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

Practical Aspects of Cavitation [and Discussion]

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XXIV. Practical aspects of cavitation

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Damage produced by cavitation under field conditions can be a serious problem. The main causes of this damage and its characteristics are discussed briefly and possible remedial measures are examined. Accelerated laboratory tests are found to play an important part in cavitation erosion research, but interpretation of results needs care.

Most past investigators have tended to treat cavitation damage and droplet erosion as unrelated phenomena and only qualitative correlations between the respective simulated tests have been possible. This paper presents an attempt to correlate quantitatively the results of three different erosion tests. A broad correlation between results of the drop impact erosion and constricted tube cavitation tests shows general agreement. A more detailed, but restricted, correlation has been obtained between results of drop impact and vibratory cavitation erosion tests. In both correlations, however, there is evidence of some discrepancies between corrodible and incorrodible materials.

A number of factors which govern the rate of damage in the various laboratory tests are of interest. In particular, in the drop impact test the velocity of collision and the jet diameter are shown to have significant effects. There is a marked similarity between the behaviour of materials in this test and in fatigue tests and also evidence of a threshold velocity below which measurable damage ceases. The other laboratory tests were found to have their own particular controlling parameters, but the general phenomenon of cavitation erosion is more complex and is not discussed in detail.

By conducting comparative tests under reproducible conditions it has been possible to classify a variety of new and traditional materials in order of relative erosion resistance and thus provide some guide to their selection for service. While the results add to the evidence that hardness is the major attribute controlling erosion resistance other properties such as ductility, elasticity and fatigue strength are seen to be significant.

1. Introduction

Cavitation is the formation of voids or bubbles containing vapour and gas in an otherwise homogeneous fluid in regions where the pressure falls locally to that of the vapour pressure corresponding to the ambient temperature. The regions of low pressure may be associated with either a high fluid velocity or vibration. Of the three main consequences of cavitation—noise, erosion and loss of efficiency—only the last named is an effective limit to the design and operation of conventional machinery. Since, however, the development in a machine of cavitation to the point where it adversely affects hydraulic performance is a gradual process, there is a range of conditions within which noise and erosion may be present. As it may be uneconomic to avoid cavitation entirely the engineer must either reduce its harmful effects or employ materials able to resist them.

It is ironical that cavitation damage was first observed on high speed ship propellers, the development of which was made possible by the advent of the steam turbine, which was later found to have its own erosion troubles. Yet, in spite of this link, for many years cavitation damage in hydraulic machinery and droplet erosion in steam turbines have been regarded as quite separate and possibly unrelated problems. It is not surprising, therefore, that in most early attempts to investigate the mechanism of either type of damage, and the relative resistance of different materials to that damage, fairly specialized test equipment has been devised. Thus, to investigate the resistance of materials to droplet erosion drop impact tests as described by de Haller (1939), Honegger (1927) and Soderberg (1935) were used. Cavitation damage was studied similarly, by de Haller (1939), Mousson (1937) and Schröter (1933), using venturi and other types of constricted tube. Of these early workers only de Haller seems to have examined the general problem of erosion, but although a fund of test data to aid selection of materials was accumulated, no concerted effort was made to correlate the results of different tests. However, the different types of damage gradually came to be compared qualitatively and treated as related instead of separate phenomena. The A.S.T.M. Symposium on erosion and cavitation (1962) represented an important milestone in this reformation.

In an attempt to satisfy the need for more positive data the author has been investigating by means of laboratory tests the quantitative correlation between erosion caused by liquid impact and that caused by cavitation damage. Initially, the correlation was investigated between the erosion produced by a repeated drop impact test and damage caused by cavitation in a constricted tube. The work now has been extended to include results obtained by use of the vibratory cavitation erosion test. At the same time there has been some demand for further information on the relative resistance of materials to erosion.

2. Cavitation erosion of turbo-machinery

The general problem of cavitation in turbo-machinery has been discussed in some detail by Shal'nev (1958) and Winternitz (1957). It is shown that the tendency for a machine or an element of a machine to cavitate can be determined by the application of dimensionless pressure groups derived from Bernoulli's theorem. Limiting values of these cavitation coefficients for a satisfactory hydraulic performance can be determined by model tests.

For a complete machine the cavitation coefficient as defined by Thoma is

$$\sigma_{\mathrm{Th.}} = (p_1 - p_{\mathrm{vap.}})/(p_2 - p_1),$$

while that for a blade element is $\sigma = (p_\infty - p_c)/\frac{1}{2}\rho v_\infty^2$.

Thus it can be seen that the conditions which cause cavitation and lead to erosion are insufficient submergence and excessive velocity. The latter could be aggravated locally by slight imperfections or roughness on the model and leakage flows at blade tips.

Cavitation damage can occur on the faces and tips of rotor blades, on the hub and on guide vanes and casings of machines.

Vibration may also cause cavitation and pitting and this has been observed in quite a different class of machinery, namely diesel engines, in which the watersides of cylinder liners have been attacked.

The characteristics of cavitation damage are varied, depending on the intensity of cavity collapse and the properties of the material being eroded. With slight attack and in the early stages of more severe damage, plastic deformation is evident and the surface takes on an 'orange peel' texture although little, if any, loss of material occurs. After

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a longer time the surface begins to show signs of pitting which occurs randomly at first, but later the surface of the whole area affected begins to fail. As erosion proceeds, pits deepen, blades may be perforated and, as a consequence of the weakening effect, fragments may actually break off. There tends to be a difference between the appearance of the damage of ductile and brittle materials. With the former, pits are surrounded by a raised rim of deformed material that is visible to the naked eye, while in the latter case this rim is apparently missing. The grain size and microstructure can also affect the texture of the eroded surface and the mode of failure.

In dealing with cavitation erosion three main courses are open to the engineer. He could design and operate his machine to avoid the occurrence of cavitation altogether; this, however, is not usually economical. The second course would be to accept some cavitation, but to reduce its harmful effects by air injection (Rasmussen 1956) or by using a thin water sheet protective layer (Mazik 1963). Where neither of these alternatives is possible, materials able to resist cavitation attack must be employed.

The selection of such materials can sometimes be based upon practical experience but, owing to the high cost and length of time necessary to conduct field trials, use is generally made of accelerated laboratory tests.

3. Laboratory erosion tests

There are two main types of laboratory cavitation erosion test and they have been in use for a number of years. The first of these is that in which cavitation is generated by a high relative velocity of fluid flow. This could be achieved by the flow through a venturi (or otherwise constricted tube) or alternatively by the rotation of a perforated disk totally submerged in water. Both of these tests require a fairly large amount of power to run them and the rates of erosion tend to be low—particularly in the constricted tube.

The second type of test produces cavitation by vibration using the principle of magnetostriction as demonstrated by Gaines (1932). This new generation of accelerated tests based on a nickel tube transducer has been widely used and a large fund of test data has been accumulated. The nickel tube transducer had several disadvantages, however, and now more modern units of the type designed for ultrasonic drilling are being employed (Hobbs 1964). Continuous and pulsed cavitation are both possible.

Over a similar period, in addition to the laboratory cavitation tests, the drop impact test has been developed along parallel, but independent, lines. In this apparatus test pieces are mounted on the rim of a wheel which is driven at high speed so that they collide with the sides of two jets of water. Material is removed from the leading faces of test pieces of most materials in a matter of minutes and the erosion rate in terms of weight loss can be obtained quickly.

All these laboratory tests enable materials to be classified in order of erosion resistance and results, in the main, have been confirmed by practical experience. There is, however, one danger resulting from the relatively short duration of test since this tends to rate corrodible materials too highly in relation to corrosion-resistant materials. Thus only materials of a given type may be compared with a fair degree of confidence. A knowledge of the corrosion resistance of materials is usually available and this can be taken into account.

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In laboratory tests the size of the test piece and the quantity of erosion obtained make gravimetric determination the most suitable. An analytical balance enables the loss of weight to be measured to an accuracy of $\pm 0{\cdot}1$ mg which is more than sufficient for most purposes.

Results of repeated exposures of a given test piece enable a plot of weight loss against time, such as that shown in figure 1, to be obtained. From this it can be seen that erosion does not start at once. More detailed investigation shows that a certain period (the incubation period) elapsed before measurable weight loss occurs. Damage then begins randomly at first, local pits being formed which grow, or increase in number, until the surface has completely failed and a near uniform rate of erosion is attained. As the pits deepen, trapping water and air, the rate of erosion tends to fall off gradually.

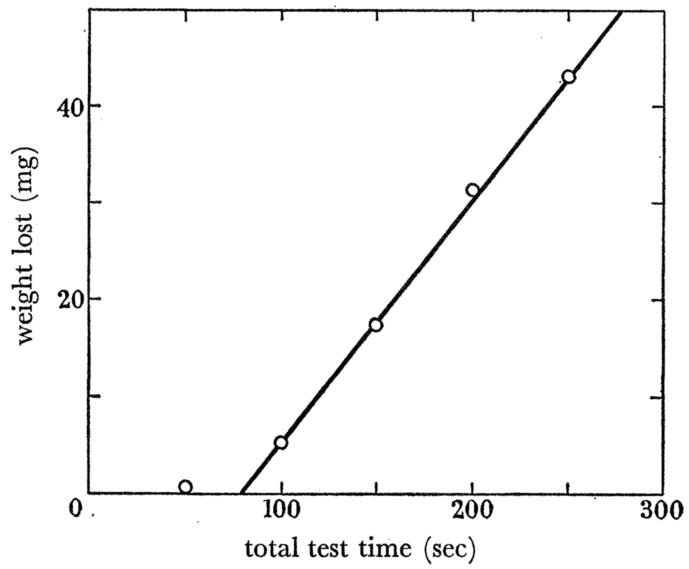

FIGURE 1. Typical plot of erosion against time.

The characteristics of main interest are the near uniform rate of erosion and, to a lesser degree, the incubation period. The latter is affected by the condition of the surface, i.e. its roughness and the presence of any hardened layer, whereas the former, when once established, is relatively unaffected by the state of the surface. In making the correlations therefore the near uniform rate of erosion was used and thus the effect of any variations in surface finish of the different types of test piece was minimized.

4. Correlation of erosion test results

The object of this study was to investigate the quantitative relation between different erosion tests. Initially the two most extreme cases were chosen; the drop impact erosion test and the constricted tube cavitation erosion test. Materials used included cast iron, steels, bronzes and aluminium alloys. The correlation shown in figure 2 appeared to be quite good over the broad range investigated but there was a need for further and more detailed examination of the more resistant materials, the corrosion resistance of which plays a bigger part. At this stage, although general qualitative agreement was obtained with vibratory tests on similar materials, no quantitative correlation was possible with vibratory erosion test data for test pieces from the same bars.

Subsequently it has been possible to begin a fresh correlation between drop impact and vibratory test results and, so far, a wide range of ferrous and non-ferrous alloys have been compared, as shown in figure 3. Once again there was generally good agreement between the results of the two tests; comparatively few materials seemed to be exceptional, that is, outside the normal scatter bands.

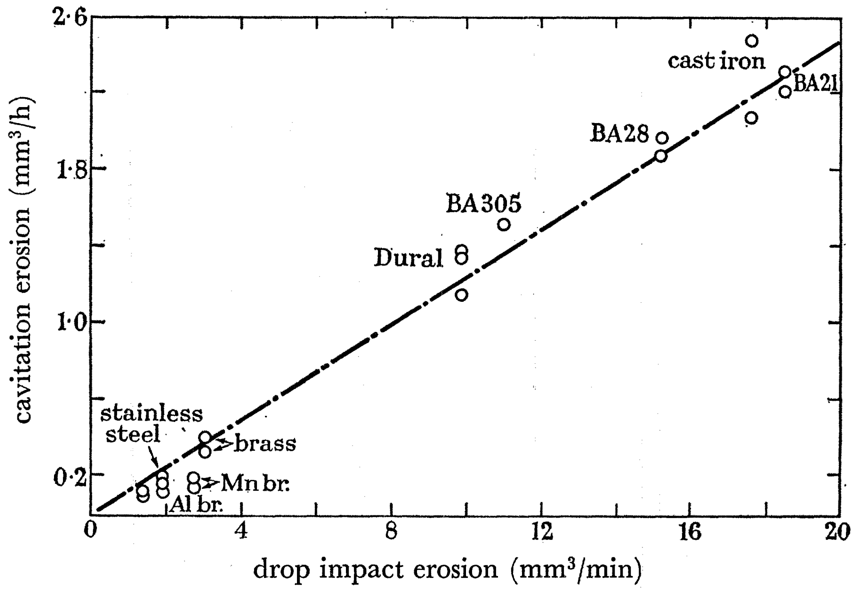

FIGURE 2. Correlation between drop impact and cavitation tests.

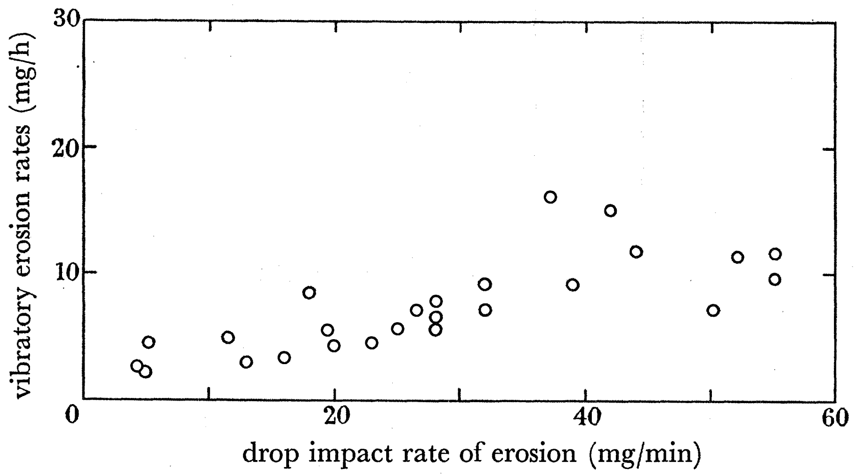

FIGURE 3. Correlation between impact and vibratory tests.

5. EFFECTS OF TEST CONDITIONS

In determining the optimum conditions for the different tests the effect of the main variables was investigated and the findings proved quite interesting and of some relevance.

The conditions causing erosion in the constricted tube test are very complex and not yet fully understood. Both the geometry of the test section and the nature of the flow past it have a marked influence on the magnitude and location of the damage. Attempts are being made to investigate the effects of these variables separately. Thus, by keeping the geometry and cavitation number constant, it has been possible to show that the velocity has a major effect on the erosion rate (figure 4).

In the vibratory test the amplitude of vibration was found to be the main variable and tests on four materials all show that the rate of erosion varies with amplitude to the power 1·5 over the working range. Frequency of vibration, which is nominally fixed and temperature of the test water have significant but less pronounced effects.

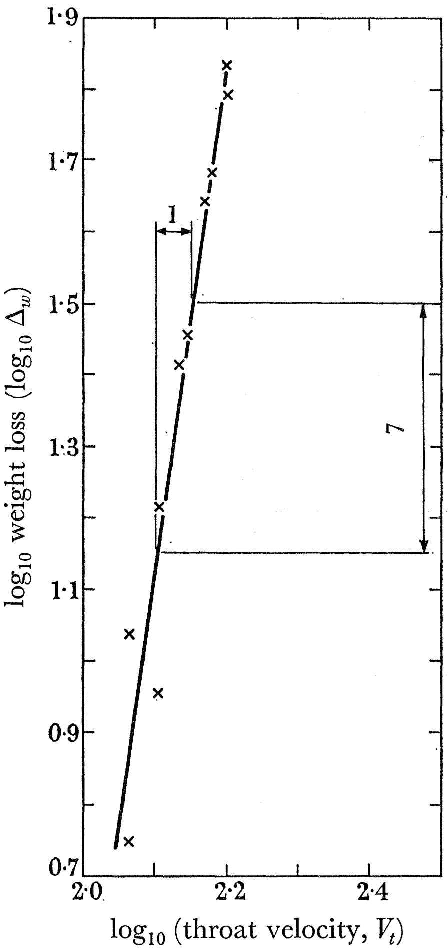

FIGURE 4

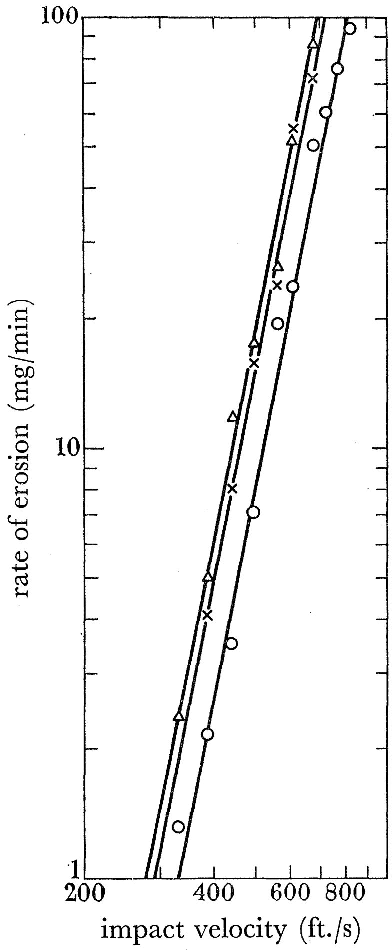

FIGURE 5

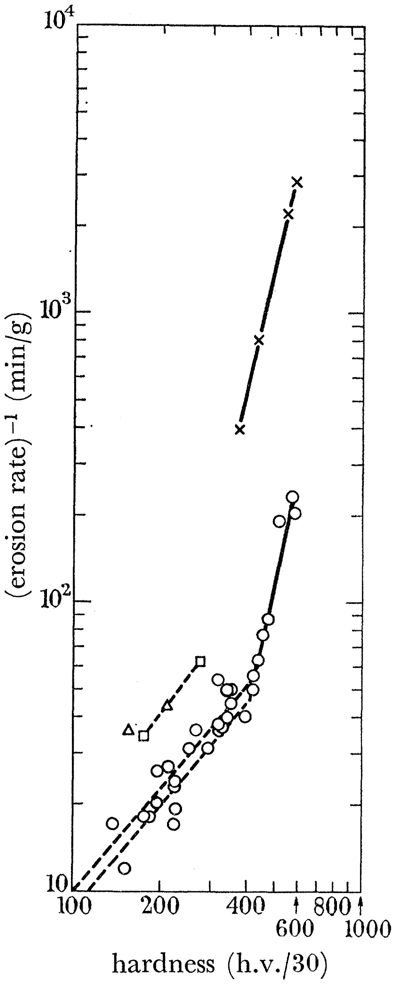

FIGURE 6

FIGURE 4. Effect of flow velocity on cavitation erosion.

FIGURE 5. Effect of impact velocity on droplet erosion. ○, Mild steel; ×, brass; △, Duralumin.

FIGURE 6. Relation between erosion rate and hardness. ×, Stellite; ○, ferrous; △, aluminium bronze; □, Monel.

The drop impact test conditions are affected to the greatest extent by the impact velocity and the diameter of the jet. The rate of erosion per unit time was found to increase with the fifth power of impact velocity over the range from 330 to 825 ft./s (figure 5). There is, however, a tendency for the test pieces to have an infinite life at velocities below a certain threshold and in this respect there is a similarity to the behaviour of materials in a fatigue test. It has also been found that the incubation periods for a number of similar types of

Table 1

material	chemical composition	erosion rates: drop impact (mg/min)	erosion rates: vibratory (mg/h)	Young's modulus (tons/in.²)	hardness h.v./30	tensile strength (tons/in.²)	elongation on 2 in. gauge length (%)
stellite 12	Co 59, Cr 29, W 9, C 1·8	0·35	—	12950	583	54	1
stellite 6	Co 66, Cr 26, W 5, C 1·0	1·24	—	13400	434	58	1
steel En24	C 0·35, Si 0·24, Mn 0·53, Ni 1·49, Cr 1·17	4·9	2·05	—	583	120	8
steel En57	Cr 17, Ni 2, C 0·25 (max.)	13·0	3·0	—	457	81	1
steel BS 1630B	Cr 13, C 0·2 (max.)	16·0	3·3	—	439	78	1
steel FV 520B	Cr 15, Ni 5·5, Mo 1·5, Cu 1·5	18·0	8·6	13000	320	63	25
s.g. iron	C 3	20·2	—	11160	345	60	1
aluminium bronze	Al 8·5 to 10·5, Ni 4·5 to 6·5, Fe 3·5 to 5·5, Cu rem.	23·0	4·2	8620	211	43	16
steel FV 566	Cr 11·5, Ni 2·3, Mo 1·4	27·0	8·7	—	325	65	21
s.g. iron	C 3	28·0	—	11160	266	50	—
aluminium bronze	Al 8·5 to 10·5, Ni 1·0, Fe 1·5 to 3·5, Cu rem.	28·0	5·6	7100	155	35	30
steel En57	Cr 17, Ni 2, C 0·25 (max.)	32·0	7·0	—	293	58	19
steel En56C	Cr 13, C 0·2	39·0	9·1	13600	197	37	33
steel En58J	Cr 18, Ni 9, Mo 3, C 0·07	52·0	11·3	—	228	40	59
steel En58B	Cr 18, Ni 9, C 0·08	55·0	11·7	14500	183	42	45
gunmetal	Sn 10, Zn 2, Pb 1·5 (max.), Ni 1·0 (max.), Cu rem.	59·0	34	5630	94	17	15
h.t. brass	Cu 55, Fe 0·5 to 2, Mn 3 (max.), Al 2·5 (max.), Sn 1·5 (max.), Ni 1 (max.), Pb 0·5 (max.), Zn rem.	80·0	44	5900	113	30	20
Ni-resist	C 3 (max.), Si 1·75 to 3·0, Cr 1·75 to 2·5, Ni 18 to 22, Mn 0·7 to 1·0	81·0	—	7810	152	27	14
mild steel	C 0·12, Mn 1·19, S 0·25	120	50	13600	200	38	16

material tested under identical conditions are, to some extent, determined by the fatigue endurance limit.

Results of a rather limited series of tests suggest that the rate of erosion is proportional to the square of jet diameter. Effects of the density and bulk modulus of the fluid and of the elastic modulus of the material under test have also been observed.

6. Results of comparative tests

By conducting comparative tests under standard conditions it has been possible to classify a range of materials in order of erosion resistance. In table 1, drop impact and vibratory test results are given for metallic materials together with a few details of the chemical composition and mechanical properties. It will be seen that high tensile and martensitic steels and aluminium bronze are among the most resistant of the more common materials. Facing alloys such as the stellites are even more resistant, as clearly demonstrated by the drop impact results.

A few plastics, including nylon, polyethylene, polypropylene, Vinyl, Fluon, Penton and Perspex, have been subjected to cavitation erosion tests and all but the last three appear to be quite promising although more intensive tests will be required to confirm these provisional results.

For metallic materials of a given type the results add to the evidence that hardness is the main attribute in determining erosion resistance. As indicated by the theory of liquid/solid impact the elastic modulus also has a significant effect. Thus, as figure 6 shows, the copper and nickel alloys have a better erosion resistance for a given hardness than the ferrous alloys. The extraordinarily high resistance of the stellites cannot be explained entirely by virtue of its mechanical properties and the reasons for this are not yet fully understood.

7. Conclusions

It has been shown that similar relative ratings of the resistance of materials can be obtained in long term cavitation erosion tests and in much faster repeated drop impact tests. The correlation must now be extended to establish that the results of these tests are in agreement with the behaviour of the same materials in the field. Thus, as there is still a great need to develop materials to resist damage by cavitation, advantage may be taken of rapid, relatively cheap, laboratory tests for their evaluation. It has been found that both the fluid velocity in the cavitation test and the impact velocity in the drop impact test have a considerable influence on the damage rates. The results of the laboratory tests also indicate that strength and elasticity are important factors in determining the resistance of a given material to erosion.

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XXV. Discussion

[Plates 55 to 58]

R. Hickling (General Motors Research Laboratories, Michigan)

Because of the difficulties involved in direct observation, it is necessary to propose models of the behaviour of cavities which may account for a variety of effects associated with cavitation. Perhaps the most fruitful concept has been that of cavity collapse, first proposed by Lord Rayleigh. Although his analysis was concerned with a spherical motion, the concept that evolved was essentially that of an almost empty hole that is being filled by liquid rushing in from all sides and becoming very highly compressed in the process. Spherical motion will produce more intense compressions, but similar compressions should occur with almost any kind of hole. Within a cavitation cloud the mitigating effect of nonspherical motion is likely to vary quite widely so that some collapsing bubbles may experience very high compressions whereas others may not. The existence of such high compressions appears to be the only way to explain many of the observed effects of cavitation. For example, the luminescence from ultrasonic cavitation (better known as sonoluminescence) is believed to be due to the incandescence of compressed gases and vapours within the collapsing bubbles. Evidence (Strinivasan & Holroyd 1961) indicates that the temperatures within the bubbles are possibly of the order of 10^4 °K. Since these temperatures are affected by heat conduction from the compressed gas into the surrounding liquid (Hickling 1963), it does not seem unreasonable to assume corresponding pressures somewhere between 10^5 and 10^6 atm. Another effect which is thought to be due to the high compressions induced by cavity collapse is the nucleation of freezing by cavitation in subcooled liquids (Chalmers 1964). This effect has been observed in water, and it has been estimated (Hickling 1965) that nuclei of an appropriate size can grow provided there are peak pressures of 10^5 atm or more.

The existence of such centres of high compression would seem to be relevant also from the point of view of cavitation damage—particularly with regard to the mechanism discussed by Professor Plesset where shockwaves are assumed to radiate from a compression centre by means of an elastic rebound. The calculations by Hickling & Plesset, that are mentioned in his contribution, indicate that shock intensities of the order of 10^3 atm may occur in the liquid at distances from the collapse centre of about two or three times the original radius R_0 of the bubble, provided the peak pressures at the collapse centre are between 10^5 and 10^6 atm. The calculations were not carried beyond the point where the emanating pressure wave steepens into a shockfront, so that the complete development of the wave was not determined. However, certain significant features in the rebound process were established. Perhaps the most important of these is that the outward motion of the interface maintains the peak pressure of the outgoing wave at a $1/r$ attenuation during the initial stages of its formation. Beyond this stage, say, beyond a radius $r = a$, weak shock-wave theory (Landau & Lifshitz 1959) for spherical N waves might be expected to apply where the attenuation goes as $(1/r)\,(1+A \log (r/a)^{\frac{1}{2}})$. In water, this kind of attenuation would be applicable for peak pressures below about 10^4 atm and A would have a value of about 1. The predicted shock intensities are then sufficient to damage metals up to distances roughly $3R_0$ from the collapse centre. For much larger distances, of course, ordinary damping (due to viscosity and thermal conductivity) would reduce the intensity to negligible proportions.

The effect of a nearby solid boundary on collapsing cavitation bubbles is not easy to determine. Does it induce such departures from symmetry that a highly compressive collapse cannot occur close enough to cause damage? Could a highly compressive collapse occur on the surface itself? It is evident that liquid jets develop inside collapsing cavities, and the potency of fast moving jets has been very clearly demonstrated in the papers presented at this meeting. Is this then a more likely cause of cavitation damage? No definite answers appear to be in sight. However, any acceptable theory must attempt to explain certain features of cavitation damage. Among the more important of these are probably the diminution in damage intensity as the liquid temperature approaches the freezing point (Bebchuk 1957; Devine & Plesset 1964), and the potency of cavitation attack in water compared to that in other liquids (Plesset, unpublished). It can be shown (Devine & Plesset 1964; Hickling 1965) that the assumption that cavitation damage is due to a highly compressive collapse does appear to provide a basis for explaining these effects.

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J. H. Brunton

Is the damage produced by a collapsing cavity, as described by Benjamin and Ellis, characteristic of a jet impact? Does it for example show shear deformation due to liquid flowing across the surface? The damage caused by a shockwave alone would be relatively smooth since there would be little movement of the liquid relative to the surface.

A. T. Ellis

In this latest work the cavities were grown from small (0·001 in. radius) hydrogen nuclei and collapsed at reduced pressure (about 0·5 Lb./in.^{2} (abs.)) in order to yield lower collapse velocities and permit more accurate photographic observations. For this reason no damage was looked for, since observed jet velocities were only of the order of 100 ft./s. In earlier work cavities were generated by a spark and collapsed at 15 Lb./in.^{2} (abs.). A cavity of 0·2 in. maximum radius yielded a pit of 0·005 in. radius in aluminium. Some suggestions of cracks were observed near the edge of the pit, but the microphotography was of insufficient resolution to be conclusive. It was also possible to obtain comparatively smooth dents in soft aluminium with these spark-generated bubbles, depending upon the original distance of the bubble centre from the material surface. It would thus appear that both jet and shockwave damage can occur according to the geometry of the situation. Jet damage might be expected to affect a smaller area and give rise to a finer structure in the damage pattern more consistent with the type usually reported in the field. However, this conclusion may be compromised by material properties such as a tendency towards fatigue cracking, which could give local damage due to repeated blows of a non-localized nature. Further experiments are planned to yield a comparison of magnitudes, durations and occurrence probabilities for stresses due to bubble collapse in both jet and shockwave producing modes.

G. E. Gadd (Ship Division, National Physical Laboratory)

Dr Benjamin has argued very elegantly that involuted, doughnut shaped cavities arise from the necessity of forming a doubly connected region in the flow field. Is there any alternative simple physical explanation of why these small high speed jets penetrating the cavities should occur?

T. B. Benjamin

The argument referring to the need for vortex formation in order to preserve impulse serves mainly to give a logical view of events *as a whole* when a cavity collapses unsymmetrically, and it is helpful in showing that the remarkable behaviour observed depends on a broad physical principle rather than on any delicate combination of experimental conditions. I do not think there is any simpler way of establishing this general picture of what happens. However, one might construct another simple explanation of the jet on the lines that it is an instance of the 'lined charge' or 'Monroe jet' phenomenon (see Birkhoff 1950, p. 68), for which the essential requirement is a flow *inwards* towards a stagnation point in close proximity to a free surface. Consider the flow field in a frame of reference moving with the centroid of a cavity, and suppose the cavity is axisymmetric and everywhere concave inwards to begin with. If the cavity were rigid, then of course its rearmost point would be a stagnation point, say O. But when the cavity is contracting, O will in fact lie inside the liquid. Moreover, at any specific instant the flow in this reference frame will be divided by a stream surface cutting the axis at O; the stream surfaces in front of this one will fold into the cavity, while those behind it will all pass away to the rear. This is essentially the same situation as is usually envisaged to explain the lined-charge effect (cf. the figure on p. 68 of Birkhoff's book); and though the fact that the flow field is continually changing in the present case obscures the interpretation somewhat, this explanation for the observed jet formation seems physically quite reasonable.

A. Silverleaf (Ship Division, National Physical Laboratory)

The analysis and experiments so elegantly described by Dr Benjamin appear to apply to cavities which are essentially vapour-filled. To what extent would the authors expect their jet formation and other remarkable cavity collapse phenomena to be affected when the cavity contains an appreciable amount of permanent gas?

T. B. Benjamin

These phenomena mainly get going during an intermediate stage in the collapse of a cavity, before the enclosed vapour or gas is compressed sufficiently to exert a significant retarding effect on the inward motion. Nevertheless their final developments, particularly as regards the vigour of the jets that may form, depends very much on the overall extent of the collapse, which is of course reduced by the presence of permanent gas inside the cavity. For this reason underwater explosion bubbles, having comparatively much larger gas contents, are generally less effective producers of high speed jets than the kind of vapour-filled bubble observed by us.

A. V. Smith (Atomic Weapons Research Establishment) (Plate 55)

It may be of interest to show that a jet can also be developed by involution of a cavity surface attracted, not by its image in a nearby solid boundary, but by a similar cavity in close proximity. A photograph (presented in figure 1, plate 55) has been selected to show typical results of experiments performed at A.W.R.E. by Warren & Price to examine the interaction between two underwater explosion bubbles oscillating out of phase. In the photograph, which shows successive frames in vertical columns, the interval between the charge firings is 6 ms and the framing rate is 3000 per second. The jet emerging from the later bubble can be clearly seen penetrating the earlier one during its collapse, and the procedure is reversed during the collapse of the later bubble, which can be seen finally moving rapidly away from its original position.

F. G. Hammitt (Plate 56)

Benjamin & Ellis describe their very ingenious experiment where bubbles, initially rising in a static liquid, being forced to grow beyond the critical radius by the sudden imposition of liquid tensile forces in the neighbourhood of the bubble, and then collapsing under conditions of zero gravity once these forces are removed, flatten on the initial high pressure side, involute into a torus, thus creating a high velocity central jet from the initial high pressure side through the torus.

High speed motion pictures we have obtained of bubbles collapsing in the diffuser portion of a cavitating venturi† show much the same behaviour (see figure 2, plate 56). Consideration of the two cases shows that they are similar in that the bubble in the venturi is 'rising' from high to low pressure with respect to the mean stream velocity, just as the bubble in a static liquid under a gravity field in the authors' experiment. As noted in our sequence herein presented, the bubble flattens on the high pressure downstream side (to the right in the pictures) and involutes into a torus, presumably with a central jet passing through in the upstream direction (away from the high pressure side of the bubble).

The paper by Shal'nev, Varga & Sebestyen shows, under certain assumptions including geometric similarity, that volume loss due to cavitation damage should vary as the third power of the size of the model and also as the fifth power of the stream velocity. While these relations may apply to certain systems, such as presumably that investigated by the

† Collapse of a cavitation bubble in viscous compressible liquid—numerical and experimental analyses, R. D. Ivany, Ph.D. Thesis, Department of Nuclear Engineering, University of Michigan, Ann Arbor, Michigan.

authors, one must inquire into what effect on the flow régime and the static pressures adjacent to the damaged body a change in velocity or size will have, before being in a position to predict its effect. Considering, for example, the cavitating venturi systems investigated in our own laboratory, it is clear that in the region where the cavitation is fully developed, the pressure will be near vapour pressure regardless of velocity, and hence the driving force causing bubble collapse will not be significantly increased by increasing velocity. On the other hand, near the downstream termination of the cavitating region, the pressure is considerably above vapour pressure, so that an increase of velocity will have a substantial effect on the pressure differential available for bubble collapse, thus presumably increasing damage strongly. As described in my own paper presented at this meeting, this is indeed the observation we have made in our own tests. Our earlier observations on velocity effect, indicating a strong dependence on velocity and referenced in the present paper, stemmed from observations in the collapse portion of the cavitating region, and hence are consistent with our present understanding of the phenomenon.

Regarding size effect, even with geometric similarity, two-phase flow systems do not appear to scale according to classical expectations, so that one might doubt the general applicability of the relation regarding the effect of model size here presented.

I note that the conclusions of the paper by Shal'nev *et al.* are based on experiments using only water as test fluid. I wonder if the authors have also data on other fluids which might confirm their expectations.

K. K. Shal'nev

The remarks of Professor Hammitt concern three aspects of the investigation of the scale effect on cavitation erosion: (1) the identity of pressure gradients in the cavitation zone and outside it at points of change in the flow velocity around the model under natural conditions; (2) the scale number of the model and of the size of the cavitation zone; (3) the effect of the kind of fluid used.

Apropos (1), it is necessary to note, that the similarity of pressure according to our paper is achieved by the identity of the cavitation development stages, i.e. the equality of the relative sizes of the cavitation zone and cavitation numbers ensure the similarity of kinematic structures and their dynamic characteristics. This is stated in §3 of our paper.

In connexion with (2) it should be said that the third power is well confirmed by our tests with geometrically similar cylinders of 6, 12, 24 and 48 mm diam. and by the theoretical conclusions of Rayleigh. According to Rayleigh the pressure, arising owing to the incomplete closure of bubbles, is proportional to the third power of their diameter ratio. As the zone of burbling cavitation alone is able to provoke erosion, and since this consists of individual cavities (accumulations of bubbles) which grow and are then swept away by the flow, the Rayleigh theory could be applied to them with some approximation.

Referring to (3) our experiments were based only on the use of water. If a possibility should arise of using the data obtained by Professor Hammitt on other fluids, we should try to analyse them under the conditions described in the paper.

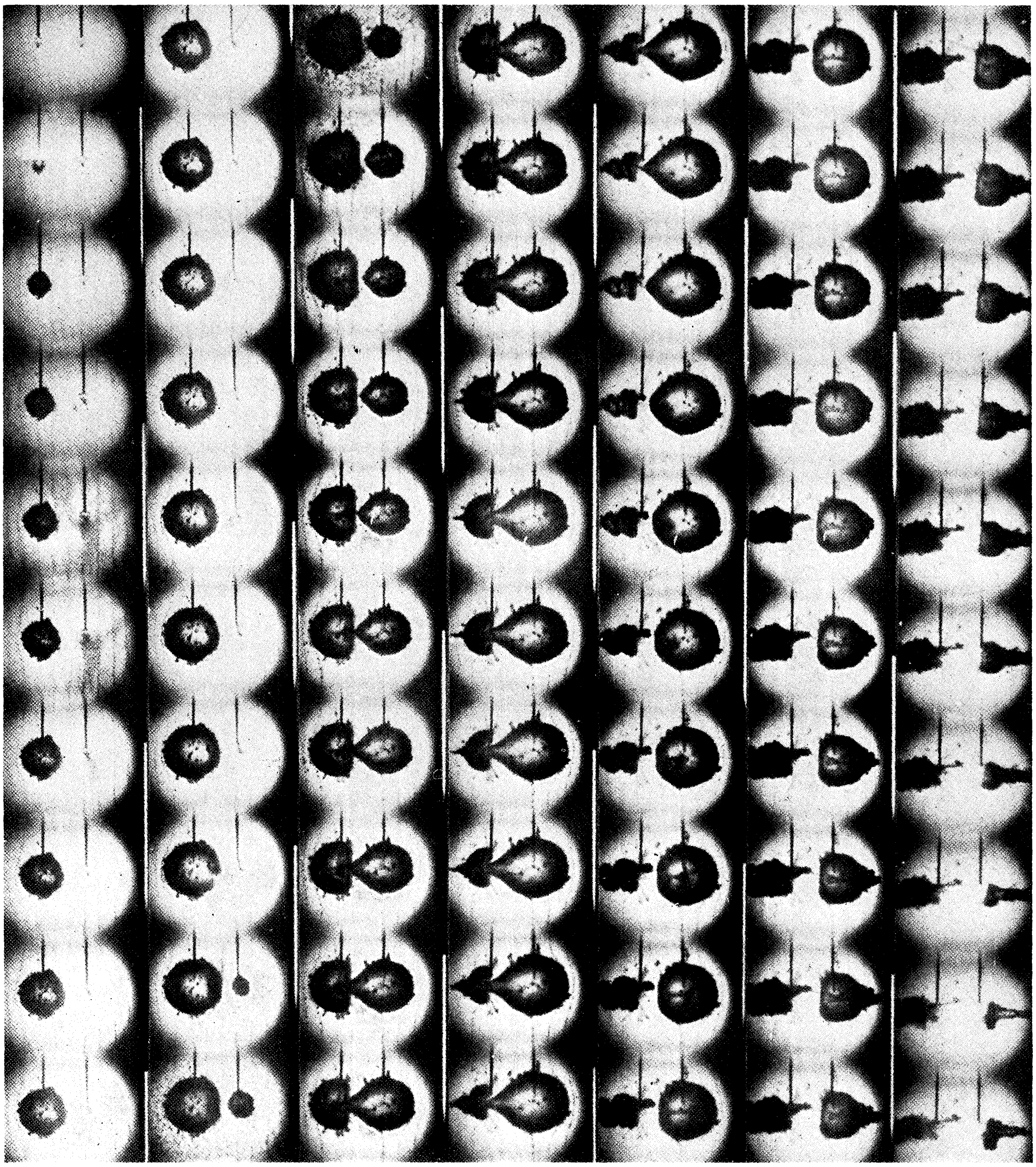

FIGURE 1. Two detonators fired with a time separation of 6 ms (Warren & Price).

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(*Facing p.* 280)

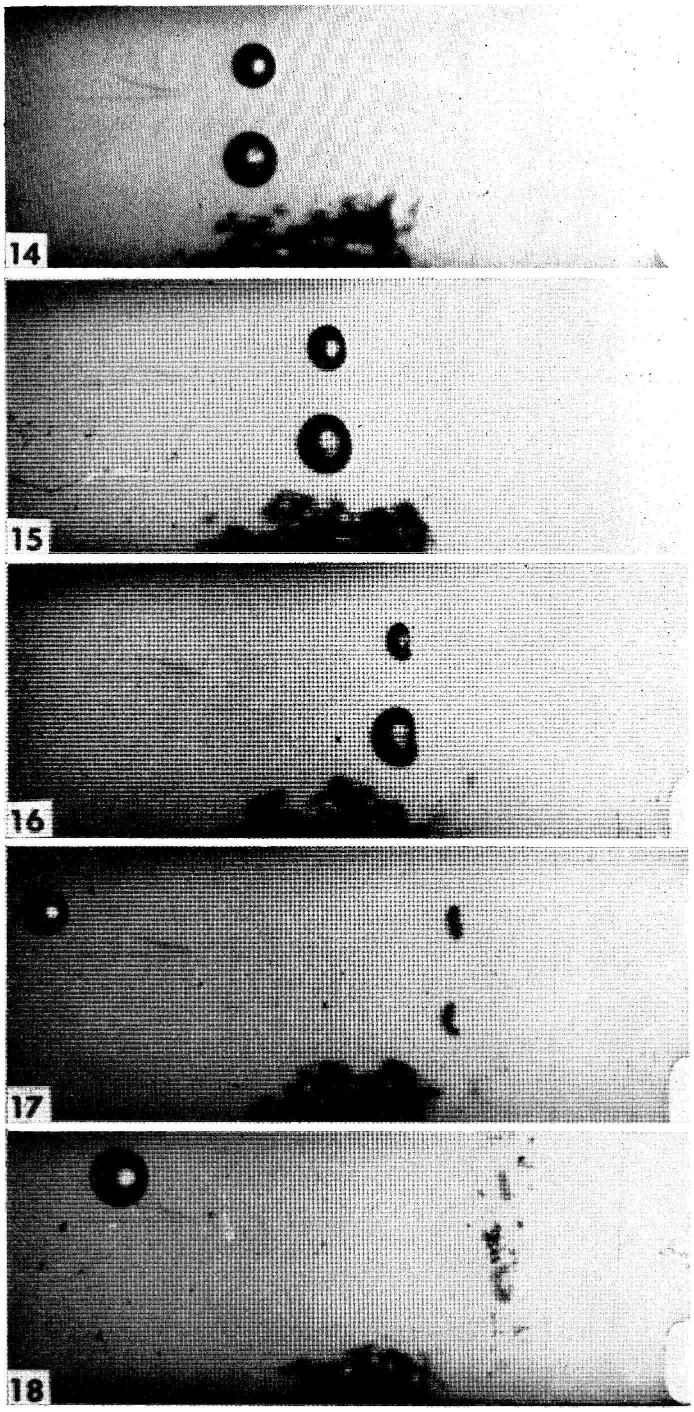

FIGURE 2

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

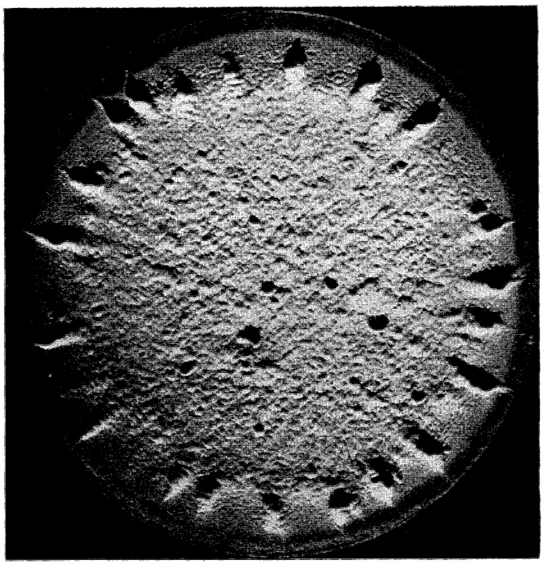

FIGURE 3. A cast nickel–aluminium–bronze specimen after 10 h test.

FIGURE 4. A typical pore (arrowed) at the tip of a rut.

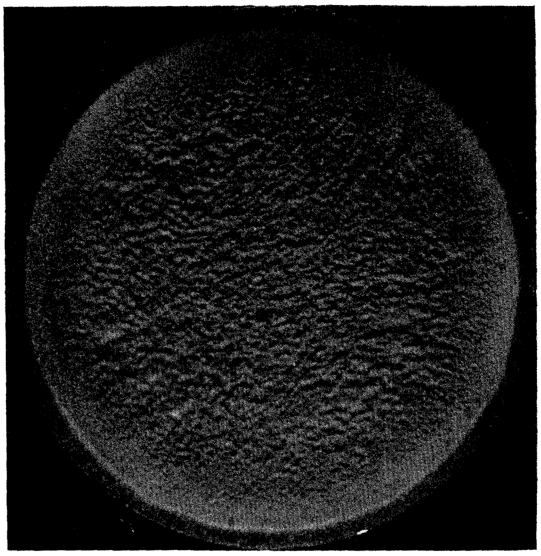

FIGURE 5. A wrought nickel–aluminium–bronze specimen after 10 h test.

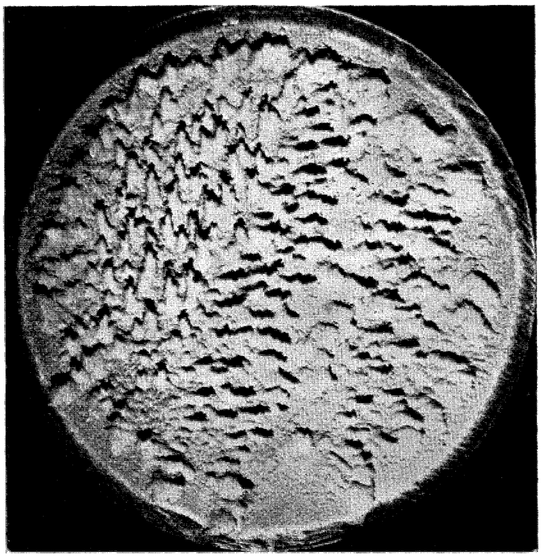

FIGURE 6. A specimen of coarse grained cast stainless steel after 10 h test.

FIGURES 3 TO 6. Specimens tested a 20 kc/s magnetostrictive oscillator, with peak-to-peak amplitudes of 51 μm (0·0020 in.). Test solution was 3 % sodium chloride kept at 25 °C.

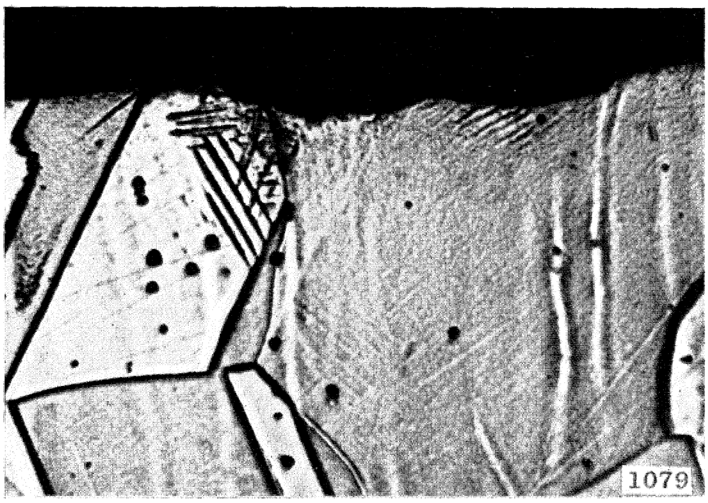

FIGURE 7. Typical section through an irregular shaped pit on stainless steel sample no. 26-3 (which had been run for 11 h at 'standard cavitation' at a throat velocity of 95 ft./s in water), showing slip lines. (Magn. × 800.)

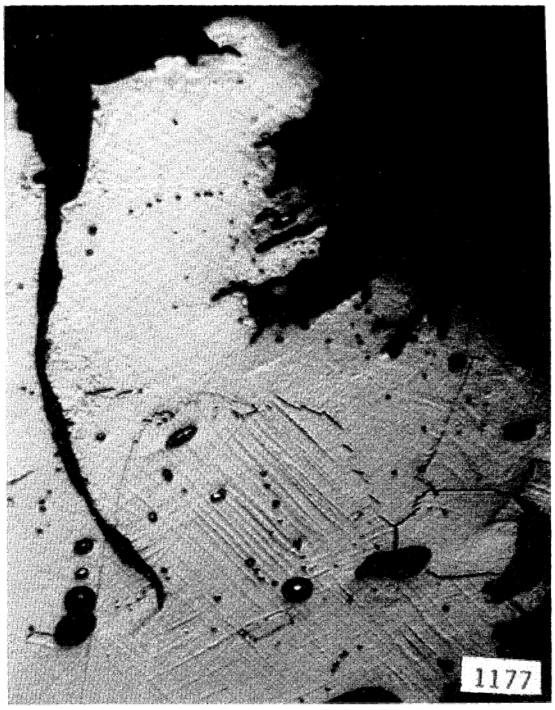

FIGURE 8. Section of type 316 stainless steel impellor in area of heavy cavitation damage from mercury. (Magn. × 800.)

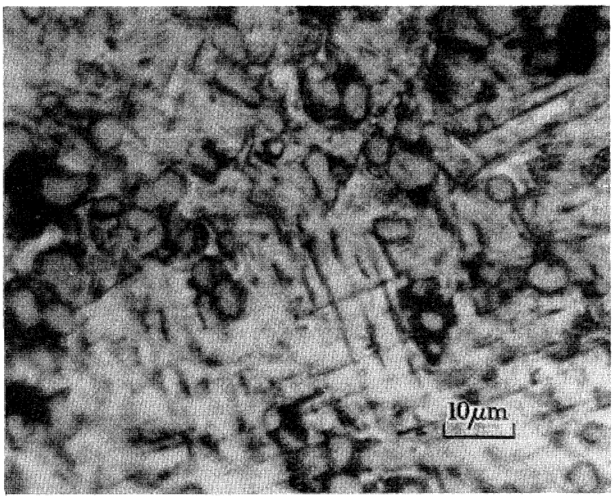

FIGURE 9. Cavitation damage on surface of specimen after magnetostriction testing.

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T. B. Benjamin

In the paper by Shal'nev *et al.* the Weber number is introduced as a dimensionless parameter upon which certain overall effects of cavitation are supposed to depend. It is defined by

$$\mathrm{We} = \rho v_\infty d/\sigma,$$

where ρ is the density of the flowing liquid, v_∞ the velocity of flow, d the characteristic linear dimension of the solid obstacle producing cavitation in its wake, and σ the surface tension of the liquid. In particular, figures 5 and 9 present measured values of the cavitation drag coefficients and rate of erosion as functions of We.

From this use of the Weber number, it would appear that the authors believe the effects in question to depend significantly on surface tension. No direct evidence in support of this belief is given, however, and the viewpoint represented in the paper is puzzling since the more usual conclusion seems to be that surface tension is an insignificant factor in present respects. Even allowing that surface tension may influence the initial growth of individual cavities from microscopic nuclei, most available theoretical and experimental evidence suggests that it has virtually no effect on the principal phases of cavity growth and collapse in typical circumstances, and hence no effect on the aggregate properties of a cavitating region—except perhaps in its incipient state. For well developed cavitation, such as to produce appreciable damage, the local hydrodynamic forces enormously outweigh surface tension forces in determining the main events, and so it seems unlikely that surface tension could have any residual influence on final average effects like cavitation drag and erosion rate. The fact that the values of We quoted in the paper are very large (of the order of 10^5) itself rather suggests that surface tension is not a relevant factor, since We may be interpreted as the ratio of typical magnitudes of the hydrodynamic and surface tension forces; to be fair, allowance should be made for the greatly reduced size scale of individual cavities, as compared with d, but this is more than compensated by the increased velocity scale for the radial motion during collapse.

The results showing that erosion rates vary considerably with We are not, of course, any proof of the importance of surface tension. The variations may well be accountable wholly to the dependence of We on d and v_∞. If surface tension were important, this fact would still, I believe, be very difficult to establish conclusively. By using different liquids in accelerated cavitation-damage tests with magnetostriction oscillators, several people have in the past obtained results showing an apparent dependence of erosion rate on surface tension (e.g. H. Nowotny 1942, *Z. Ver. dt. Ing.* **86**, 279). But the significance of such findings is made very doubtful by the possible relevance of other differences in the properties of the liquids, such as in viscosity, compressibility, concentrations and diffusion rates of dissolved gases, and chemical properties.

Would Professor Shal'nev and his co-authors care to comment on this matter, perhaps outlining the reasons for their belief in the importance of surface tension?

My second comment refers to their figures 3 and 4. It does indeed seem remarkable that the rate of erosion has such a pronounced maximum at approximately $h/d = 1$ (i.e. span of cylinder = diameter). The maxima of erosion rate as a function of λ (= length of cavitation region as a multiple of d) are also very interesting, though perhaps more readily understood than the first result. Could the authors suggest simple explanations for these phenomena? In particular, could they explain why the erosion rate becomes small for large h/d and for large λ?

K. K. Shal'nev

The observations of Dr Benjamin refer to three interesting aspects of cavitation erosion: (i) the role of liquid surface tension in the erosion process; (ii) the physical explanation of the influence of the model shape parameter h/d (for a circular cylinder) on the erosion intensity; and (iii) the physical explanation of the influence of the cavitation size parameter λ on the erosion intensity.

Of the large number of cavitation similitude criteria formulated by various authors (Noskievic 1957; Holl 1961) we chose the Weber number for an analysis of the cavitation erosion effect on the following grounds.

The Weber number is a function of surface tension which, according to Novotny (1942), influences the erosion intensity at a rate greater than σ^2.

In our experiments and in those of Konstantinov (1946) which we have used, the surface tension was varied only in connexion with the change in water temperature in the range $T = 7$ to 30 °C. While these changes are relatively small, it is possible, if cavitation erosion is investigated in other liquids, to achieve, for example with mercury and butanol, the value $(\sigma_{Hg}/\sigma_B)^2 \sim 600$. Compared with the hydrodynamic forces the surface tension is not large numerically but this does not diminish its importance in the erosion process. The vibration frequency of bubbles is related to capillary waves on their surface (Kurtze 1958). Owing to the bubble oscillations, high frequency pressure pulsations occur in the cavitation zone (Shal'nev & Rubina 1964) which are in my view, although of small amplitude, the basic cause of erosion. It should be recalled that for the practical prevention of erosion of the external surfaces of diesel cylinders, additives are used in the cooling water, the action of which is based on the reduction of the surface tension of the water (Bogachev & Mince 1959). Of course, in this erosion problem, in connexion with surface tension there are many other uncertain matters demanding special investigation. By means of the interconnexion of oscillating bubbles and cavities (agglomerated bubbles) with cavitation erosion it is also possible to explain two other points emerging from experiments on the influence of h/d and λ on erosion intensity. Table 1 gives the results of our experiments on cavitation and erosion behind a circular cylinder at various flow speeds and ratios with $\lambda = 2\cdot5$ to $3\cdot0$ (Shal'nev 1958). Our nomenclature here is N, the number of collapsing cavities, determined from the formula $N = Sv/d$, where $S = 0\cdot15$ from the experimental data (Shal'nev 1954); f, the characteristic vibration frequency of the cavity calculated from the Minert–Schmidt approximation $f = 0\cdot66d^{-1}$ kHz; d (cm) the diameter of the bubble or cavity.

It can be seen from table 1 that the erosion maximum in figure 3 of the paper for $v = 17$ m/s occurs at $f/N = 2\cdot05$, that is at double the collapse frequency of the cavity or when the characteristic vibration frequencies of the cavity equal the frequency of perturbations produced by the collapse of the cavity from both sides of the cylinder. In calculating f we adopted $h = d = 0\cdot6$ cm, i.e. a cavity whose span equals its diameter at the instant of its departure from a cylinder, on the basis of cinematographic studies of the cavitation zone (Shal'nev 1954). We note that in our experiments on cavitation erosion by the method of irradiation with sound waves the erosion intensity maximum occurred at a separation between the specimen and the end of the vibrator tube which was such that it could contain bubbles having a characteristic vibration frequency equal to the vibrator frequency of the tube (Shal'nev 1949).

The influence of the cavitation parameter λ is connected with the periodic structure of the cavitation zone. An erosive effect is exhibited only by those zones which consist of cavities which appear periodically and are removed by the flow. For values of $\lambda > 8$ the cavitation zone becomes stationary. Only its end continues pulsating and this region exhibits slight erosion after an extremely long experimental period (Shal'nev 1958). The erosion maximum at $\lambda = 3$ coincides with the maximal cavitation noise strength (Shal'nev 1956), which further supports our case for the connexion between erosion intensity and the vibrations of cavities and cavitation bubbles.

TABLE 1

V (m/s)	9	14	17	23	30	f (Hz)	h (cm)
N	283	441	536	725	945	—	—
f/N	11·36	7·48	6·15	4·55	3·49	3300	0·2
f/N	7·77	4·99	4·10	3·04	2·33	2200	0·3
f/N	3·89	2·49	2·05	1·52	1·17	1100	0·6

References (Shal'nev)

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A. Tuffrey (Stone Manganese Marine Ltd) (Plate 57)

In our own work we have observed the star-shaped cloud covering the test face of a specimen subjected to magnetostrictive oscillation (mentioned by Professor Hammitt); it does not seem to be noticeable at peak-to-peak amplitudes greater than about 40 μm. At amplitudes of about 50 μm an apparently shapeless cloud attacks the surface. However, this can produce star-shaped damage patterns (figure 3, plate 57) and we have found every time that each arm of the star or 'rut' is the direct result of the presence of small defects situated towards the rim of the test face (figure 4, plate 57). A material completely free from any surface defects would, therefore, be expected to be attacked most uniformly (figure 5, plate 57), and in our experience this has been borne out in practice.

I should like to ask Professor Hammitt which types of stainless steel he examined and whether any special surface preparation techniques were used to eliminate work hardening of the test surfaces. Tests with a magnetostrictive vibrator have shown that work hardened layers can alter damage/time relations, and can give misleadingly low loss rates for alloys like stainless steels. We have found that crystal orientation also has a profound effect on rate of attack, and this can be of importance in the assessment of coarse grained materials by laboratory means. Figure 6 shows a 16 Cr–10 Ni–2½ Mo specimen cut from a heavy casting. The differing rates and even modes of attack will readily be seen.

F. G. Hammitt

I should like to thank Mr Tuffrey for his interesting discussion and the new information which he presents. Our observations also confirm that the star-shaped cloud is more prevalent at the lower amplitudes. In almost all cases our damage has been quite uniform, much like Mr Tuffrey's figure 5. In cases where the damage has been allowed to proceed to a greater extent, the specimen face becomes concave, and a relatively undamaged rim is left at the periphery. Thus the specimens tend to achieve the approximate shape once suggested by M. S. Plesset (1962 *Corrosion*, **18**, 181–188) to assist in obtaining uniform damage.

Our specimens are generally in the as-machined condition, being neither polished nor ground. Hence, in the usual case, no special techniques are employed to eliminate work hardening of the surface. Since the specimens have all been fabricated from wrought bar stock, I am quite sure there are no surface imperfections of the magnitude shown in Mr Tuffrey's figures 3 and 4. In Mr Tuffrey's case, I wonder if these 'pores' could be formed as a result of the cavitation rather than having been initially in the specimen?

Our tests on stainless steels to date have been limited to the austenitic types 302, 304 and 316.

F. J. Heymann (Steam Division, Westinghouse Electric Corporation, Philadelphia, Penn.)

Does Professor Hammitt get a steady state erosion rate?

F. G. Hammitt

No, we do not. We observe an initial peak in rate almost always, followed, if the test is continued long enough, by several additional peaks. We have never had any indication that an eventual steady state condition would be reached. We feel that the rate at a given instant is primarily a function of the surface roughening, etc., at that instant, which thus controls the local flow geometry and hence the cavitation régime. Of course there may be secondary surface hardening effects, etc. Since damage is highly sensitive to minor geometrical changes, there is no reason to expect a steady state rate to materialize in most real flow situations. If it did, in my opinion, it would be merely a fortuitous temporary combination of various competing mechanisms.

In our vibratory facility tests we have found that the damage is quite linear with time (as have numerous previous investigators) once the initial relatively uncertain phase of the test is past. If the test is carried still further, the geometry of the specimen is materially changed, in that it becomes concave with a relatively undamaged peripheral lip. In the test which we carried to the largest overall damage, the damage rate then increased.

Generally the geometrical changes of the specimen become substantial, as for example by a local breaking away of the lip, etc., and hence relatively unpredictable. The progress of damage and geometrical change of the specimen differ to some extent between materials, and even for specimens of the same material, so that the damage rate tends to become unpredictable after the linear damage–time relation achieved relatively early in the test.

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

In Professor Hammitt's cavitation results the plot of weight loss against duration of erosion had not an induction period but an initial very rapid rate of weight loss which appeared to be followed by a curve similar to that shown in an induction period. It is well known to electrodepositors that metal surfaces prepared by mechanical processes have a layer of fragmented and badly adherent metal upon them, as illustrated in the photomicrographs published by Steer (*J. Electrodepos. Tech. Soc.* 1950, **25**, 125–146). It is suggested that the initial rapid weight loss found by Hammitt may have been due to his use of a mechanically prepared surface, and that surfaces from which the fragmented layer has been removed, for example by electropolishing, might give him results showing a typical induction.

F. G. Hammitt

Although the rate of loss was high initially in our tests in almost all cases, as was the rate of pitting on the polished surface, the total amount of weight loss during this period was small, and hence not of great practical importance. As argued in the paper, if the pitting is in fact single-event cratering, there is no reason to expect an 'induction period', whereas, of course, if the damage results primarily from fatigue failure, such a period would be expected. As suggested by Mr Popple, we too have ascribed the high initial damage rate to surface imperfections, inclusions, etc.

We have never tested an electropolished surface, and hence this would be an interesting experiment. However, the mechanical preparation of the surface is such that we do not believe there is sufficient distortion of the surface to affect the cavitation results. The 'polished surface' of the specimens is produced by finish polishing with $\frac{1}{4}$ μm diamond dust followed by Linde B, leaving, we believe, a very minimum of surface distortion.

T. Broom

Do cavitation pits exhibit cracks?

F. G. Hammitt (Figure 58)

Generally, in the microsectioning of single craters we have not found cracks beneath the crater, although slip lines are often observed (figure 7, plate 58). However, cracks are sometimes observed beneath heavily damaged areas, i.e. areas where many layers of individual pits have overlapped to form a grossly roughened surface (figure 8, plate 58). Both of these examples are from austenitic stainless steel.

R. E. H. Rasmussen (Technical University of Denmark)

What are the effects of air absorbed in the water used in the cavitation-erosion experiments?

F. G. Hammitt

We have not yet made any experiments to relate cavitation damage to absorbed air content, although we plan such tests in the future. As I am not aware of any systematic experiments of this type for a flowing system, I can only speculate. Of course it is known that large quantities of entrained gas will significantly inhibit cavitation damage in field installations, presumably through the buffering effect of the gas. In our own water venturi we have noted that large quantities of gas reduce the cavitation noise substantially, and hence might be expected to reduce damage. However, if corrosion is an important effect in a particular system, presumably this form of attack might be accelerated by entrained or dissolved oxygen.

In a given system, it is conceivable that small quantities of entrained gas could either increase or diminish cavitation damage since competing mechanisms are involved. In a given flow situation the nucleation of bubbles would be enhanced by additional 'nucleation sites' so that bubbles would perhaps nucleate further upstream, thus having an opportunity to grow to a larger maximum size before collapsing. The forces applied to structures adjacent to the collapse would then be increased. On the other hand, the existence of increased quantities of non-condensable gas within the bubbles would prevent their reaching as small a volume in collapse as otherwise, so that the violence of collapse would be reduced.

The effect of dissolved rather than entrained gas would be presumably similar but perhaps less pronounced, depending upon the existence of sufficient time for the dissolution and subsequent solution of the gas in the cavitation region.

Experimental data in water on the effect of various cover gases on damage in an ultrasonic vibratory facility (Bebchuk, A. S. & Rozenberg, L. D. 1960 *Akust. Zh.* **6**, 498–499) showed that the damage always decreased for an increase in dissolved gas, and in fact almost vanished for those cover gases having a very high solubility in the water.

J. H. Brunton

Could Professor Hammitt explain how he produced the high speed liquid droplets?

F. G. Hammitt

Actually a high speed jet rather than droplets was produced. The equipment† consisted of a converted hydraulic press capable of producing pressures, in an approximately 3 in. diameter piston and cylinder assembly, of about 50000 Lb/in.^{2}. The length of the cylinder is approximately 18 in. so that appreciable durations of a small diameter jet can be obtained. The nozzle used for the tests reported in the paper was 0·003 in. diameter, and the velocity computed for an ideal fluid was about 2700 feet per second.

† High energy liquid jets as a new concept for wood machining, E. L. Bryan, Doctoral Dissertation, Department of Wood Technology and Science, University of Michigan, 1963.

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J. M. Hobbs

So far not a great deal has been done at the National Engineering Laboratory to examine the metallographic changes resulting from cavitation and liquid impact. However, a study of microsections of gunmetal and bronze showed some evidence of cold working, fatigue cracking and signs that certain constituents were preferentially attacked in a manner typical of corrosion.

J. B. Marriott (Plate 58)

A magnetostriction cavitation test was carried out on a sample of Haynes alloy 6B for 12 h using 0·004 in. amplitude. After this period the specimen had suffered no detectable weight loss. Considerable local surface damage had, however, occurred in a 'star' type of pattern. Metallographic examination (figure 9, plate 58) by the Nomarski technique indicated the presence of craters and persistent slip lines. Cracks were seen at carbide/matrix boundaries and some extended into the matrix. The effect of the cavitation attack would seem to be very similar to that observed in the 'incubation period' of the jet impact test on the same material.

Examination of jet impact test results carried out by the English Electric Company shows that the order of erosion resistance of materials can vary with the length of test and the behaviour of materials when subjected to gross material removal. Can Dr Hobbs give details of the test conditions used to obtain the comparison between jet impact and magnetostriction testing?

J. M. Hobbs

In both types of test the rate of erosion was found to vary with time, as discussed in the paper. The comparisons were therefore made of the rates when they were nearly uniform. Actual test conditions used in the drop impact were, test-peripheral velocity 660 ft./s, diameter of water jet $\frac{1}{16}$ in., velocity of water jet 60 ft./s. For the vibratory test the frequency was 20 kc/s, peak-to-peak amplitude 0·002 in., test piece diameter $\frac{5}{8}$ in.

A. Silverleaf

I welcome the emphasis in the papers by Professor Hammitt and by Dr Hobbs on studying cavitation erosion by experiments in flowing liquids, since there have been many doubts about the validity of drop impact and magnetostriction techniques. However, I am puzzled by the apparent introduction of flow velocity as a principal parameter; unless the form and nature of the cavity flow remain essentially unaffected by changes in velocity, which is unlikely, then it is possible that the erosion rate is affected more by the nature and extent of the cavity collapse zone (which should be evident visually) than by the flow velocity itself.

J. M. Hobbs

Mr Silverleaf's comments are most welcome. In these tests with flowing liquids there are many factors which may affect the rate of erosion and it is difficult to isolate them. Velocity was chosen for this investigation as previous work by R. T. Knapp (1955, *Trans.*

Am. Soc. mech. Engrs, **77**, 1045–1055) on pitting rates and Kerr & Rosenberg (1958, *ibid.*, **80**, 1308–1314) on erosion of radioactive paint had both indicated that there would be marked effects of velocity on erosion. This, it is believed, is one of the first attempts to correlate bulk erosion loss with velocity and to do this all other known parameters were kept constant.

Hence the cavitation number was kept constant and, as a result, although the magnitude of the damage changed as shown, the length of the cavitation cloud and the area pitted were only slightly greater at the higher velocities. The number of cavities formed and the vigour with which they collapsed were certainly velocity dependent and it is the combination of all these factors which is thought to be responsible for the high power relating velocity and erosion.

F. G. Hammitt

I fully agree with Dr Silverleaf's remarks regarding the limitations of flow velocity as a principal parameter in cavitation damage. The general approach suggested by Dr Silverleaf is developed more fully in the written version of the paper under 'Fluid velocity effects', with special emphasis on observations in our cavitating venturi, although I am afraid I did not stress this in the oral presentation owing to lack of time.

I believe that velocity is often discussed as a parameter in this type of test principally because it has been emphasized by investigators in the past, and because a simple power law dependence of damage on velocity has been found to represent results from some types of experimental facilities quite closely.

J. M. Hobbs

Effects of air content and also of temperature have been observed in erosion tests at N.E.L. In general, the presence of both free and dissolved air has been to reduce erosion and this agreed with the findings of the questioner. For the comparative tests described the dissolved air content was kept constant throughout.

D. Pearson

In his experiments on erosion caused by the impact of a water jet, Dr Hobbs has shown that erosion resistance increased as the test specimen hardness was increased. This has often been observed in the research with the C.E.G.B. erosion rig, but a number of significant anomalies have also been found. For very high hardnesses, erosion resistance seems to deteriorate as hardness increases. It would be of interest to know if Dr Hobbs has obtained similar results.

J. M. Hobbs

Mr Pearson's experience is most interesting and not unique. It is gratifying, however, to note that the general trend is that increased hardness gives increased resistance.

The results presented in the paper were all for materials which had been through-hardened. We have, however, tested a small number of case-hardened (nitrided) steels and with them the opposite trend was indeed found. The hardness ranged from 980 to 1180 Kg/mm^2 and the erosion resistance decreased steadily, and by a considerable amount, with increasing hardness. These very hard test pieces were extremely brittle and had a poor resistance to shock loading.

D. Tabor, F.R.S.

Dr Hobbs is very lucky in having found a simple and direct correlation between erosion resistance and hardness. Erosion resistance apparently increases linearly with hardness but for steels above a hardness of about 400 Kg/mm^2 there is little increase in erosion

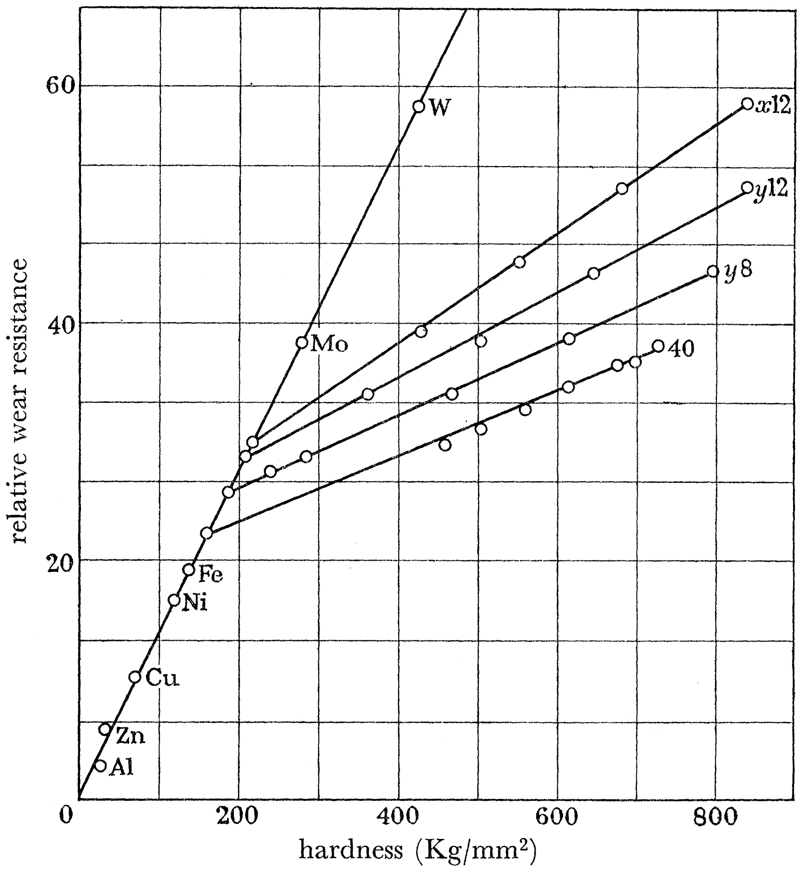

FIGURE 10. Wear resistance of pure metals and steels as a function of indentation hardness (from Khruschov 1957). The steels are indicated as follows: 40, carbon 0·41 %; *y*8, carbon 0·83 %; *y*12, carbon 1·10 %; *x*12, carbon 2·35 %; chromium 11·9 %.

resistance with increasing hardness. I should like to point out that this is very similar to the abrasion resistance of metals. A typical result described by Khruschov (1957) is shown in figure 10. In the experiments abrasion resistance is the reciprocal of the wear rate observed when the metal rubs on abrasive papers. The mechanism for abrasive wear is fairly well understood (Avient, Goddard & Wilman 1960; Samuels & Mulhearn 1962) and it is now apparent that the linear relation should really be between abrasion resistance and the hardness of the *fully work-hardened metal*. This accounts for the relatively slow increase in wear resistance of steels as the specimen hardness is increased. Although the erosion process is not properly understood and is presumably different from abrasive wear it would be interesting to know if Dr Hobbs would find this correlation to apply to his erosion results.

References (Tabor)

Avient, B. W. E., Goddard, J. & Wilman, H. 1960 *Proc. Roy. Soc.* A, **258**, 159.
Khruschov, M. M. 1957 *Inst. Mech. Engrs Conf.* on *Lubrication and Wear*, paper 46.
Samuels, L. E. & Mulhearn, T. O. 1962 *Wear*, **5**, 478.

J. M. Hobbs

The correlation between erosion resistance and hardness is not quite as simple as suggested. There is a certain similarity between the erosion resistance and the abrasive wear resistance, and, up to a hardness of about 400 Kg/mm², they both increase linearly with hardness. Above this hardness the similarity breaks down, for unlike abrasive wear, a relatively small increase in hardness appears to give a considerable increase in erosion resistance. The elastic modulus shows a marked effect on the erosion rate/hardness relation which is absent from the Khruschov plot (figure 10).

Although microhardness measurements indicate that repeated impact and cavitation both cause work-hardening, it has not been possible to show whether the fully work-hardened state is achieved before material is removed. Thus, although it is true that the correlation should be between hardness of the fully work-hardened metal and abrasion resistance, this has yet to be verified in the case of erosion.

J. H. Brunton

Dr Hobbs's results emphasize the superior erosion resistance of stellites over steels of equivalent strength. I think that this is a most important result, and one which at the moment is not properly understood. I do not think it is due to the relative strain rate sensitivities of stellites and steels. From the point of view of the structure alone one would expect iron based alloys to show a greater increase in yield strength under impact than the cobalt based stellites.

J. M. Hobbs

Dr Brunton's comments are much appreciated although it is disappointing that the relative strain rate sensitivities do not account for the outstanding superiority of the stellites. However, there is every incentive to make further investigations in order to explain this.

A. A. Fyall

In Dr Hobbs's paper the rate of damage was said to be proportional to the seventh power of the velocity. At the Royal Aircraft Establishment, it was shown, some years ago, that rain erosion rate also varied (approx.) as this power of the velocity. The concept of a 'threshold velocity' was then introduced (this being the velocity below which no erosion occurred) and the rate was then shown to be proportional to the third to fourth power of the velocity.

Typically,

$$\text{rate} = k(V - V_{\text{threshold}})^n,$$

where k, $V_{threshold}$ and n are constants; for Perspex, $V_{threshold} = 208$ mi./h and $n = 3{\cdot}4$. A physical explanation of this dependence may be nearly achieved by postulating also the total energy absorbed by the surface from impacting raindrops is proportional to their kinetic energy (V^2) and the number of drops impacted proportional to V, or

$$R \propto V^2 V \propto V^3.$$

This concept of a threshold velocity is also described in the Dornier paper and in the papers on turbine erosion

$$(\mathrm{d}m/\mathrm{d}\omega)_{\max.} = K\,(V \sin\theta - V_c)\ \mathrm{cosec}\ \theta.$$

It would be interesting to see if the constants obtained in the papers by Busch *et al.* and Baker *et al.*, and also that in Dr Hobbs's paper (if he calculated a threshold velocity) bear any correlation with these R.A.E. results.

J. M. Hobbs

Mr Fyall's contribution is most helpful and it is encouraging that the velocity effects observed with the repeated drop impact test were similar to those obtained in studies of rain erosion.

With our apparatus, quite low threshold velocities were found. Values obtained using a $\frac{1}{16}$ in. diameter water jet were as follows: mild steel 270 ft./s, 184 mi./h; brass 290 ft./s, 198 mi./h; duralmin 260 ft./s, 177 mi./h. The low values may be because the energy of a cylindrical drop is somewhat greater than for a spherical one. All three materials gave erosion rates per impact proportional to the fourth power of velocity although different powers have since been obtained for non-metallic materials.

F. J. Heymann

Dr Hobbs presents a curve in which erosion rates found by one test method are plotted against those of the same materials as found by another method. For the poorer materials the correlation is quite good and the points fall along a straight line, but for the better materials the correlation is less satisfactory. Is this perhaps due to the difficulty, if not impossibility, of exposing the better materials over a sufficient length of time for a 'steady state' erosion rate to set in? The relative duration of the 'incubation period' and the shape of the initial erosion rate curve will probably depend more strongly on the surface preparation and the intensity parameters of the erosion attack, which will differ between different test methods. If, therefore, the plotted data for the better materials are still from the realm of the 'variable' portion of the erosion rate curve, then one would expect more scatter, or at least a deviation from the straight line relation, in the correlation curve for these materials.

J. M. Hobbs

Mr Heymann has touched upon a very likely cause of the less satisfactory correlation between results of different erosion tests on the more resistant materials. Although, as far as possible, the steady state erosion rate was used in the correlations this could not always be guaranteed. Thus the low cavitation erosion values for the bronzes and stainless steels would be explained.

B. J. S. Barnard and G. A. Cooper (Department of Metallurgy, Cambridge University)

A series of experiments has been carried out to determine the damage caused to a stressed specimen by the formation and collapse of a spark-induced bubble in water.

Specimens of vacuum-cast oxygen-free high conductivity copper were mounted in an Instron testing machine so that they could be immersed in water while under stress. Electric sparks were produced in the water between a pair of tungsten electrodes. The specimen was found to have elongated after the passage of a spark, and the resulting strain was deduced from the movement of the loading crosshead necessary to return the stress to its original value.

Experiments were conducted to determine the variation of this strain with applied stress, the energy of the spark and with its distance from the surface of the specimen. The variation in strain per spark with distance from the specimen surface is shown in figure 11 for three different spark energies, when the specimen was at yield. The effects of decreasing the applied stress for various spark conditions are shown in figure 12. Each point is a mean of ten readings.

The main observations may be stated as follows:

(*a*) Under given conditions, the strain caused by a single spark-bubble is dependent upon the difference between the applied and yield stress, not upon their absolute magnitudes.

(*b*) The strain caused by a bubble increases uniformly as the electrodes are moved closer to the specimen, until a particular distance is reached, after which the damage becomes approximately constant. This distance corresponds well with the position of a bubble which would just be tangent to the specimen when at its largest size. These positions are marked by vertical bars in figure 11. The maximum diameters attained by the bubbles were measured from high speed ciné photographs.

(*c*) If a series of sparks is made near the specimen under a constant applied stress, the strains caused by successive sparks decrease at a greater rate than would be expected merely from a knowledge of the increase in yield stress due to work-hardening occurring as the material strains. Points *A* and *B* in figure 12 illustrate this effect. Point *B* shows the strain per spark found in a specimen which had been subjected to shock damage at 2·6 Kg/mm^2 below the yield stress immediately after unloading from the yield stress. Point *A* was determined after the specimen had suffered cumulative damage from five hundred bubbles at this stress.

It is concluded that, although the possibility of damage by liquid jets is not excluded, it is the shockwaves associated with the growth and collapse of the bubble which cause the greatest damage, because significant strain still occurs when the bubble is far removed from the specimen, and no sudden transition to a condition of greater damage is found for bubbles produced close to the specimen. The strains observed indicate that the combination of the transient stresses induced in the specimen with the applied stress exceeded the yield stress of the material. The yield stress of the f.c.c. metals is known to be very little affected by strain rate, and so it appears that the actual strains observed are a function of

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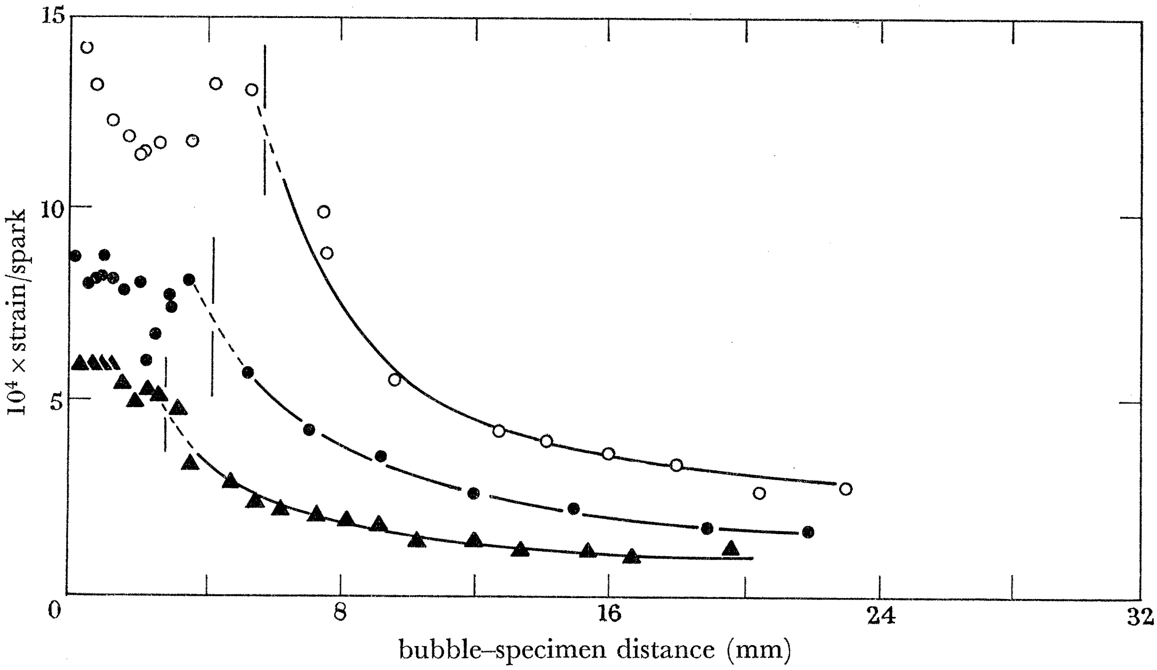

FIGURE 11. Spark energy: ○, 4·6 J; ●, 1·0 J; ▲, 0·5 J.

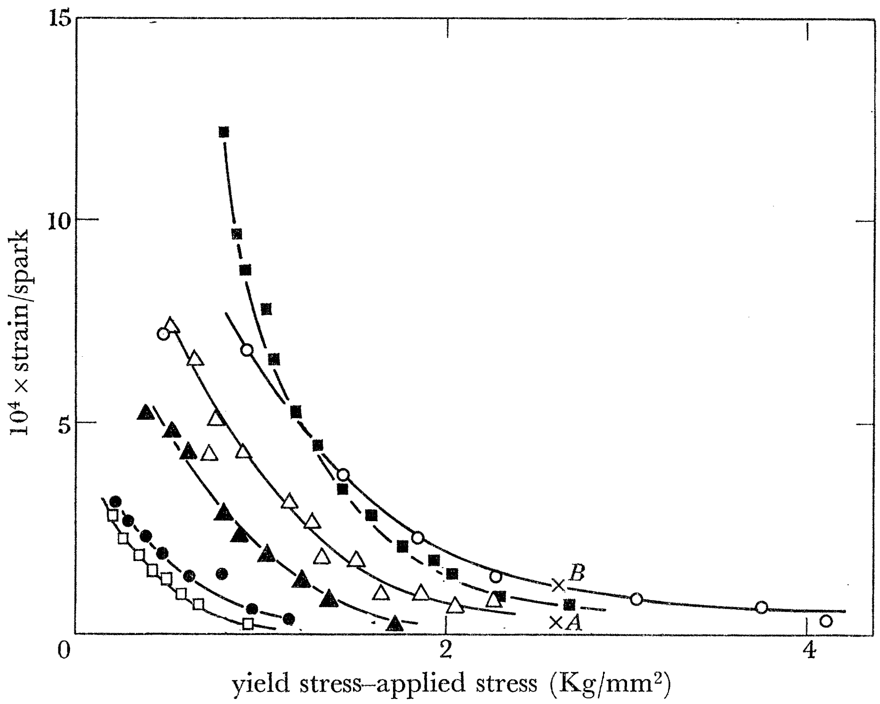

FIGURE 12. Spark energy and separation: ○, 1·0 J, 1·48 mm; △, 1·0 J, 1·5 mm; ■, 4·6 J, 1·5 mm; ▲, 0·5 J, 1·5 mm; □, 4·6 J, 14·2 mm; ●, 1·0 J, 5·7 mm.

the elastic properties of the machine and the time for which the yield stress is exceeded, rather than some property of the material such as the limiting dislocation velocity. This view is supported by the observation in (*a*) that the strains were independent of the actual magnitude of the stresses involved.

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The explanation of the diminishing damage after repeated shocks at a constant stress level is that, in the early stages, dislocations in situations favourable to glide are active, but that eventually more and more move into positions where they are too firmly anchored to proceed.

Although it seems probable that eventually there will be no more dislocations available to move, and the strain per spark may decrease to zero, no evidence for this condition was found, and on one occasion a specimen was elongated to failure without the u.t.s. ever being recorded.

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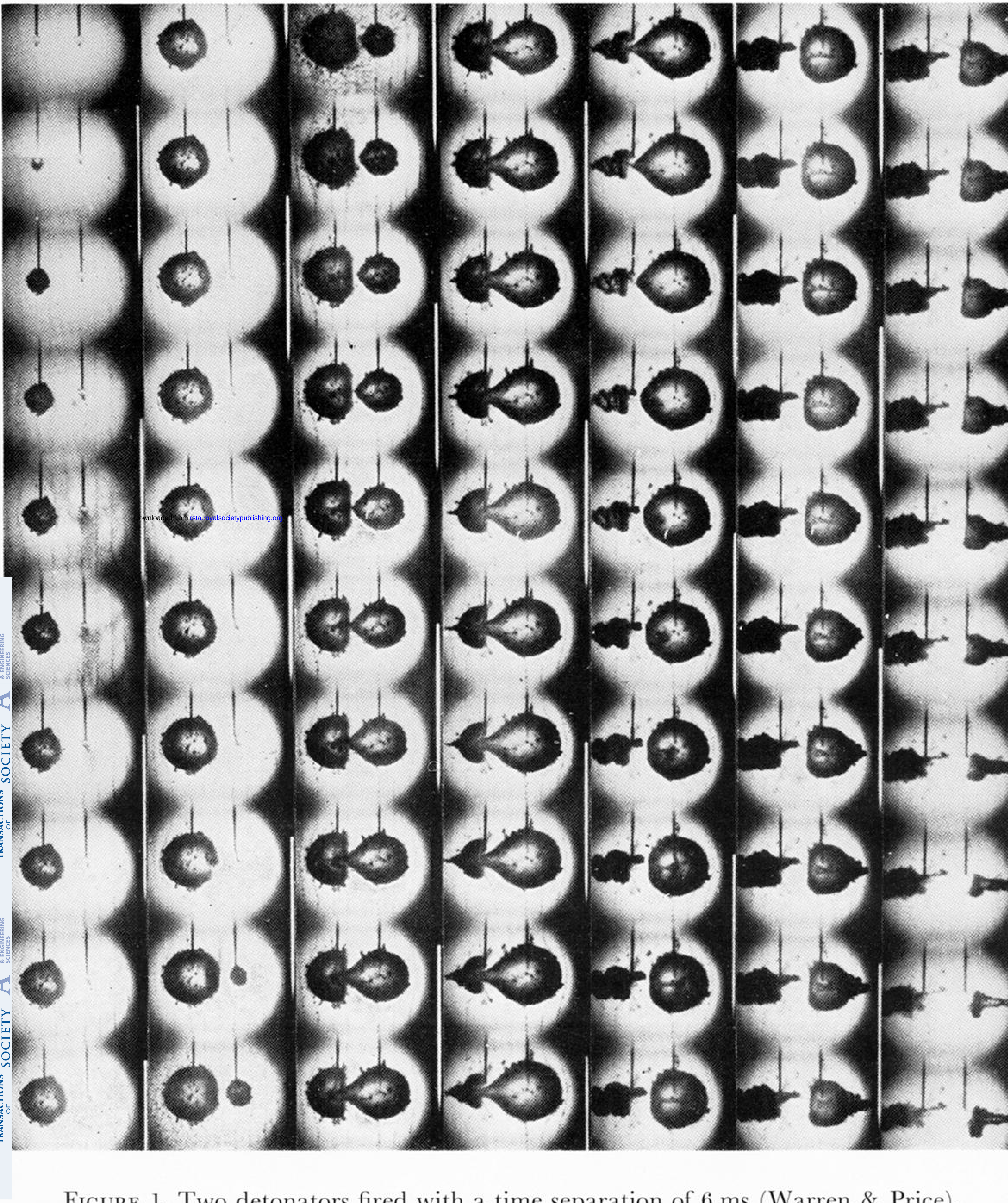


FIGURE 1. Two detonators fired with a time separation of 6 ms (Warren & Price).

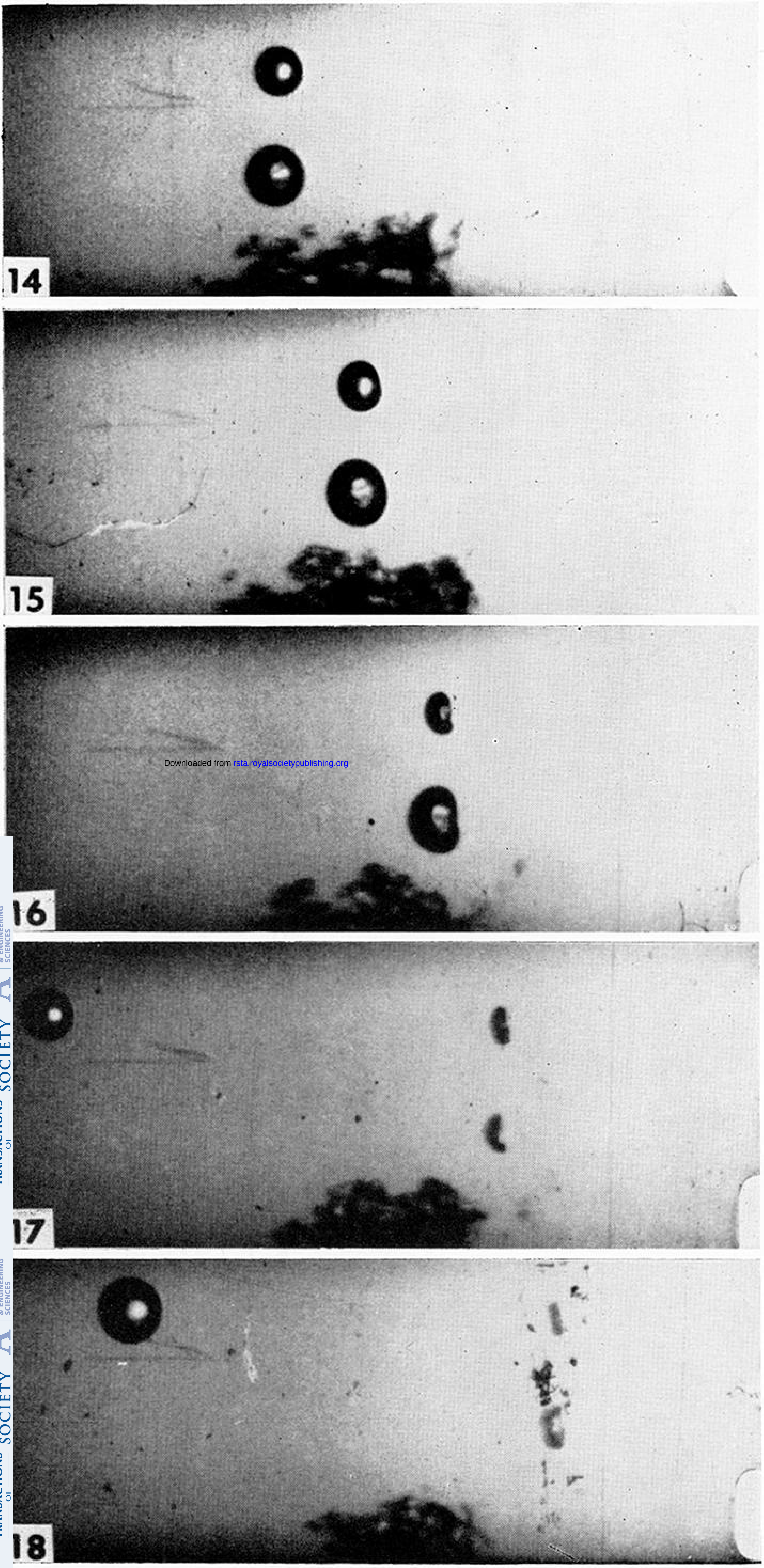


FIGURE 2

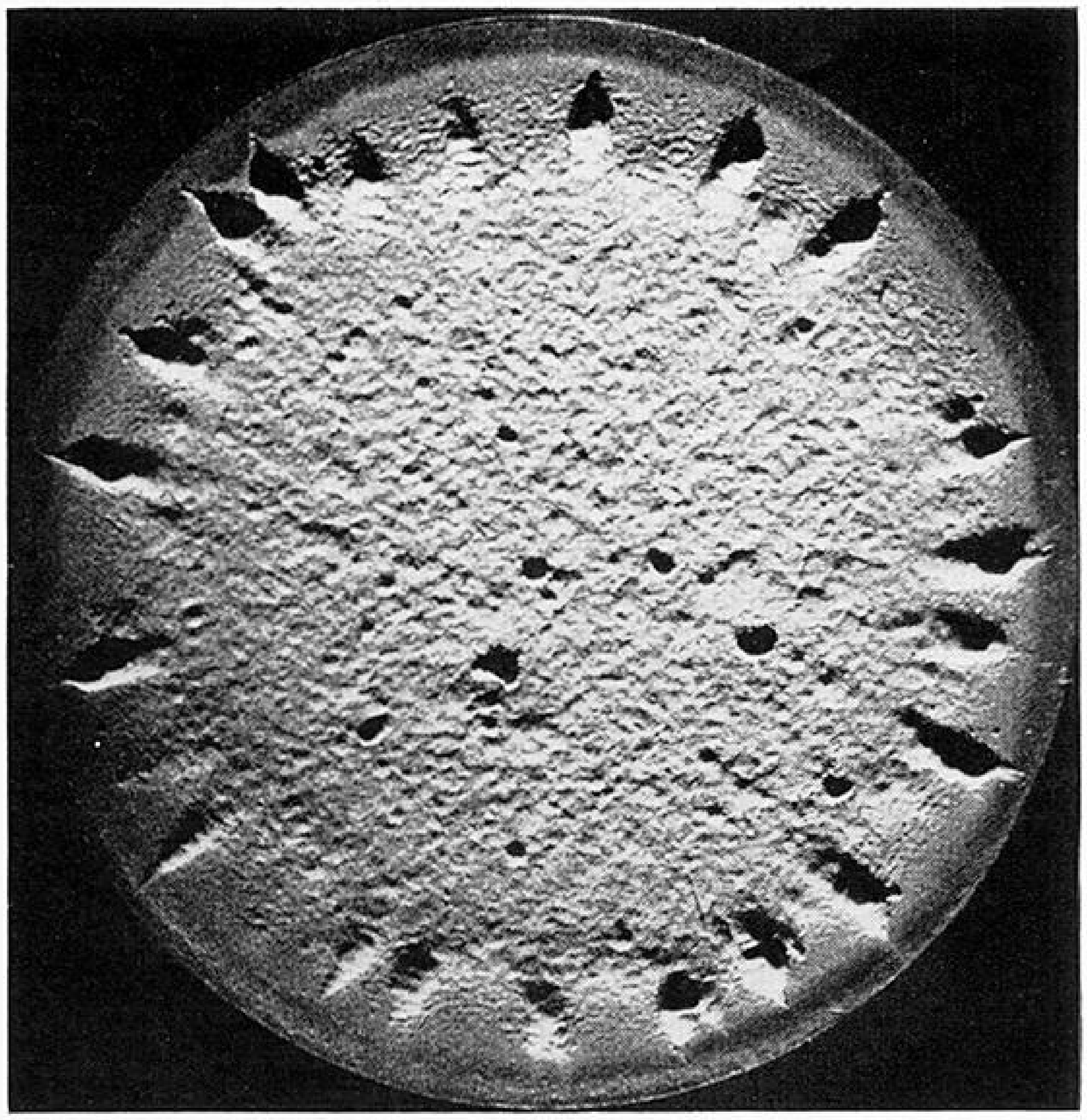


FIGURE 3. A cast nickel–aluminium–bronze specimen after 10 h test.

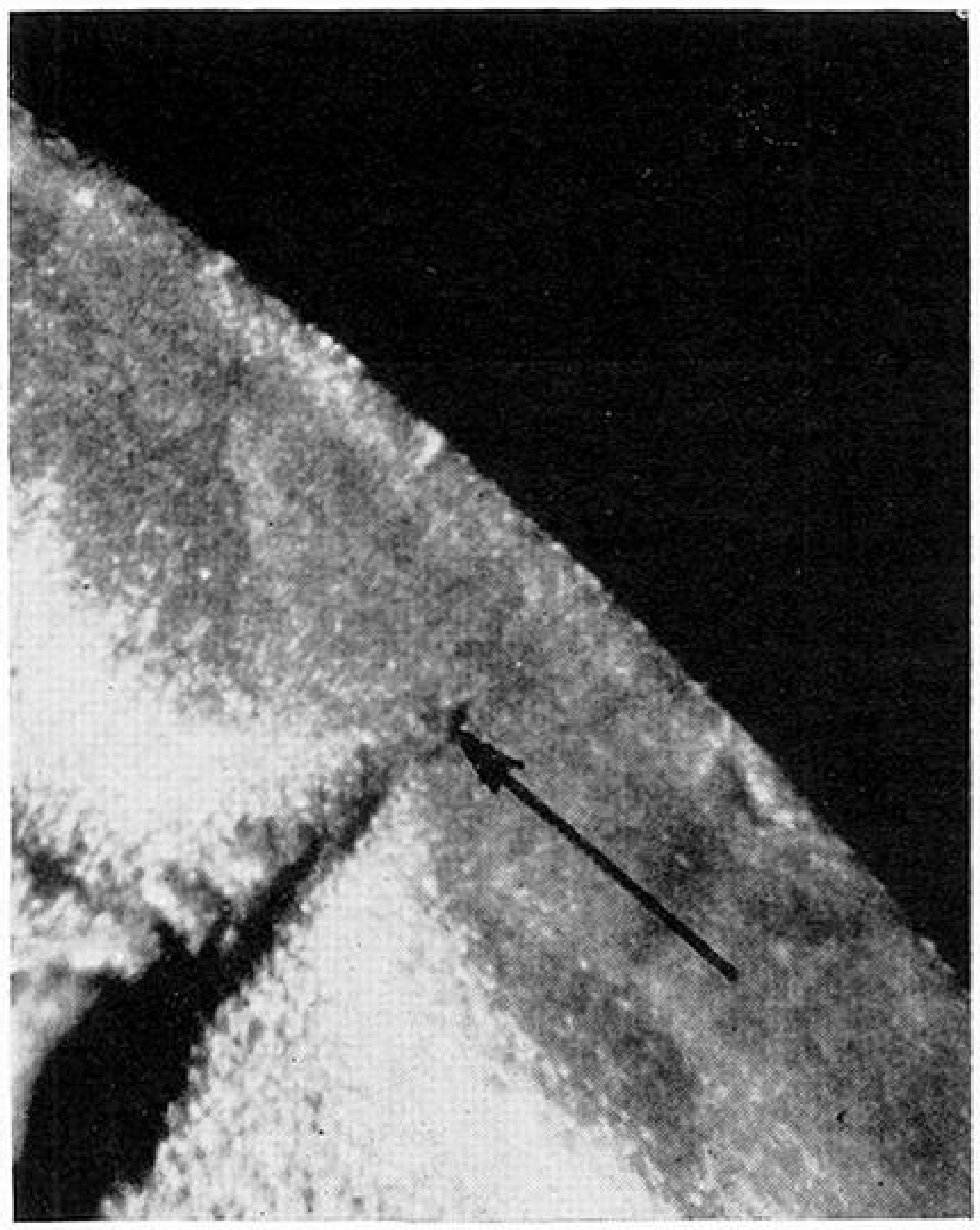


FIGURE 4. A typical pore (arrowed) at the tip of a rut.

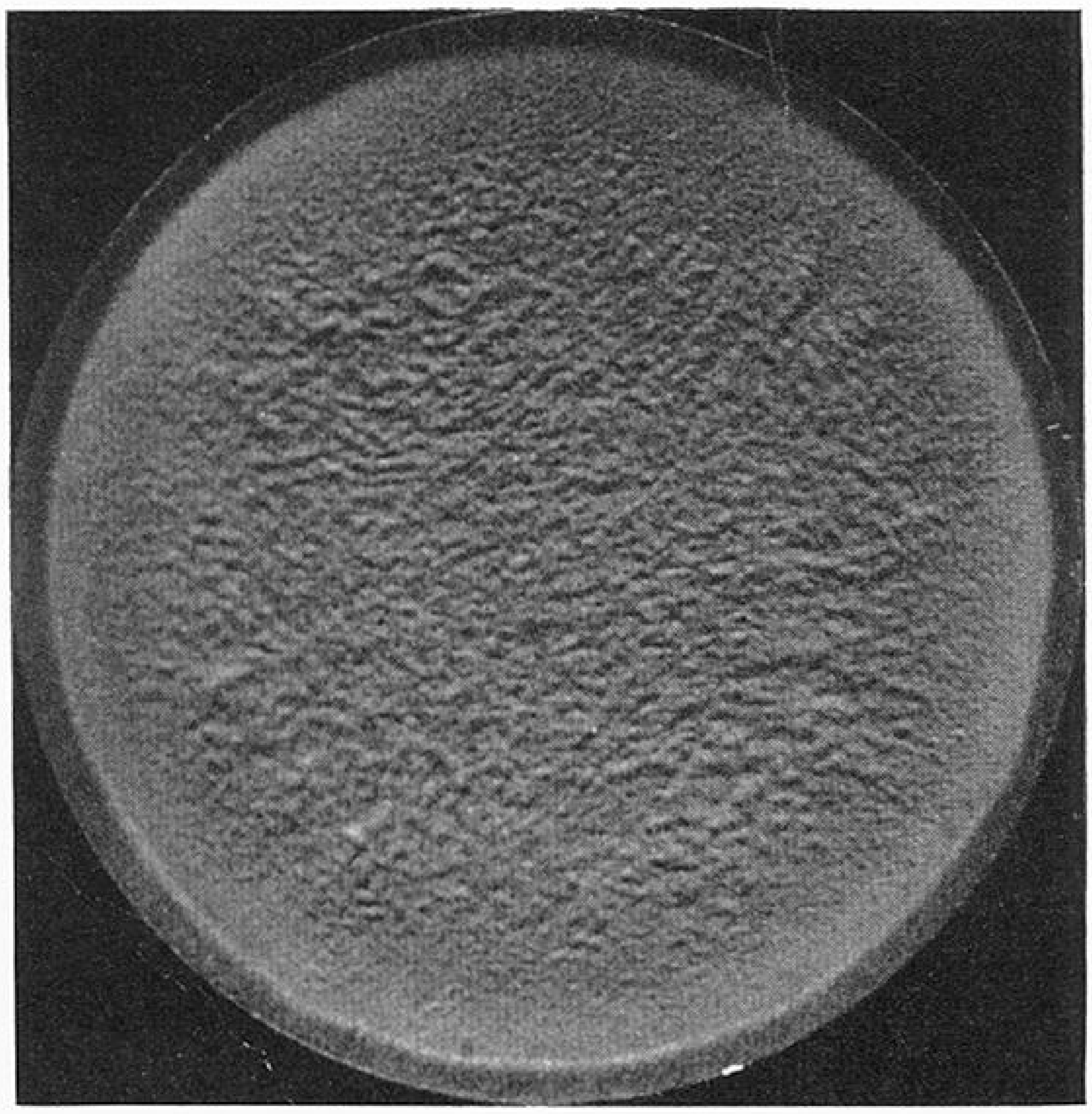


FIGURE 5. A wrought nickel–aluminium–bronze specimen after 10 h test.

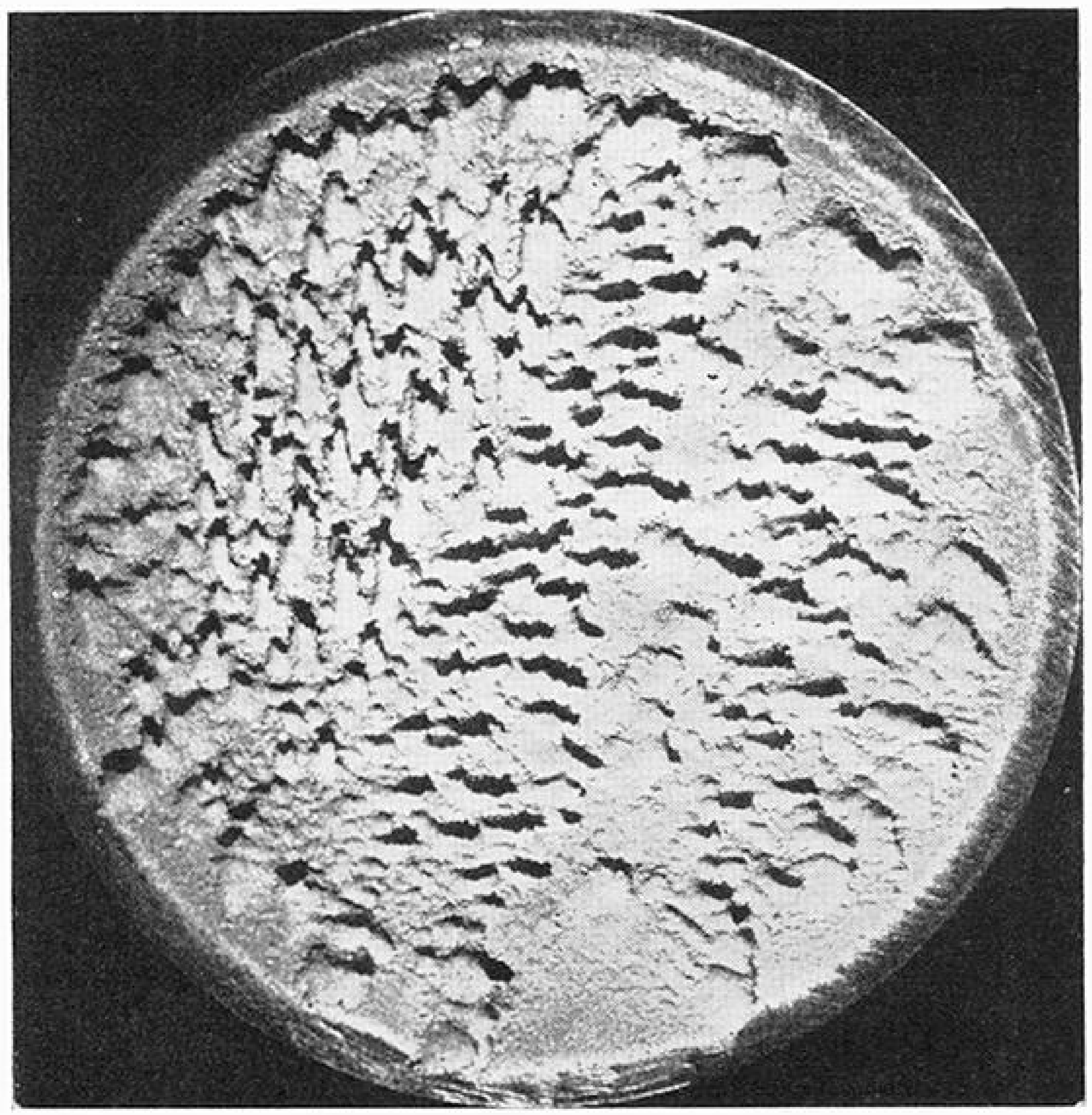
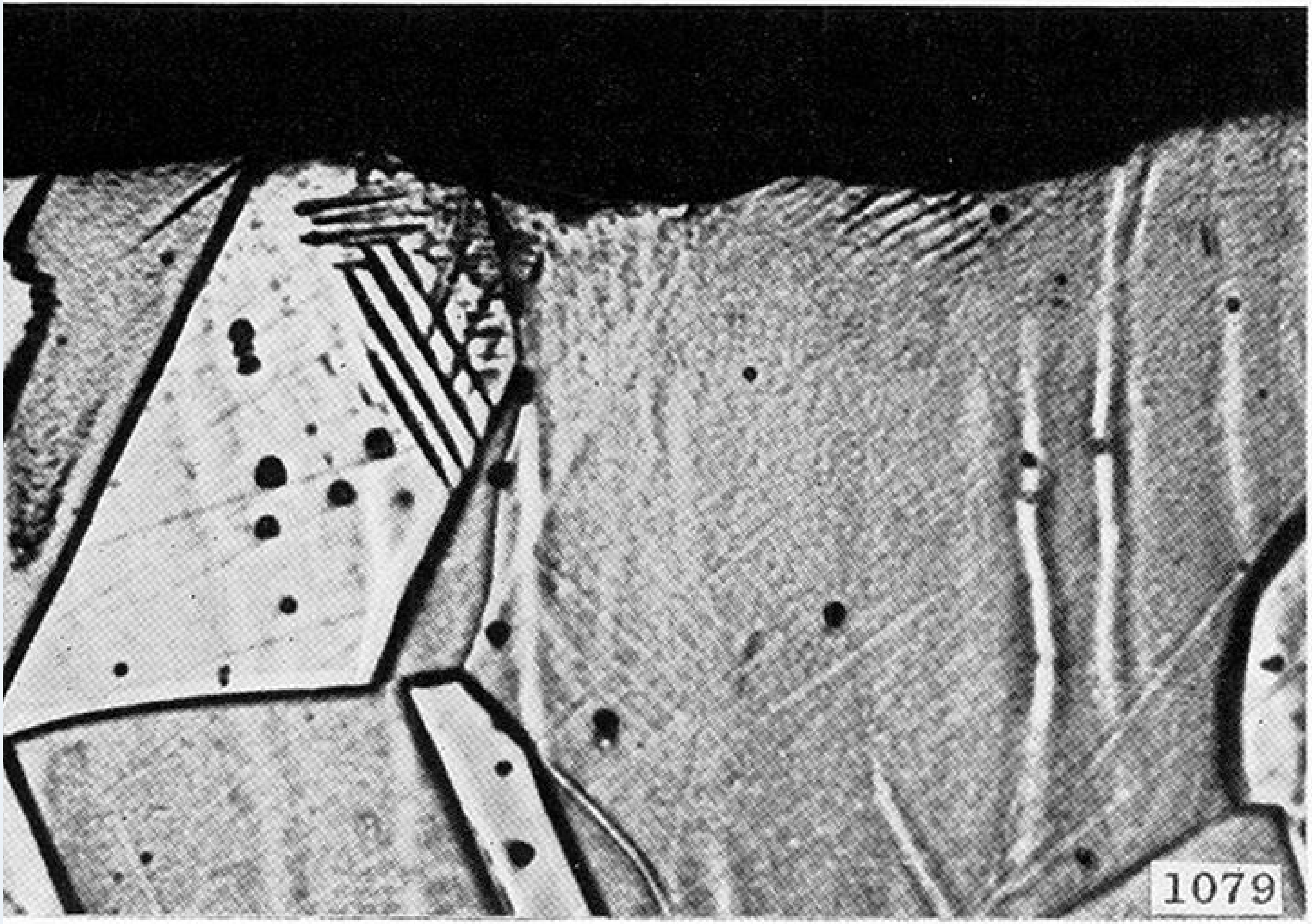


FIGURE 6. A specimen of coarse grained cast stainless steel after 10 h test.

FIGURES 3 TO 6. Specimens tested a 20 kc/s magnetostrictive oscillator, with peak-to-peak amplitudes of 51 μm (0·0020 in.). Test solution was 3 % sodium chloride kept at 25 °C.



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IGURE 7. Typical section through an irregular shaped pit on stainless steel sample no. 26-3 (which had been run for 11 h at 'standard cavitation' at a throat velocity of 95 ft./s in water), showing slip lines. (Magn. ×800.)

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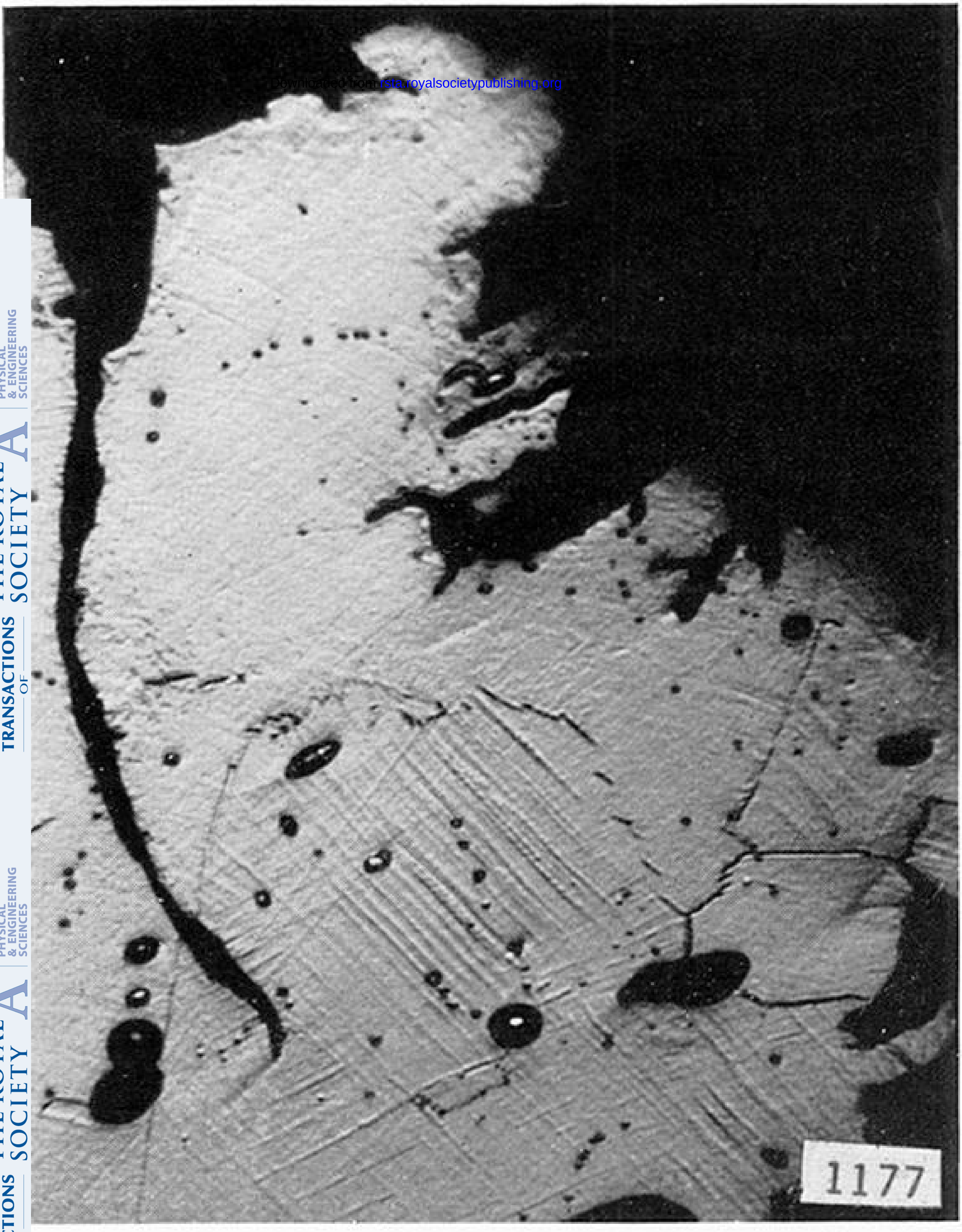

'IGURE 8. Section of type 316 stainless steel impellor in area of heavy cavitation damage from mercury. (Magn. × 800.)

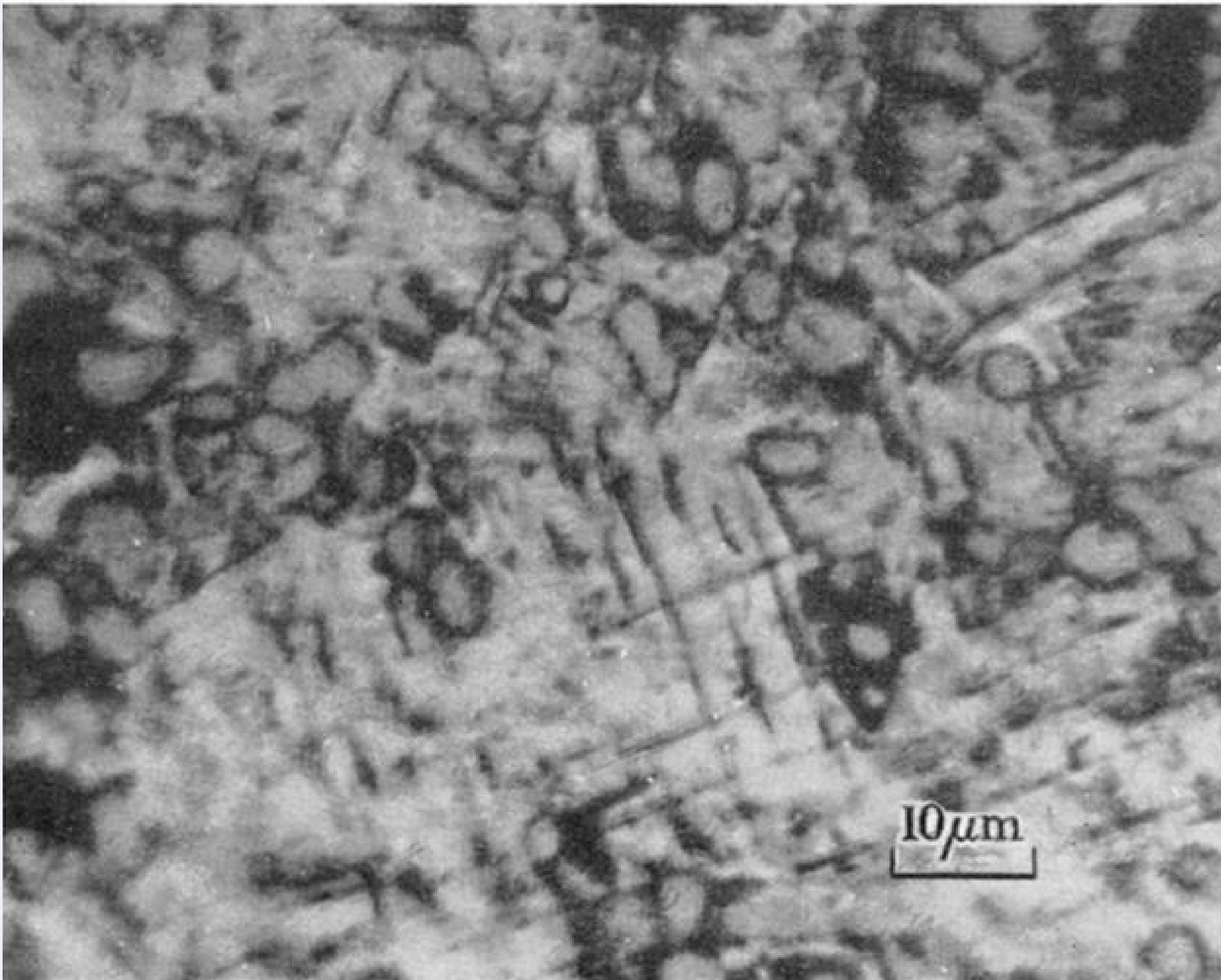

FIGURE 9. Cavitation damage on surface of specimen after magnetostriction testing.