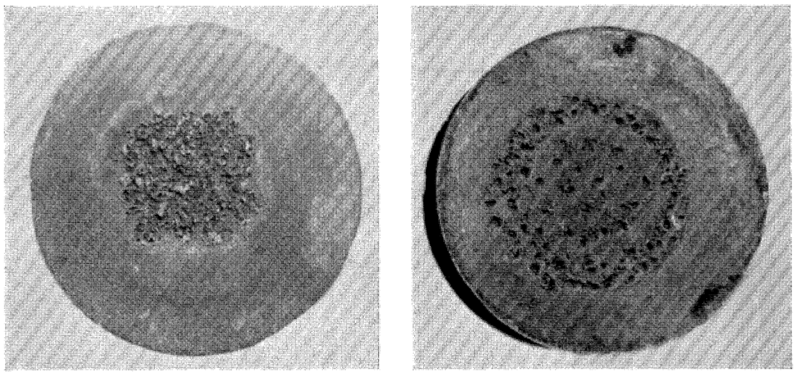


FIGURE 2. Cavitation erosion of the front surface of the specimens 1 (2) and 2 (4). (Magn. × 1·5.)

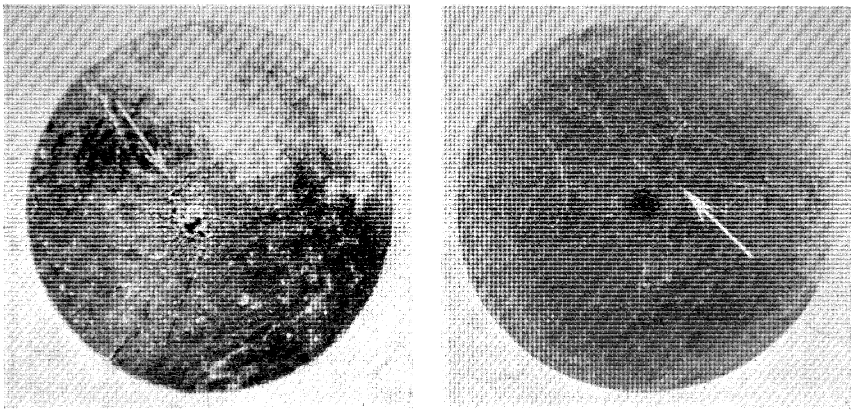


FIGURE 3. Local pits on the rear surface of specimens 1 (2) (magn. × 1·5), and 2 (4) (magn. × 1·6).

L. A. Thomas (The General Electric Co., Ltd., Wembley)

It is natural for an applied scientist to inquire the extent to which the basic studies by Dr Brunton and Dr Field have thrown up unexpected results which could indicate a new approach to the problems encountered in practice. Valuable as the detailed findings are, is it fair to comment that no unusual features are disclosed apart, perhaps, from the possible role of the high speed Munroe jets in the erosion process?

An aspect of obvious importance is the nature of the target. There is a whole range of choice, as between brittle and ductile materials, amorphous solids and crystals, and so on. Dr Field's experiments appear to cover part of this range but there is undoubtedly scope for further study. He mentions a comparison between etched and non-etched glass surfaces. The strength of glass is well known to depend on its surface characteristics and can be readily modified by both mechanical treatment and by chemical action such as leaching which produces a change in surface composition. The etching of a glass surface does not necessarily remove a disordered layer in the same sense as removing lattice defects from a crystalline surface. If there is an experimental advantage in having a transparent material additional information on the role of structure could be obtained by using crystals such as periclase (MgO), α-quartz (SiO_2) and corundum (Al_2O_3). Specimens of the latter can be selected with varying degrees of crystalline disorder which could be relevant to the erosion process.

Dr Field has already drawn attention to the possible importance of the acoustic characteristics of the target material in connexion with the 'scabbing' fracture in thin specimens. It is, therefore, interesting to note that many of the experiments carried out both by him and by Dr Brunton have employed Perspex, which has a relatively high acoustic dissipation. It undergoes thermal decomposition when irradiated with quite a low power ultrasonic beam and it may not be a very suitable choice of material for investigation in relation to practical problems.

P. F. Tomalin (English Electric Co., Whetstone)

Mr Thomas has remarked on the importance of careful selection and understanding of target materials for fundamental work on droplet impact. I should like to support this comment and refer particularly to metals and alloys.

It is common practice when examining fundamentals of material behaviour to select simple materials in which the effect of test conditions is as uncomplicated as possible. However, materials used in engineering practice may be complex in such a way that factors not observed in simple materials may influence their behaviour.

For example, in the case of water droplet erosion of steam turbine blades, a useful material to resist erosion is a cobalt–chromium type of alloy consisting structurally of hard particles in a solid solution matrix. As Marriott and Rowden show, this material exhibits cracking between the carbide particles and the matrix at an early stage of erosion and it is possible that this is a factor in the development of erosion damage.

Hence, if the fundamental work on this subject is to have engineering problems in mind it is important that the targets for water droplets should include materials consisting of hard particles in a softer matrix, and other typical metallurgical structures.

J. H. Brunton and J. E. Field

We trust that when Mr Thomas and Mr Tomalin read the full version of our papers their queries will be to some extent answered. Briefly, the object of our single impact work was first to try to understand the physics of the impact process and to separate out the various possible deformation mechanisms. A material we have used extensively has indeed been Perspex, but this can be justified by its ease of specimen preparation, transparency and birefringent properties. But, of course, Perspex, glasses, ceramics, aluminium and steels besides being good basic materials to experiment with are also all materials found on forward-facing structures of aircraft. The fracture behaviour of several crystalline solids including magnesium oxide, α-quartz, sapphire and diamond have been studied. Their behaviour under liquid impact is briefly discussed by Dr Field in his paper and other fracture studies are described in other papers (Field 1962, 6*th Int. Congr. High Sp. Photogr.*; Field & Heyes, 1965, 7*th Int. Congr. High Sp. Photogr.*).

The repeated impact work performed at Cambridge is described in the papers of Brunton & Hancox and Thomas (this volume). Again the approach involved the use of 'simple' materials in an effort to understand some of the deformation mechanisms taking place during impact. However, present work is also very much concerned with materials such as high strength alloys and composite materials.

A. G. Atkins (Cavendish Laboratory)

I should like to ask Dr Jolliffe, in the calibration of the rosettes produced by static indentations with pyramids, is the orientation of the indenter relative to the slip directions of importance?

K. H. Jolliffe

No. Rosettes of similar size are obtained with both ball and diamond indenters, regardless of their orientation relative to the ⟨100⟩ crystal direction.

D. Tabor, F.R.S. (Cavendish Laboratory)

How large are the rosettes compared with the size of the water drops, and to what size of indentation does this correspond?

K. H. Jolliffe

The largest rosettes produced by 2 mm water drops had diameters of 160 μm, and the central depressions were roughly 40 μm across.

C. Edeleanu (I.C.I. Ltd, Billingham)

The difference in the pattern of the rosettes resulting from liquid impact is interesting, and presumably the effect is due to a difference in the mobility of dislocations. Is, in fact, the effect the one we might have expected?

K. H. Jolliffe

According to Gilman & Johnston (1962, *Solid St. Phys.* **13**, 147) the velocity of the screw components of the dislocations at the stress levels encountered in our experiments is about

0·2 mm/μs, and the edge dislocations move as much as fifty times faster, so that a stress pulse lasting a few microseconds should be ample for the formation of a rosette 50 μm in diameter, which is typical for the liquid impacts which we studied. The scarcity of dislocations of either type on the $\{110\}_{90}$ planes suggests that the stress components acting on these planes are comparatively low.

J. E. Field

Could Dr Jolliffe comment on his remarks about pressures greater than ρCV? Surely the momentum during the impact cannot be changed at a speed greater than the sound speed, or at high pressures, the shock speed? The question of C, the sound speed, being replaced by a shock speed is already important for liquid impact velocities of a few hundred metres per second. Taking as an example an impact velocity of 500 m/s, and using the data of Cook, Keyes & Ursenbach (1962, *J. Appl. Phys.* **33**, 3413), a shock of speed 2500 m/s should be developed; this compares with the stress wave speed of 1500 m/s. The water-hammer pressure thus becomes about 125 Kg/mm^2 rather than 75 Kg/mm^2.

K. H. Jolliffe

I agree with Dr Field that strictly speaking the velocity C used in the water-hammer equation should be the shockwave rather than the sound wave velocity, but for the modest velocities used in our experiments (not more than 65 m/s) the error involved is much less than the scatter in the experimental results. It must be emphasized that only a small percentage of the impacts produce pressures as high as those shown in my figure 8, and the values recorded therein should be regarded as maximum pressures which are apparently only produced in particularly favourable circumstances. The stress levels have been calculated from the sizes of the rosettes which they produce, and it is possible that the unexpectedly large rosettes are due either to structural inhomogeneities acting as stress raisers within the crystal, or to reinforcement of the shockwaves by a geometrical factor arising from the particular way in which the droplet breaks up, but in either case the model of a truly spherical drop deforming against a perfectly elastic plane surface is probably an oversimplification.

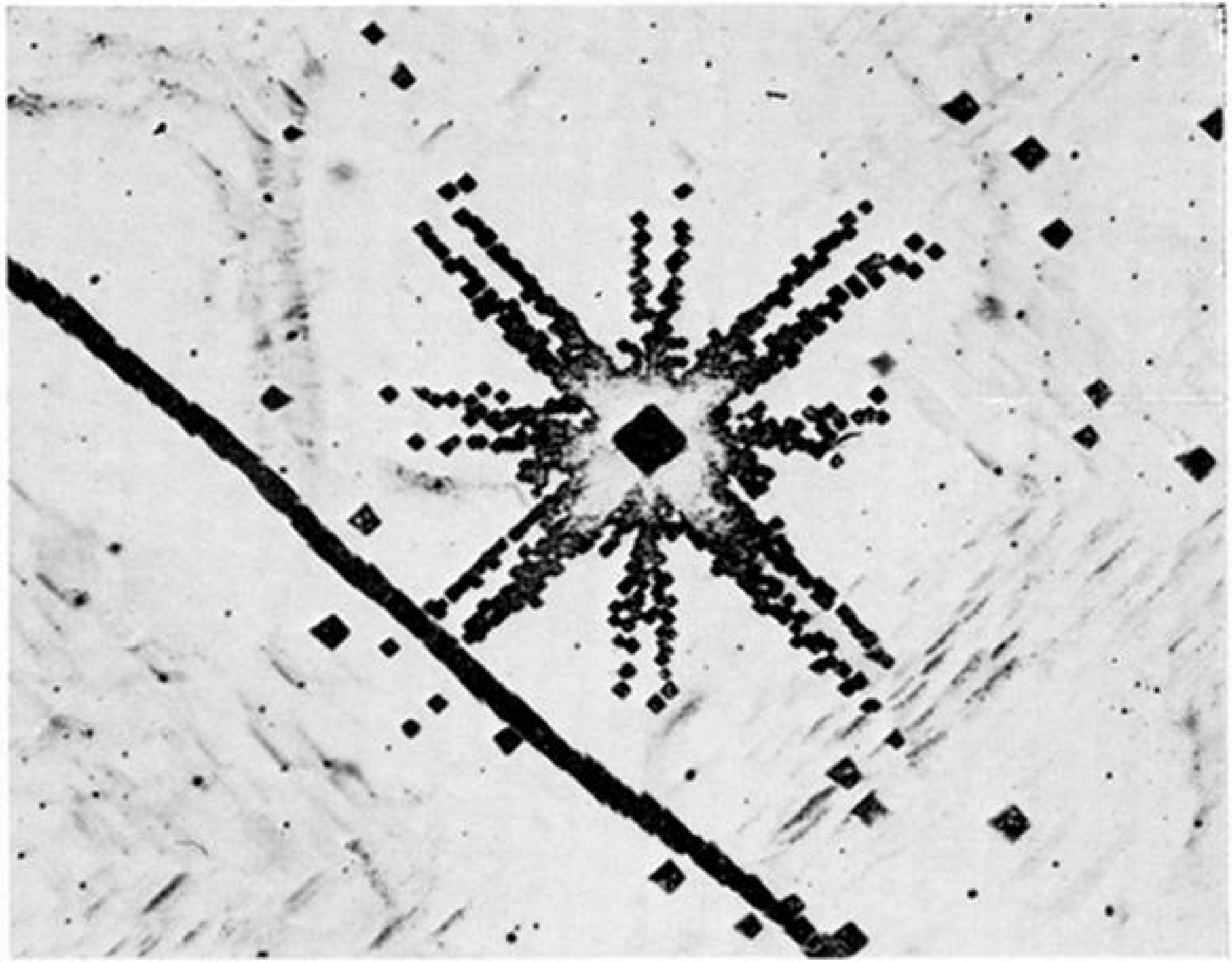
D. Tabor, F.R.S.

In a paper by Benjamin & Ellis (this volume, p. 221) it is shown by a most elegant analysis that cavitation can be immensely effective in producing surface damage. I should therefore like to ask whether this may not be the mechanism responsible for the damage observed with low velocity impacts between solids and drops or jets of liquid? Low velocity impacts would provide adequate time for several compressive and reflected tensile stresses to occur before the liquid had flowed away. This would presumably favour conditions for the formation and collapse of cavities, and in this way damage could occur even when the pressures due to the simple water-hammer theory were in themselves too small to produce deformation.

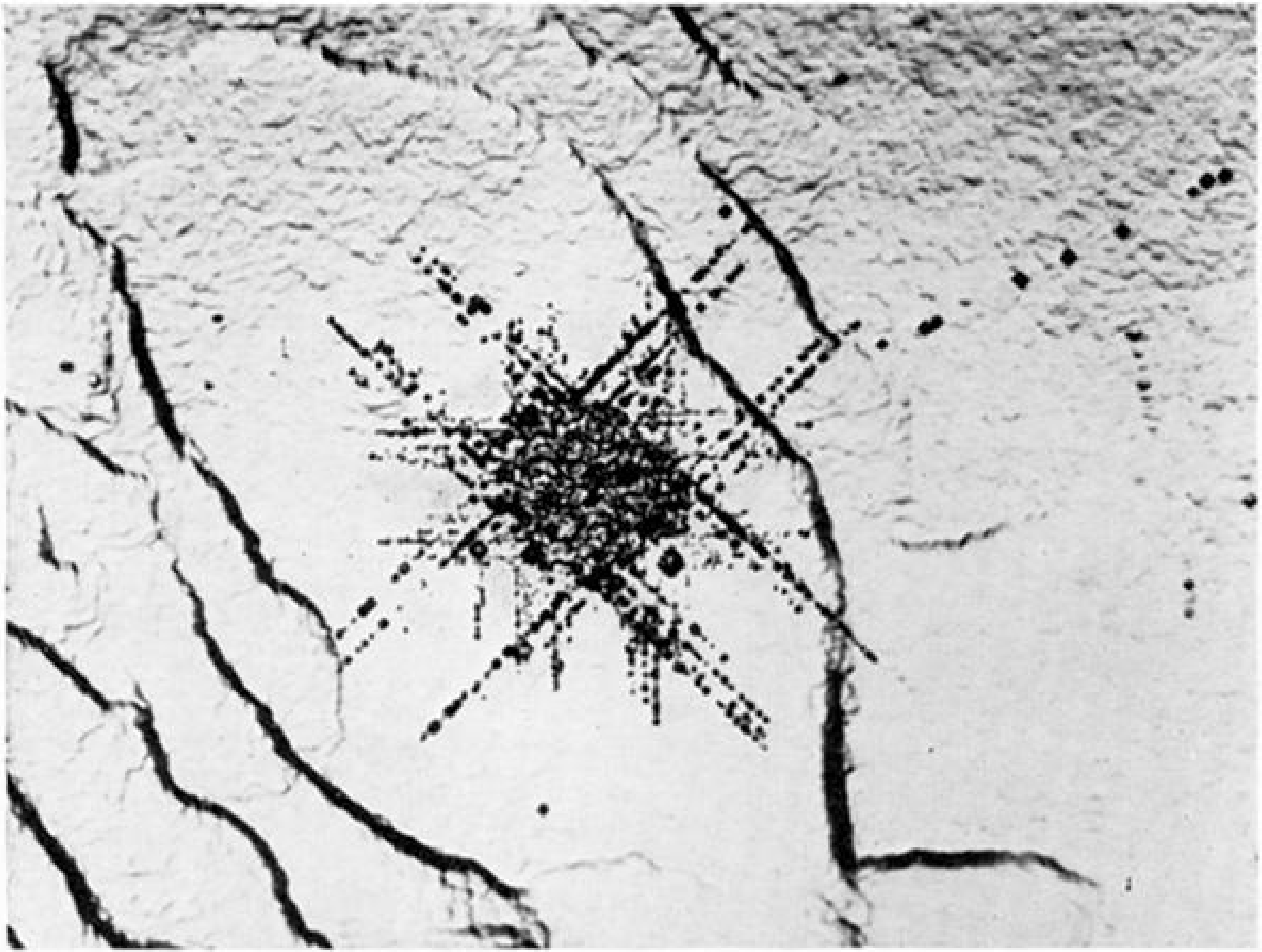
In a similar way this might explain the observation that mercury gives less damage than expected; because of the high surface energy of mercury it may be more difficult for reflected tensile stresses to produce cavities than in, say, water.

K. H. Jolliffe

It is certainly true that during a low velocity impact there is ample time for the shock-wave to be reflected backwards and forwards several times before the liquid has flowed away, and a cavitation mechanism does provide a plausible explanation of the apparently anomalous behaviour of mercury, but I think that if cavitation was occurring, one would expect the damage to be nucleated at numerous points spread over an area roughly equal to the cross section of the drop, rather than being concentrated in a single rosette centred on the initial area of contact. It is unfortunate that it is not yet possible to give a more detailed mathematical description of the various stages of deformation of a liquid drop after impact.



IGURE 3. Dislocation rosette surrounding diamond impression. Load = 16 g. (Magn. × 200.) Crystal orientation corresponds with figure 2(*a*).



IGURE 4. Rosette produced by the impact of a 1 mm steel ball. Velocity, 165 cm/s. (Magn. × 200.)

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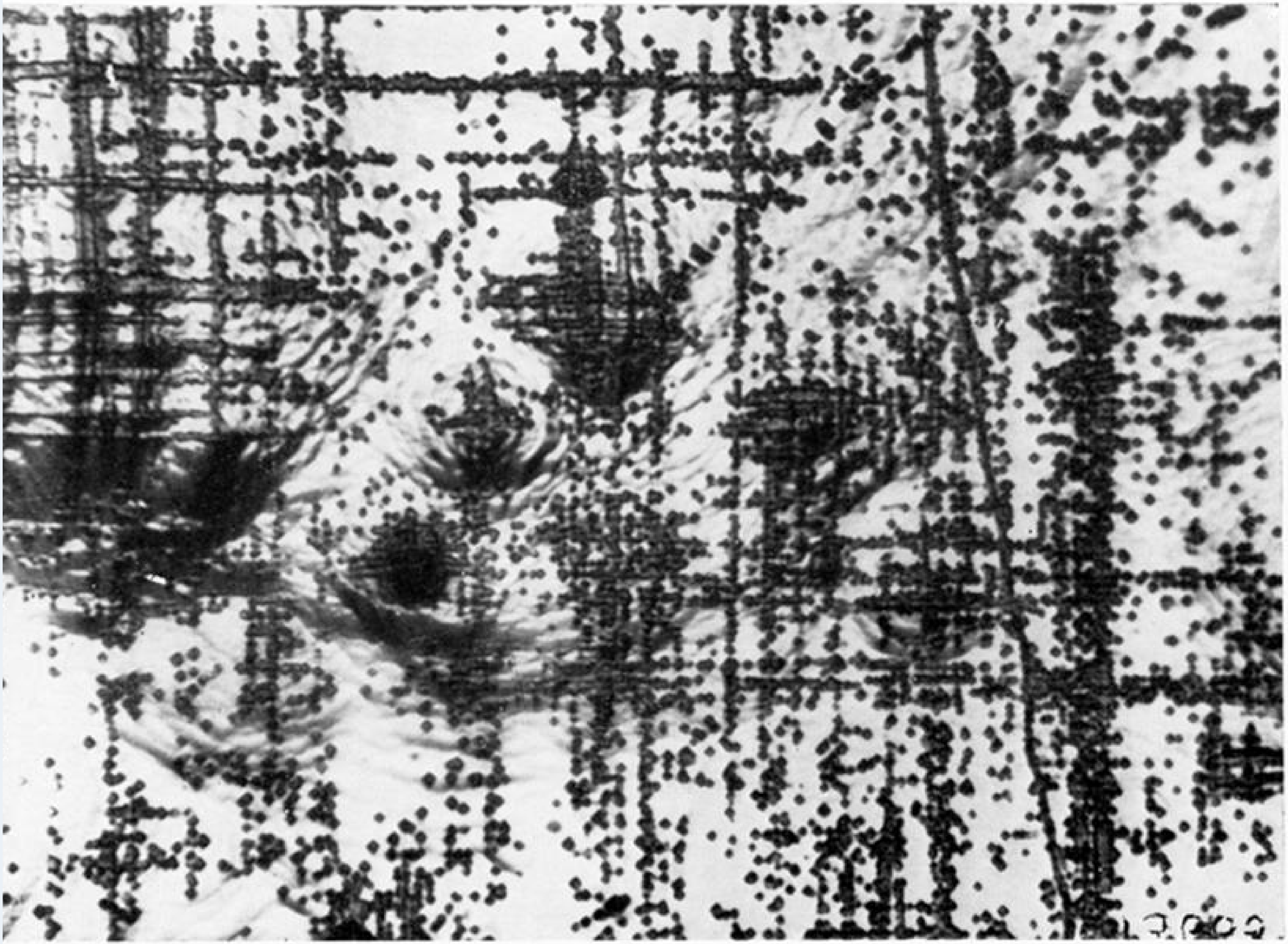


FIGURE 9. Development of slip lines after 100000 impacts with methanol drops. (Magn. × 300.)

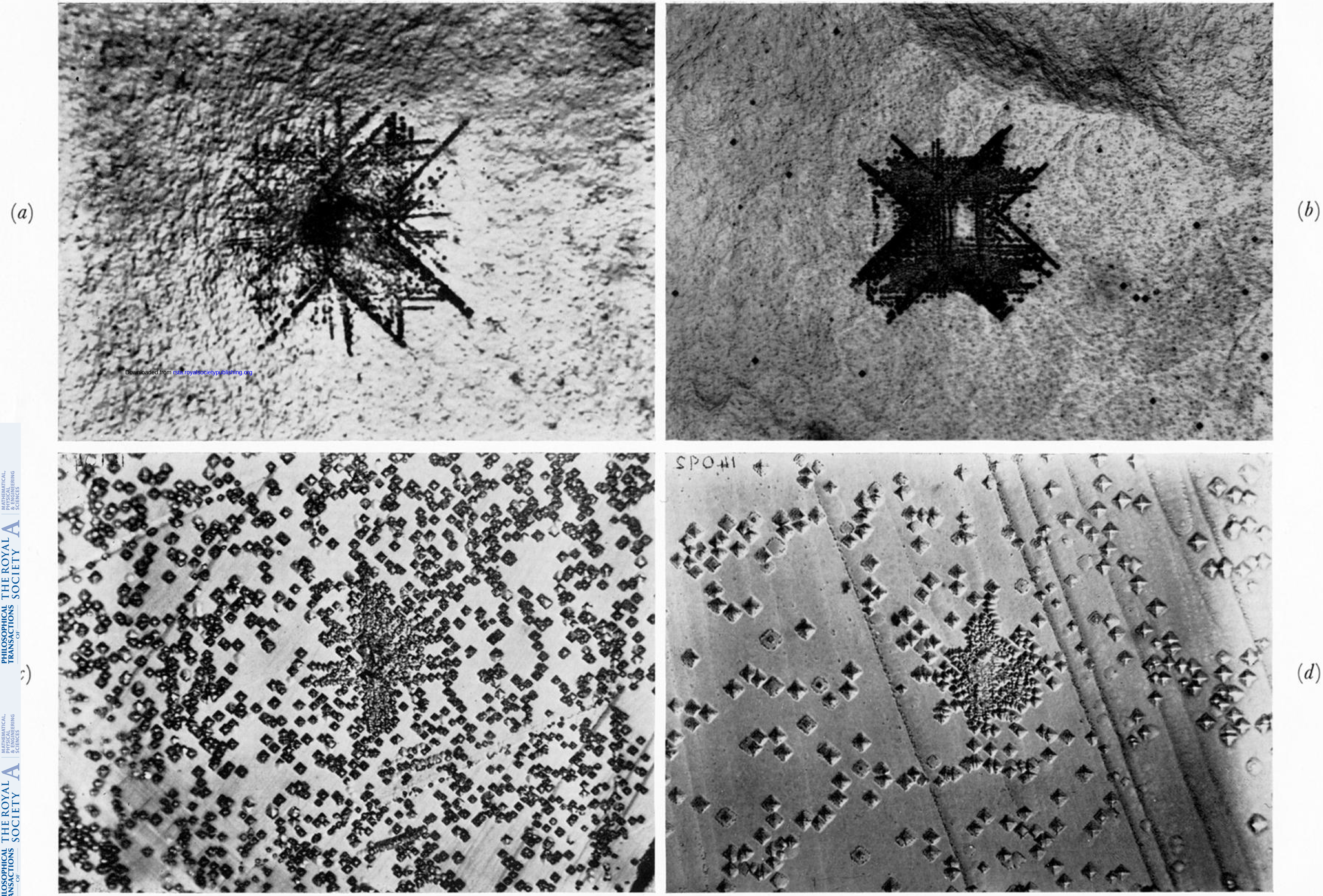
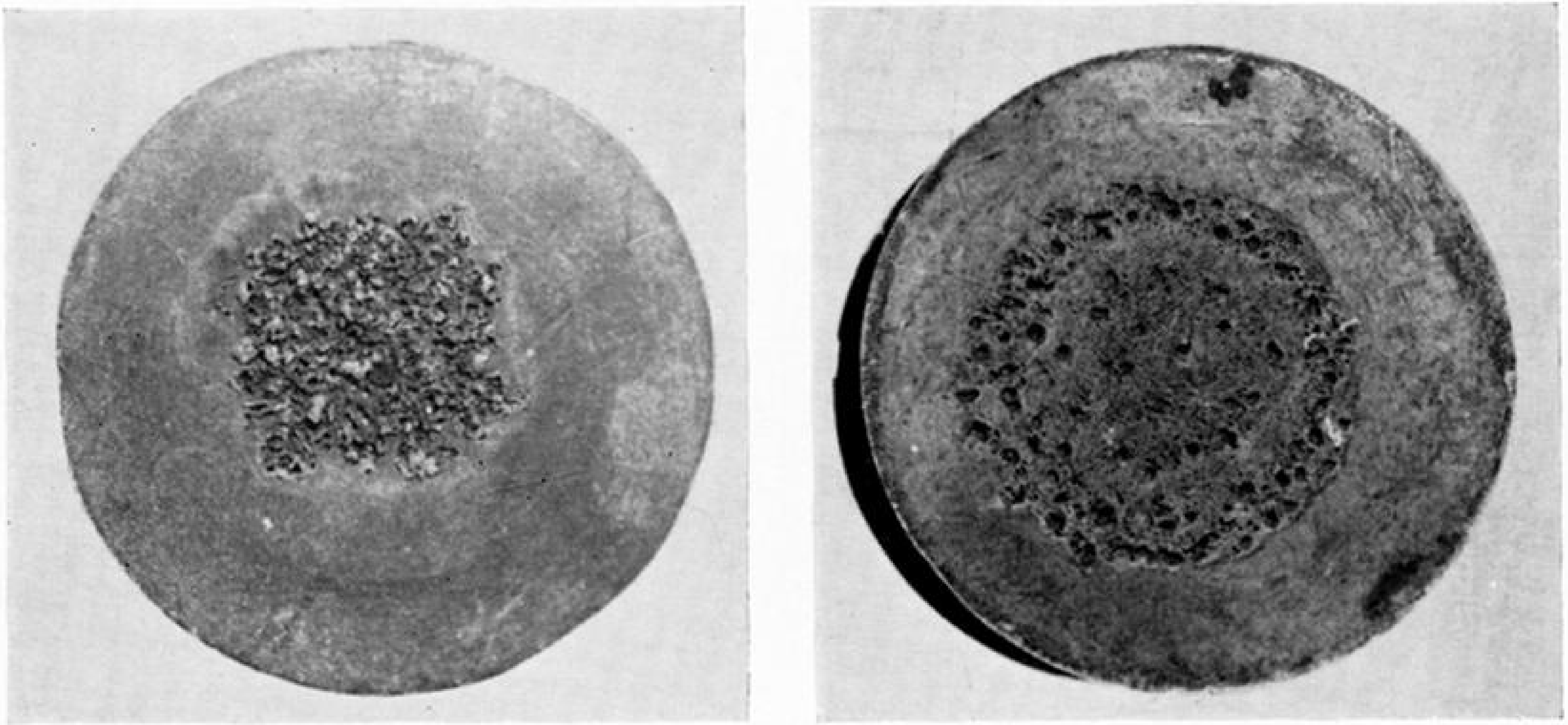
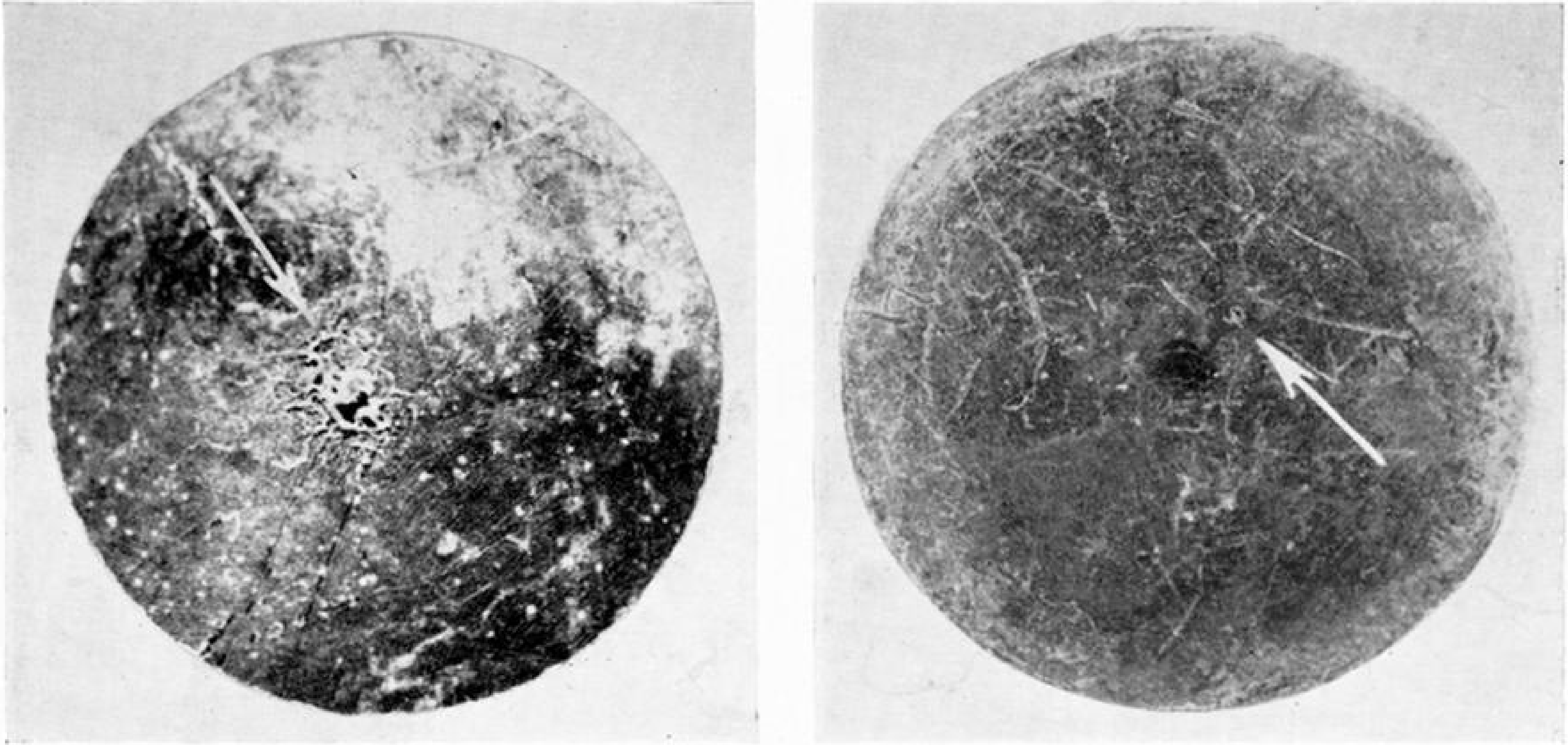


FIGURE 7. Rosettes produced by liquid impacts. (*a*) 1·5 mm water drop, 15 m/s. (Magn. × 400.) (*b*) 2·5 mm water drop, 26 m/s. (Magn. × 400.) (*c*) 3 mm methanol drop, 65 m/s. (Magn. × 500.) (*d*) 3 mm mineral oil drop, 65 m/s. (Magn. × 500.)



IGURE 2. Cavitation erosion of the front surface of the specimens 1 (2) and 2 (4). (Magn. × 1·5.)



IGURE 3. Local pits on the rear surface of specimens 1 (2) (magn. × 1·5), and 2 (4) (magn. × 1·6).