The Behaviour of Single Crystals of Aluminium under Static and Repeated Stresses

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PHILOSOPHICAL TRANSACTIONS.

I. *The Behaviour of Single Crystals of Aluminium under Static and Repeated Stresses.*

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[Plates 1–3.]

In a previous paper* were recorded the results of an investigation into the effects of repetitions of stress on the micro-structure of various metals in the form of crystalline aggregates, the main purpose of the investigation being a study of the causes of fracture under repeated stresses of relatively low magnitude. One important conclusion derived from the experiments was that the action of slipping was not, as had been previously stated, a weakening process in itself. Up to a point the effect of slip was actually to increase the resistance of the metal to further slip. Eventually, however, this strengthening action was exhausted, and failure commenced by the formation of a crack. It was suggested that failure occurred when the amount of strain-hardening by slip exceeded a certain limiting amount. No definite evidence could be obtained on this point, but it was considered that further information might be obtained if attention was directed to a material more simple in structure than a crystalline aggregate. In particular, it was desired to eliminate the effects of the crystal boundaries, whose nature is at present unknown. This could be accomplished if specimens cut entirely from one crystal were employed. Further, it should be possible to verify the assumption, commonly made, that slip bands represent the traces of actual "slip planes" on the surface of the specimen, and to relate these with the atomic structure of the material.

Through the kindness of Prof. Carpenter and Miss Elam a number of large single crystals of aluminium were prepared and presented and have been used throughout this work. At that time the necessary experimental facilities for X-ray work were not available to the authors at the National Physical Laboratory. Prof. Carpenter offered to arrange for the X-ray analyses to be undertaken by his assistant, Miss C. F. Elam, at the Royal School of Mines. This offer was gratefully accepted and the authors are greatly indebted to Miss Elam for carrying out this section of the work.

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* "The Behaviour of Metals subjected to Repeated Stresses," 'Roy. Soc. Proc.,' A, vol. 104, p. 538 (1923).

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Scope of the Experiments.

The research has included a study of the behaviour of single crystal specimens subjected to the following straining actions :—

1. Reversed direct stresses (Haigh machine).
2. Reversed torsional stresses (Stromeyer machine).
3. Single blow tensile impact (impact machine of double pendulum type).
4. Slow cycles of repeated tensile loading (single-lever testing machine).

(*Note.*—The distortion of an aluminium crystal under a gradually increasing tensile strain has been investigated by TAYLOR and ELAM.*)

The Relation of Slip-Bands with Crystallographic Planes.

Since the essential object of the tests was to study the phenomena accompanying fatigue, the authors were considerably restricted in the use of reference marks on those portions of the specimens which were actually under test. (Such a system of reference marks was used by TAYLOR and ELAM.*) Previous work has shown that the effect of a scratch on the surface of a specimen is much more marked under repeated than under static stresses. In any case, such reference marks are only essential when the resulting total distortion of the test piece is to be studied, and, as will be seen later, fatigue failure is not necessarily accompanied by measurable total distortion. The reference marks used were therefore confined to the enlarged ends of the test piece, and consisted of a series of fine lines parallel to the axis and equally spaced (usually at 30° intervals) around the circumference. The entire surface of the reduced parallel portion of each specimen was etched to remove all machining effects and was then given a careful metallurgical polish. Most of the work has been based on the changes in microstructure of this surface, in particular on the slip bands which appeared. Further information has been sought, in some cases, from the appearance of the cross-section of the test-pieces when cut through after fracture, and also from such changes in the shapes of the cross-section as occurred.

It was essential at the outset to verify the above-mentioned assumption that slip bands represent traces of actual planes, and for this purpose it was necessary to measure accurately the inclination of the slip bands at any point. The method by which this was accomplished is illustrated in fig. 1.

In this figure the specimen is seen to be supported between centres in a holder attached to the stage of a projection microscope. Fuller details of this holder are shown in fig. 2. By rotating the specimen until the pointer attached to the holder comes into alignment with one of the reference marks, the plane containing any pair

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* "The Distortion of an Aluminium Crystal during a Tensile Test," 'Roy. Soc. Proc.,' A, vol. 102, p. 643 (1923).

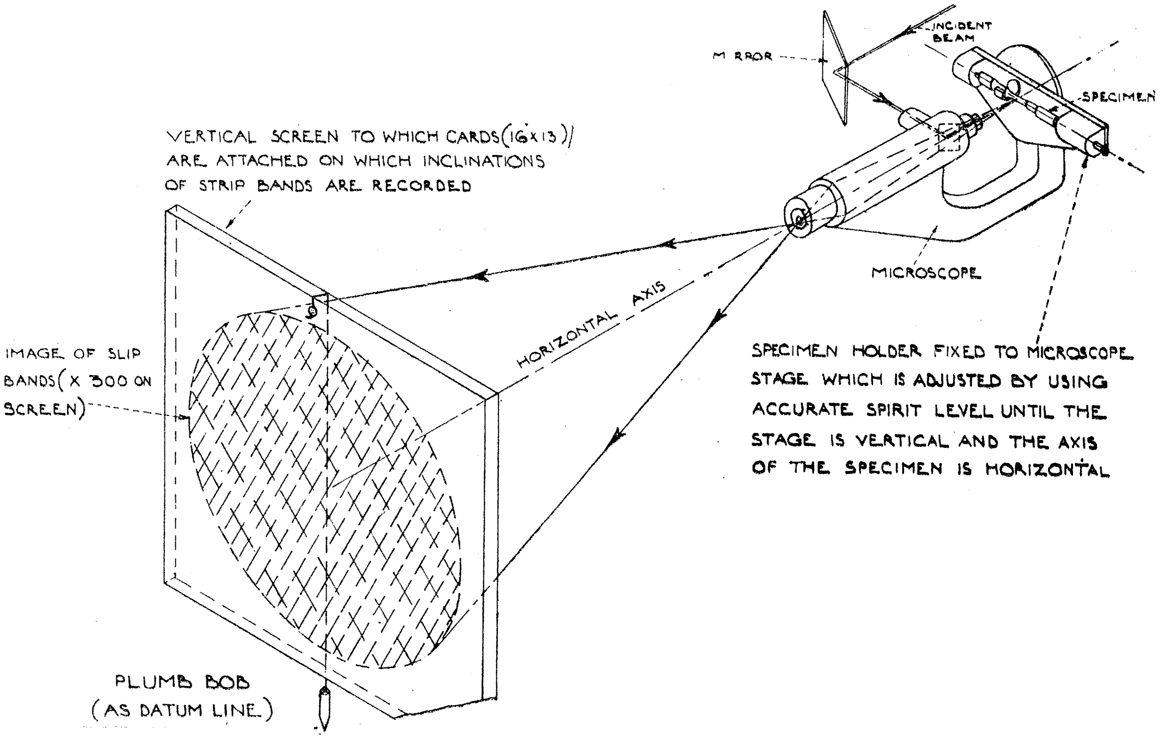

Fig. 1.—Diagram representing Method of Recording Inclination of Slip-Bands with respect to Specimen Axis and Reference Lines.

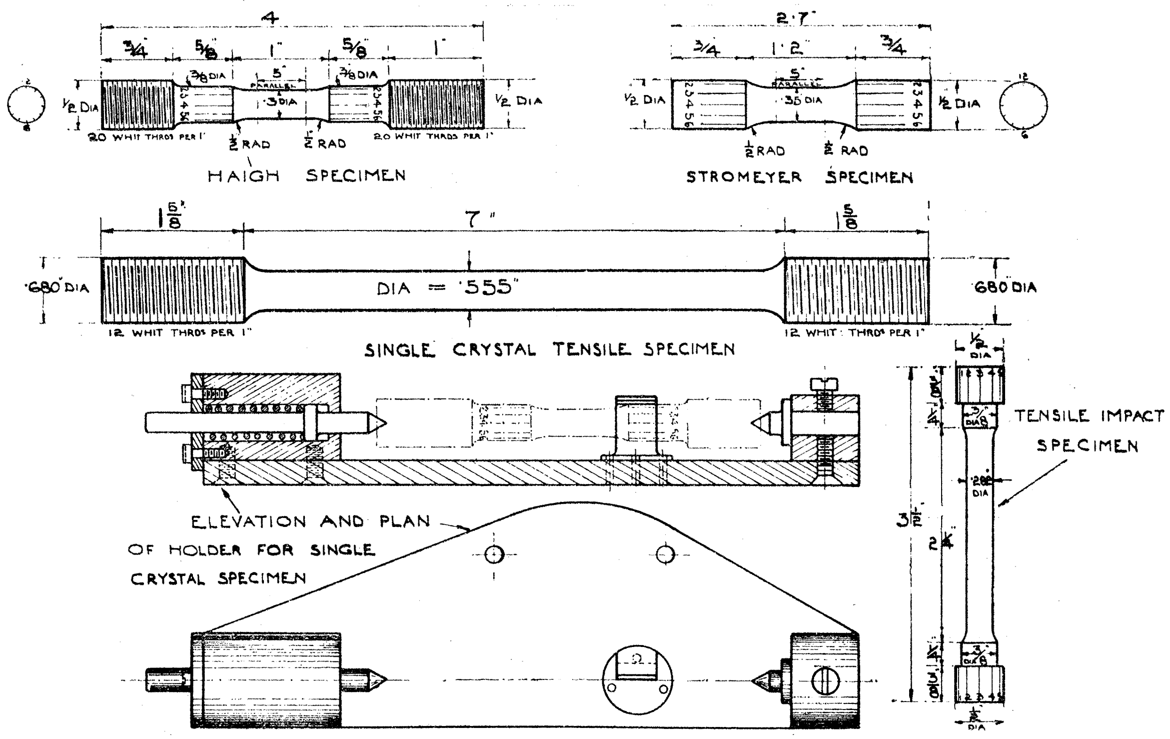

Fig. 2.—Details of Specimens and Holder.

of opposite marks can be set at right angles to the stage of the microscope. At the same time the stage may be rotated in a vertical plane until the axis of the specimen is horizontal. The microscope is then focused on the polished surface and an image (× 300) of the slip-bands appearing there is thrown on the screen. The angle between these bands and a vertical datum line marked on the card by means of a plumb-line is then measured. This angle is referred to as the inclination of the trace at the reference mark in question. At any stage in the test at which the inclination of slip-bands was measured, traces were taken at as many of the reference marks as possible. The inclinations of individual traces were then compared with those of a mean plane deduced from all the observations, and thus the degree of accuracy with which the experimental traces represented a plane could be exhibited.

The results of a typical case are shown in Table I, which refers to one stage in the test on HAIGH specimen No. BLL7A, at which only one series of slip-bands appeared on the testpiece. Photomicrograph No. 3 shows a view of these bands, and it will be seen that their uniform direction made accurate measurement possible. The inclination was recorded at eleven out of the twelve reference marks: the results are set down in Table I, Col. A.

TABLE I.

Reference Mark on Specimen.	Col. A. Inclination of Observed Trace.	Col. B. Trace of Mean Plane.	Col. C. Error.
0	41° 50′	43° 23′	1° 33′
1	48° 13′	49° 5′	0° 52′
2	45° 17′*	46° 29′	1° 12′
3	36° 17′	33° 51′	2° 26′
4	5° 9′	6° 11′	1° 2′
5	−24° 11′	−25° 48′	1° 37′
6	−45° 22′	−43° 23′	1° 59′
7	−51° 33′	−49° 5′	2° 28′
8	—	−46° 29′	—
9	−33° 28′	−33° 51′	0° 23′
10	− 4° 31′	− 6° 11′	1° 40′
11	+24° 31′	+25° 48′	1° 17′

* Although a gap in the bands existed at this point it was possible to estimate a reading from the lines appearing at each side of the gap.

The mean plane referred to above was then deduced as follows: The set of readings was first reduced to a set of six at points 0, 1, ... 5 by taking the mean of the values recorded for opposite pairs, such as 0–6, 1–7, &c., and affixing the appropriate sign. The traces on 0 and 3 (which marks are 90° apart on the specimen) were then regarded as the traces of a plane whose equation was calculated with reference to convenient axes.

Let this equation be

$$ax + by + cz = k.$$

The pairs of traces 1–4 and 2–5 were then similarly treated and equations referred to the same axes were deduced as

$$a_1x + b_1y + c_1z = k$$

and

$$a_2x + b_2y + c_2z = k.$$

It was found that corresponding coefficients such as a, a_1 and a_2 were very nearly identical; the mean plane was then taken as

$$\frac{a + a_1 + a_2}{3}x + \frac{b + b_1 + b_2}{3}y + \frac{c + c_1 + c_2}{3}z = \mathrm{K}.$$

The inclinations of the theoretical traces of the plane deduced in this way are given in Table I, Col. B, while in Col. C the errors in individual traces are set down. It will be seen that the greatest error is about $2\frac{1}{2}°$, while the mean error is no greater than $1\frac{1}{2}°$; a result which indicates with very little doubt that the slip bands observed are due to a set of parallel planes.

In order to determine whether the mean plane representing a set of bands corresponded with any crystallographic plane, its spherical co-ordinates were calculated and plotted on a polar diagram on which the positions of the principal crystallographic planes had been found by X-ray analysis.

It was found that in all cases the observed bands corresponded very closely with one or other of the four octahedral planes of the crystal. Considerations of space forbid the inclusion of the diagrams themselves, but in every case the spherical co-ordinates of the mean plane have been tabulated alongside those of the octahedral planes. Further, in some cases, the inclinations of individual traces have been compared with the traces of the corresponding octahedral planes.

Changes in Cross-Section of Specimens.

Although for reasons already given, it was not possible to make detailed measurement of the distortion of the test-pieces as a whole, any changes in cross-section were measured at all stages. The method adopted was to place the specimen in a horizontal gauge projection apparatus and to project a silhouette on to a screen at a magnification of about 50 diameters. Thus the position of any number of pairs of tangents to the cross-section could be determined with reference to the centre line. These were afterwards used to draw the envelope of the cross-section to a large scale in its correct position with reference to the axis of the specimen, and hence any change of shape together with any excentricity could be detected.

The experiments made on the various specimens will now be described in detail.

1. *Behaviour of Single Crystals subjected to Reversed Direct Stresses.*

*Repeated Stress Test made on Specimen No. BLL*7A.—Machine used : Haigh machine.

Frequency of Loading :—2,200 cycles per minute. A Haigh machine specimen (*see* fig. 2) was prepared. It was polished and etched (30 seconds) in a 10 per cent.

solution of NaOH, followed by a further etching (70 minutes) in a 50 per cent. solution, after which it was repolished. Photomicrograph No. 1 was then taken. From the X-ray analysis, the spherical co-ordinates of the octahedral planes were deduced and are given in Table II.

TABLE II.

Octahedral planes		111	$\bar{1}11$	$1\bar{1}1$	$11\bar{1}$
Spherical co-ordinates	θ	26°	90°	46° 15′	78°
(Reference plane 6–0).................	ψ	−97° 20′	122° 30′	60°	−167° 40′

A projection of the envelope of the specimen showed that the latter was truly circular, concentric, and of diameter 0″·290. All ranges of stress given below, unless otherwise stated, will be calculated on this initial area of section (0·0661 inch²). The specimen was then subjected to 6·834 × 10^6 reversals of a range of load of ± 0·0394 tons (f = ± 0·6 tons/inch²). Examination of the surface of the specimen revealed four sets of slip-bands, of which the measurements given in Table III, Col. (a), were made. It was found possible to take readings of any particular set of traces only at certain reference marks, as at other portions of the specimen the traces were either entirely absent or were too indistinct to be recorded with accuracy. Photomicrograph No. 2 illustrates a typical spot at which only two sets of traces were visible. Sufficient

TABLE III.

Reference Mark on Specimen.	Inclination of Trace to Plumb Line.							
	No. 1 Series.		No. 2 Series.		No. 3 Series.		No. 4 Series.	
	(a) Observed trace.	(b) Calculated for $\bar{1}11$ plane.	(a) Observed trace.	(b) Calculated for $1\bar{1}1$ plane.	(a) Observed trace.	(b) Calculated for 111 plane.	(a) Observed trace.	(b) Calculated for $11\bar{1}$ plane.
0	—	90°	−42° 45′	−43° 52′	—	24° 38′	—	—
1	—	90°	—	−48°	21° 46′	22° 50′	—	—
2	—	90°	—	−43° 52′	—	15° 10′	−74° 44′	−75° 58′
3	—	90°	−30° 30′	−29° 3′	2° 30′	2° 44′	−75° 35′	−76° 9′
4	—	90°	− 2° 15′	0°	−11°	−10° 37′	—	—
5	89° 20′	90°	28°	29° 3′	−21°	−20° 28′	—	—
6	88° 50′	90°	41° 30′	43° 52′	−25° 15′	−24° 38′	—	—
7	—	90°	47°	48°	−22° 40′	−22° 50′	—	—
8	—	90°	43°	43° 52′	−15° 7′	−15° 10′	—	—
9	—	90°	30°	29° 3′	− 3° 54′	− 2° 44′	76° 24′	76° 9′
10	89° 10′	90°	− 0° 15′	0°	—	10° 37′	—	—
11	89° 30′	90°	−28°	−29° 3′	19° 30′	20° 28′	—	—

traces of Series 2 and 3 were observed to calculate the spherical co-ordinates of the corresponding mean planes, and the latter are tabulated in Table IV.

An X-ray analysis was again made of the specimen, and the spherical co-ordinates of the octahedral planes are also given in Table IV, and compared with the mean planes calculated from the observed slip-bands.

TABLE IV.

Octahedral plane…………………… Reference 6–0		111	$\bar{1}11$	$1\bar{1}1$	$1\bar{1}1$
Spherical co-ordinates deduced from X-ray analysis	θ	24° 45′	90°	48°	76° 30′
	ψ	−94°	123° 30′	60°	−166° 45′
Spherical co-ordinates calculated from observed slip-bands	θ	24° 45′	—	47° 3′	—
	ψ	−96°	—	58° 34′	—

It will be seen that the calculated mean planes are in close agreement with two of the octahedral planes, the divergences, measured by means of the stereographic net, having values of 2° and 1° respectively for the 111 and the $1\bar{1}1$ planes. The inclinations of the traces of the four sets of octahedral planes have been calculated and tabulated in their appropriate columns (*b*) in Table III, and may be compared with the inclinations of the observed slip bands. In the case of Nos. 2 and 3 series, good agreement exists between the inclination of individual traces. For Nos. 1 and 4 series, insufficient traces existed to justify the calculation of a mean plane, but it will be seen that the agreement between the inclinations of theoretical and observed traces is again good. The envelope of the cross-section of the specimen was measured, but no change in shape could be detected, and the specimen was then lightly polished and etched. The specimen was replaced in the Haigh machine, and the range of applied load adjusted to the value of ± 0·071 tons (± 1·08 tons/inch^2). While starting up the machine, it was noticed that the specimen became slightly buckled. This occurred while the air-gaps were being adjusted, and a compressive mean stress was temporarily super-imposed on the cycles of reversed stresses. The adjustment was quickly made, but the distortion persisted unchanged during subsequent repetitions of this range of stress. After 10,000 reversals, examination revealed the existence of one system of slip-bands. The test was then continued until a total of $3 \cdot 382 \times 10^6$ reversals of this stress range had been applied, when the specimen was removed from the machine. A projection of the envelope of the cross-section of the mid-portion of the specimen showed that the specimen was still circular (0″·289 diameter), but the excentricity of the axis was 0″·031. It is believed that this excentricity may be entirely ascribed to the buckling produced during the first few reversals in the manner described above.

Only one set of slip-bands was visible on the surface of the specimen. This system, however, consisted of closely-spaced slip-bands which could be followed right round the specimen, except at the reference marks 2 and 8, where "gaps" appeared. Photomicrographs 3 and 4, taken at reference marks 4 and 8, indicate the appearance of the specimen at two typical spots. Measurements made of the inclinations of the slip-bands at each of the reference marks have been previously recorded in Col. A, Table I.

The specimen was again X-rayed. Table V contains the spherical co-ordinates of the deduced octahedral planes, together with those of the mean plane calculated from the observed traces (Table I).

TABLE V.

Octahedral plane		111	$\bar{1}11$	$1\bar{1}1$	$11\bar{1}$
Spherical co-ordinates deduced from X-ray analysis	θ	23°	89° 20′	50° 20′	74° 30′
	ψ	−91°	−57°	60°	−167° 30′
Spherical co-ordinates of mean plane corresponding to observed slip bands.	θ	—	—	47° 36′	—
	ψ	—	—	54° 30′	—

The planes corresponding to the slip-bands are seen to be in fairly close agreement with the $1\bar{1}1$ planes. Measured on the net, the actual divergence is 5°. This is the largest discrepancy yet encountered, and it is considered that the excentricity of the mid-portion of the specimen with respect to the portion bearing the reference marks is mainly responsible for the degree of the error, which cannot, in the circumstances, be regarded as excessive.

The specimen was again polished and etched and replaced in the Haigh machine. Under reversals of a range of load of ± 0·104 tons ($f = \pm 1\cdot58$ tons/inch^2), the specimen at once began to extend, the cross-section assuming an elliptical shape. The rate of drawing down, at first very rapid, decreased under subsequent reversals until, after 54,000 reversals had been endured, it had become very slow. The test was then discontinued. The envelope of the cross-section of the specimen was re-determined. The section was found to be elliptical, the greatest divergence of any point on the envelope from a true ellipse being 0″·002. The centre of the envelope was found to be concentric with the axis of pull to within 0″·0008. The axes of the envelope were 0″·294 and 0″·173 respectively, the inclination of the minor axis to the reference plane (0–6) being 41°. Examination of the surface of the specimen revealed the presence of a very heavily marked, closely spaced, system of slip-bands, together with a small number of wide bands passing round the specimen in a direction different from that of the system of slip-bands. Photomicrograph No. 5 is typical of the general appearance of the main system of slip-bands, while photomicrograph No. 6 shows one of the broad bands. Owing to the shape of the specimen, measurements of the inclinations of the slip-bands could usefully be made only at the points corresponding to the major and minor axes of the ellipse. From these measurements, the spherical co-ordinates of a mean plane were deduced, and are recorded in Table VI. An X-ray analysis of the crystal was again made and the deduced octahedral planes are also recorded in Table VI.

TABLE VI.

Octahedral plane…………………		111	$\bar{1}11$	$1\bar{1}1$	$1\bar{1}1$
Spherical co-ordinates deduced from X-ray analysis.	θ	20°	90°	65° 15′	58° 20′
	ψ	−53° 30′	116° 15′	47° 15′	−177° 15′
Spherical co-ordinates of plane calculated from observed slip bands.	θ	—	—	66° 20′	—
	ψ	—	—	45° 15′	—

The total divergence between the plane corresponding to the slip-bands and the octahedral plane, $1\bar{1}1$, is 2°. As seen in photomicrograph No. 6, the "broad-bands" can be resolved into a system of slip-bands, but it was not possible to obtain sufficient measurements of their direction to correlate them with any of the crystallographic planes.

The specimen was again polished and etched, and replaced in the machine and subjected to further reversals of the previously-applied range of load $\pm$ 0·104 tons ($f = \pm$ 1·58 tons/inch^2). During 30,000 reversals no further extension could be detected, and no slip-bands could be detected on the specimen. Again, after a further 330,000 reversals, no slip-bands were seen. The following tests were then made, the surface of the specimen being carefully examined, under the microscope, after each test.

(*a*) 10,000 reversals of a range of load of $\pm$ 0·111 tons ($f = \pm$ 1·68 tons/inch^2).

Remarks :—No change on surface or extension of the specimen.

(*b*) 10,000 reversals of $\pm$ 0·117 tons ($f = \pm$ 1·77 tons/inch^2).

Remarks :—As for (*a*) above.

(*c*) 22,000 reversals of $\pm$ 0·126 tons ($f = \pm$ 1·90 tons/inch^2).

During this test, a very slow steady creep occurred. The whole of the surface of the specimen became covered with a set of wavy broken markings (*see* photomicrograph 7). The general appearance of these markings differed considerably from the previous slip-bands. While they seemed to pursue a general direction, wide variations from this are observed in any one marking, and no estimation of their inclinations was practicable.

(*d*) Further 66,000 reversals of $\pm$0·126 tons ($f = \pm$1·90 tons/inch^2).

Remarks :—Steady creep continued and wavy lines increased in intensity of marking and number.

(*e*) Further 112,000 reversals of ± 0·126 tons ($f = \pm 1 \cdot 90$ tons/inch^2).
Remarks :—Rate of creep diminished to zero value.

(*f*) Further 728,000 reversals of ± 0·126 tons ($f = \pm 1 \cdot 90$ tons/inch^2).
Remarks :—No further creep or change in microstructure detected.

(*g*) 20,000 reversals of ± 0·134 tons ($f = \pm 2 \cdot 03$ tons/inch^2).
Remarks :—As for (*f*) above.

On the range of load being increased to ± 0·141 tons ($f = \pm 2 \cdot 14$ tons/inch^2), the specimen at once began to extend, the rate of creep becoming more and more rapid. After 10,000 reversals, the specimen suddenly " necked " in the middle of the parallel portion. The general appearance of the specimen is seen from photomicrograph No. 8. Examination under the microscope revealed the presence of one direction of slip-bands at each of the points corresponding to the minor axis of the ellipse, while two opposed systems were apparent at the ends of the major axes. Photomicrographs Nos. 9 and 10 are representative. Whilst the nature of these markings did not permit of accurate measurement of their inclinations, it may be mentioned that their general appearance was consistent with slip on two octahedral planes ($1\bar{1}1$ and $11\bar{1}$). Only one direction of slip-bands was observed at the ends of the minor axis because the traces of the two planes were parallel at those points.

An X-ray photograph,* taken through the " necked " portion of the specimen, failed to reveal any indications of internal cracks. An X-ray analysis of the crystal was then made and the deduced results are as stated in Table VII.

TABLE VII.

Octahedral planes		111	111	$1\bar{1}1$	$11\bar{1}$
Spherical co-ordinates deduced from X-ray analysis. Reference (6 — 0).	θ	20°	89° 30′	60°	63° 30′
	ψ	—67°	118° 15′	56°	—173° 15′

The envelope of the " necked " portion was determined and the cross section of the specimen was found to be a true ellipse (within 0″·001) the lengths of whose axes were 0″·289 and 0″·125 respectively. The minor axis was inclined at 31½° to the reference plane (0–6). The centre of the ellipse coincided with the axis of pull to within 0″·002.

The specimen was then polished and etched. A Laué photograph (photograph 11*) was taken and attention is drawn to the character of the reflections obtained.

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* These photographs were kindly taken by Mr. PRESTON, of the Physics Department, National Physical Laboratory.

The specimen was then replaced in the Haigh machine and subjected to the following tests :—

(*h*) 10,000 reversals of a range of load of ± 0·043 tons ($f = \pm\ 0\cdot65$ tons/inch^2).
Remarks :—No creep during test. No slip-bands appeared.

(*j*) 10,000 reversals of ± 0·070 tons ($f = \pm\ 1\cdot06$ tons/inch^2).
Remarks :—As for (*h*) above.

(*k*) 10,000 reversals under ± 0·094 tons ($f = \pm\ 1\cdot42$ tons/inch^2).
Remarks :—As for (*h*) above.

(*l*) 18,000 reversals under ± 0·126 tons ($f = \pm\ 1\cdot9$ tons/inch^2).
Remarks :—A pronounced series of short wavy markings (similar to those shown in photograph 7) appeared.

(*m*) Further reversals under ± 0·126 tons ($f = \pm\ 1\cdot9$ tons/inch^2).
Remarks :—No creep could be detected, but after a further 12,000 reversals, the specimen suddenly fractured.

Certain Conclusions as to the Nature of the Distortion.

(i) *Slip-Bands as Traces of Planes.*—From the measurements made of the inclination of the slip-bands observed at various stages of the test, it has been shown (*see* earlier discussion) that slip-bands may now be definitely regarded as intersections of planes with the surface of the specimen.

(ii) *Correlation of Slip Planes with Certain Crystallographic Planes.*—At various stages of the test, the spherical co-ordinates of mean planes have been deduced from the observed inclinations of the slip-bands. These spherical co-ordinates have been compared with those of the octahedral planes as determined by X-ray analysis, and any differences found have been within the possible range of experimental error. The actual total errors observed were 2°, 1°, 5° and 2°, and in the case of the 5° error, reasons were given for this, comparatively, high value. It may, therefore, be regarded as proved that the slip-bands observed coincided with the traces of octahedral planes.

(iii) *Nature of Distortion.*—Under applications of the smallest range of loading, slipping occurred on all the four systems of octahedral planes. Little movement had occurred on two of these sets of planes, as was shown by the nature and number of the slip-bands. (These planes were the $\bar{1}11$ and $11\bar{1}$ respectively.) Even in the case of the other planes (111 and $1\bar{1}1$) the amount of slip was insignificant in comparison with the deformation occurring at later stages of the test. (As the values of the shearing stresses on these planes were widely different, it may here be remarked that in the authors' experience of many single crystals subjected to various types of straining action, a process of "settling-down" or "adjustment" first occurs during which slip usually occurs on all four sets of octahedral planes. In the process a stage of "stability" is reached, after which distortion takes place only by slip on the plane or planes of maximum shear stress.)

From this stage onwards—up to and including the reversals of that range of stress under which the specimen drew down into an elliptical cross-section—the observed slip was confined to one set of octahedral planes, namely, the $1\bar{1}1$ planes. Reference to the tables of spherical co-ordinates will show that this plane is that octahedral plane in closest agreement with a plane of maximum shear. It may be concluded, therefore, that during the *stages of the test referred to above*, this set of planes ($1\bar{1}1$) only is of importance, and that any change of shape of the specimen may be studied as arising from shear on this set of planes. Consideration may now be given to the *direction* of slip on these planes.

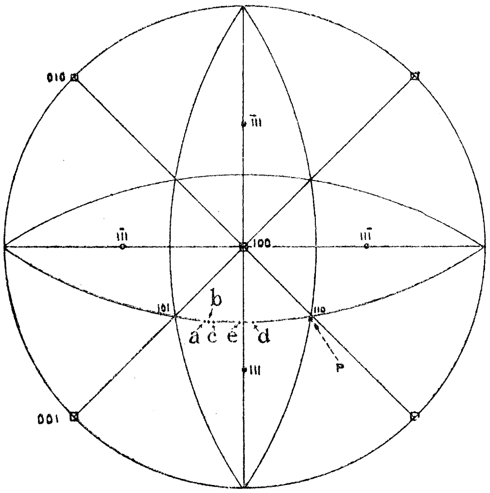

Fig. 3.—Diagram showing Change of Position of Axis of Specimen relative to fixed Crystal Axis.

The Pole of the Diagram is the Cubic Axis 100.

a. Axis of Specimen before Test.
b. Axis of Specimen after 6,834,000 Reversals at ± 0·60 ton/inch^2.
c. Axis of Specimen after 3,382,000 Reversals at ± 1·08 tons/inch^2.
d. Axis of Specimen after 54,000 Reversals at ± 1·58 tons/inch^2.
e. Axis of Specimen after 10,000 Reversals at ± 2·14 tons/inch^2.

(iv) *Direction of Slip*.—(*a*) *Relative Movement* (*during test*) *of crystal and specimen axes*.—Fig. 3 is a polar diagram in which the pole is one of the cubic axes (100). The other two cubic axes are seen to be situated at 90° apart on the circumference of the diagram, while the four octahedral planes are disposed symmetrically about the centre. The great circles shown represent the intersections of the four octahedral planes with the sphere. The points marked *a*, *b*, *c*, *d*, *e* represent the axis of the specimen at various stages of the test (*see* footnote to fig. 3). As has been demonstrated by TAYLOR and ELAM,* the movement of the axis of the specimen—in a diagram of this nature—during the course of shear on *one* set of planes, should be along a great circle which contains the original position of the axis and also the point representing the direction of slip. *The actual direction of slip must, therefore, be represented by the intersection of the great circle and the great circle representing the slip plane.* In the present test, the θ co-ordinate of the $\bar{1}11$ plane was always approximately 90° (greatest variation was 0° 40′). In fig. 3, therefore, the axis of the specimen will always lie on the great circle representing the $\bar{1}11$ plane. *The conclusion is, therefore, drawn that in the present instance the direction of slip was the line of intersection of the slip plane* ($1\bar{1}1$)

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* "The Distortion of an Aluminium Crystal during a Tensile Test."—TAYLOR and ELAM, 'Roy. Soc. Proc.,' A, vol. 102 (1923).

with the $\bar{1}11$ *plane, i.e., is represented by the point on the diagram marked* 110. The latter point is the normal to the 110 plane, and this direction may be referred to as the 110 direction.

(*b*) "*Gaps*" *in System of Slip-Bands.*—Reference to Table I will show that at one stage of the test—when traces of one set only of slip-planes ($1\bar{1}1$) were observed, two definite gaps entirely devoid of slip-bands were observed on opposite sides of the specimen. These gaps can be explained and related to the direction of slip. If a specimen of elliptical cross-section be distorted by shear on a system of parallel planes having a common direction of slip, it is apparent that the direction of displacement of neighbouring particles will vary from a direction perpendicular to the boundary to one tangential to the boundary. Hence, if the polished surface of such a distorted specimen is viewed through a (reflecting) metallurgical microscope, the intensity of the shadows (representing the slip-bands) will vary from a maximum value through zero value to the same maximum value *twice* as the specimen rotates through 360°. In the present instance, the fact that the "gaps" observed had definite regular widths is explained by the absence of a perfect surface and also by the limits of resolution of the optical system employed. The slip-bands faded away as the gaps were approached, and the width of the latter was approximately $0''\cdot 02$. The positions of the centres of the gaps could, however, be estimated with considerable accuracy, and were found to coincide with the reference marks 2 and 8. It is easily shown that in such a case the position of maximum intensity of slip-bands will correspond with the ends of that diameter of the slip-plane which is parallel to the direction of slip, also that the position of the gaps will correspond with the ends of the conjugate diameter of the same elliptical section (the slip-plane). In the present instance, the spherical co-ordinates of the diameter of the slip-plane, conjugate to that which passes through reference marks 2 and 8 (*i.e.*, through the centre of the gaps) have been calculated. In constructing fig. 3, when the point *c* (which represents the axis of the specimen at the stage at which these gaps appeared) was rotated into position, the point representing the above diameter was rotated with it. The point P in fig. 3, shows the resulting position of this diameter, and it will be seen that it almost coincides with the point representing the normal to the 110 plane.

Thus there is additional experimental evidence that the direction of slip was the 110 *direction.*

(*c*) *Stress Considerations.*—In view of the fact that the experimental evidence indicates that the direction of slip coincides with one of the principal lines of atoms in an octahedral plane, an analysis has been made of the shear stress throughout the test in each of the three similar crystallographic directions on the four octahedral planes. The results are given in Table VIII. It will be seen that the stress on the $1\bar{1}1$ plane in the direction of its intersection with the $\bar{1}11$ plane (*i.e.*, in the 110 direction) was always greater than any of the other eleven components given, until the drawing-down stage began, and therefore from stress-considerations if slipping of the nature

TABLE VIII.—Analysis of Sheer Stresses in Haigh Specimen BLL7A throughout Test.

Stage of Test.	Area of Cross-Section.	Tensile Stress on Cross-Section.	Shear Stress on 111 Plane in direction of Intersection with			Shear Stress on $\bar{1}11$ Plane in direction of Intersection with			Shear Stress on $1\bar{1}1$ Plane in direction of Intersection with			Shear Stress on $\bar{1}11$ Plane in direction of Intersection with		
			$\bar{1}11$	$1\bar{1}1$	$11\bar{1}$	$1\bar{1}1$	$11\bar{1}$	111	$11\bar{1}$	111	$\bar{1}11$	111	$\bar{1}11$	$1\bar{1}1$
	Sq. in.	tons/in.^{2}	tons/in.^{2}			tons/in.^{2}			tons/in.^{2}			tons/in.^{2}		
On application of ± 0·0394 tons	0·0661	0·60	0·161	0·070	0·231	0	0	0	0·230	0·054	0·282	0·053	0·122	0·069
After 6·8 × 10^6 reversals of ± 0·0394 tons	0·0661	0·60	0·144	0·066	0·226	0	0	0	0·223	0·050	0·281	0·058	0·136	0·078
On application of ± 0·071 tons	0·0661	1·07	0·257	0·118	0·403	0	0	0	0·397	0·089	0·501	0·103	0·243	0·138
After 3·4 × 10^6 reversals of ± 0·071 tons	0·0656	1·08	0·224	0·150	0·388	0·009	0·012	0·003	0·389	0·104	0·504	0·113	0·276	0·163
On application of ± 0·104 tons	0·0656	1·59	0·330	0·221	0·571	0·013	0·017	0·004	0·573	0·153	0·742	0·166	0·406	0·240
After 0·054 × 10^6 reversals of ± 0·104 tons	0·0400	2·60	0·149	0·789	0·639	0	0	0	0·624	0·351	0·971	0·357	1·143	0·783
On application of ± 0·141 tons	0·0400	3·52	0·202	1·122	0·865	0	0	0	0·845	0·500	1·314	0·483	1·547	1·060
After 0·01 × 10^6 reversals of ± 0·141 tons	0·0284	4·96	0·162	1·259	1·426	0·037	0·038	0·002	1·423	0·669	2·095	0·677	1·960	1·267

described above took place, the 110 direction on the $\bar{1}11$ plane was the most probable direction.

(The shear stress on the $1\bar{1}1$ plane in the 110 direction is given by

$$T \cos \theta_{1\bar{1}1} \cos \theta_{110},$$

where the θ's are the ordinary spherical co-ordinates, and T is the applied tensile stress. The values of the θ's can be read directly from fig. 3 by means of a stereographic net.)

(*d*) *Evidence of Nature of Slip from the Distortion of the Test Piece.*—Assuming the plane on which slip has occurred and the direction of slip in this plane, it is possible, knowing the spherical co-ordinates of the slip-planes before and after distortion, to calculate the change in shape of the cross-section of the specimen due to this slipping. The required data are as follows :—

α = Included angle between assumed direction of slip and the line of greatest slope of the slip-plane.

θ_1 = Angle between axis of specimen and the slip-plane before test.

θ_2 = Angle between axis of specimen and the slip-plane after test.

d = Original diameter of the specimen.

ϕ = Angle of shear.

The value of ϕ is calculated directly from the values of θ_1 and θ_2, as determined by X-ray analysis.

In the present case the values recorded were $\theta_1 = 45°45'$, $\theta_2 = 24°45'$, $d = 0''\cdot 290$. Assuming slip to have occurred on the $1\bar{1}1$ planes and in the 110 direction, the values of ϕ and α become 49° 11′ and 20° respectively. The calculated axes and orientation of the new elliptical cross-section are compared with the experimental results in Table IX.

TABLE IX.

	Measured.	Calculated.
Major axis	0″·294	0″·296
Minor axis	0″·173	0″·173
Angle between reference plane 0–6 and the minor axis	41°	41° 15′

The agreement is so close that little doubt can be expressed as to the accuracy of the assumptions on which the calculations were based, namely, that slip occurred on the $1\bar{1}1$ *planes and in the* 100 *direction.*

(v) *Nature of the Distortion in the Final Stages of the Test.*—It has been seen that—with the exception of some preliminary slipping on all four sets of octahedral planes—

all the slipping has occurred on the $1\bar{1}1$ plane and in the 110 direction. This applied up to and including that stage of the test at which 54,000 reversals of ± 1·58 tons/inch^2 stress were endured by the specimen. Reference to the polar diagram of fig. 3 shows that when the axis of the specimen reaches a position on the line joining the points $\bar{1}11$ and 111, it is then placed symmetrically with regard to the two planes $1\bar{1}1$ and $11\bar{1}$ when the tendencies to produce slip on the $1\bar{1}1$ plane in the 110 direction, and on the $11\bar{1}$ plane in the 101 direction will be equal. During the course of the application of 54,000 reversals of ± 1·58 tons/inch^2 it will be seen (fig. 3) that the specimen axis, moved from *c*, through this intermediate position to a point, *d*, slightly beyond. In this position, the tendency to slip on the $11\bar{1}$ plane is now slightly the greater. Whilst no general indication of slip in this direction on this plane at this stage was obtained, it is considered likely that the broad bands previously referred to (*see* p. 8, and photograph No. 6) were connected with this slip. After 10,000 reversals of ± 2·14 tons/inch^2 nominal stress, the specimen suddenly necked and two systems of slip bands were observed, such as would be consistent with slip on these planes. In fig. 3 it will be seen that the axis of the specimen had now moved back to *e*, which is slightly towards the original side of the symmetrical position. This indicates that the amount of slipping on the $1\bar{1}1$ plane, during this stage, was greater than on the $11\bar{1}$ plane. *From the above consideration it is concluded that during the final stages of the test, slipping had proceeded alternately on these planes, the axis of the specimen moving from one side to the other of the neutral position.* The fact that the axis moves through the neutral position a certain indeterminate amount before slip commences on the next set of planes now subjected to a greater shear stress, indicates that the effect of slip on one plane is to increase the resistance to slip on other planes which intersect it. In other words, the effect of slipping produces a transverse hardening effect in addition to its known hardening effects in its own plane.

2. *Behaviour of Single Crystals subjected to Reversed Torsional Stresses.*

Repeated Stress Test on Specimen No. BLL8A. Machine used : Stromeyer Machine. Frequency of Loading : 200/520 cycles per minute.

The dimensions of the specimen, after machining, are given in fig. 1. The specimen was polished and etched in a 10 per cent. solution of NaOH for 30 seconds. An X-ray analysis gave the following co-ordinates of the four octahedral planes.

TABLE X.

Octahedral planes		111	$\bar{1}11$	$1\bar{1}1$	$1\bar{1}1$
Spherical co-ordinates. Reference Plane 6 – 0.	θ	86° 30′	88° 50′	31°	39° 15′
	ψ	—20′	89° 30′	35° 50′	—148′

The envelope of the specimen was truly circular with a diameter 0″·348; all stresses are calculated on this cross section which did not change until the specimen eventually cracked. The specimen was subjected to $0 \cdot 247 \times 10^6$ reversals of a torque of 4·44 inch-lbs. (speed 200 cycles/minute; stress ± 0·24 tons/inch^2). Examination of the surface showed a series of slip-bands nearly parallel to the axis of the specimen, gaps occurring at four points ($1\frac{3}{4}$, $4\frac{3}{4}$, $7\frac{3}{4}$ and $10\frac{3}{4}$). The measurements of the inclinations of these bands are given in Table XI.

TABLE XI.

Reference Mark.	Inclination of Trace.
0	—86° 30′
3	—87° 15′
6	87° 45′
9	88° 54′

From these measurements it was not possible to identify satisfactorily any slip-plane. Photomicrograph No. 12 shows the appearance of the surface at reference mark 6.

The specimen was then given $0 \cdot 592 \times 10^6$ reversals of a range of torque of 18·13 inch-lbs. (speed 400 cycles/minute; stress ± 0·98 tons/inch^2), and again examined. The ends of the specimen had become twisted relatively to one another through an angle of 11°. Two further sets of slip-bands had appeared whose traces could be seen in the gaps left after the first stage of test. The measurements given in Table XII were taken.

TABLE XII.

Reference Mark.	Inclination of Traces.		
	Series 1.	Series 2.	Series 3.
0	—83° 36′	—	—
2	—	39° 18′	—26° 48′
3	—84° 45′	—	—
6	—88° 18′	—	—
8	—	—34° 45′	34° 45′
9	—87° 55′	—	—
11	—	8° 36′	—7° 0′

As before, these traces were insufficient to identify with certainty corresponding slip-planes. The identification was therefore postponed until the cross-section of the specimen could be examined. Photograph No. 13 shows a view of the specimen at reference mark 8. The specimen was then subjected to $1 \cdot 131 \times 10^6$ reversals of a range of torque of 27·01 inch-lbs. (speed = 480 reversals/minute ; stress ± 1·46 tons/inch²). Traces of slip-bands were again measured and the results are given in Table XIII.

TABLE XIII.

Reference Mark.	Inclination of Traces.		
	Series 1.	Series 2.	Series 3.
0	− 84° 6′	—	—
2	—	39° 33′	− 27° 51′
3	− 84° 38′	—	—
5	—	*4° 21′	—
6	− 89° 24′	—	—
8	—	− 34° 36′	34° 10′
9	− 89° 9′	*7° 11′	*− 4°

* At these points the change of curvature in the bands was very rapid so that the accuracy of the measurements is not great.

Of the gaps, previously referred to, those at 4$\frac{3}{4}$ and 10$\frac{3}{4}$ were now covered with roughly horizontal markings. No change in cross section nor in the orientation of the crystallographic axes could be detected.

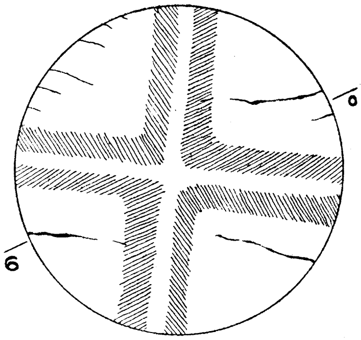
The specimen was then lightly polished and etched and replaced in the machine under a range of torque of 32·37 inch-lbs. (speed 520 reversals/minute ; stress = ± 1·75 tons/inch²). After $0 \cdot 269 \times 10^6$ reversals it was found that the machine had been stopped by the cut-out gear. The specimen had cracked in 14 places. With one exception, all these cracks were approximately parallel to the axis of the specimen and as nearly as could be observed were parallel to a closely spaced system of slip-bands which covered the whole surface. The remaining crack extended the whole length of the parallel portion and consisted of alternate steppings in directions parallel to and perpendicular to the general directions of the other cracks. Photomicrograph No. 14 shows a typical portion of this crack. Attention is drawn to the longitudinal direction of shear indicated by the relative movement of adjacent portions of the specimen.

The measurements of the inclinations of slip-bands, of which photomicrograph No. 15 is representative, are given in Table XIV.

TABLE XIV.

Reference Mark.	Inclination of Traces.
0	− 87° 36′
3	− 88°
6	87° 36′
9	87° 56′

An X-ray analysis again showed no change in the orientation of the crystal axes. It was noticed that a relative twist between the two ends of the specimen had occurred in the reverse direction to and of a greater amount than that previously recorded, so that the final relative angular displacement was 4°.



The parallel portion of the specimen was enclosed in Fusible Alloy (melting-point 60°) and cut across in a direction perpendicular to the axis. The cross-section was etched to remove the effects of the saw-cut and then polished. In addition to the cracks a double system of markings was revealed. The specimen was repeatedly polished; but each time these markings were observed. Photograph No. 16 is a view of the cross-section showing both the cracks and the markings referred to. The markings, of which a diagrammatic representation is here given, while clearly distinguishable under the low magnification used in the above photograph, could not be detected under high magnifications. It should be emphasised that these markings appeared after *polishing* only, no etching being necessary, and therefore they indicate differences in hardness in adjacent portions of the specimen.

Conclusions Drawn from the Results of the Test.

One of the conclusions drawn from the Haigh specimen described in the earlier portion of this paper was that the process of slip results in a hardening effect on the planes involved. This being so, the markings described above may reasonably be regarded as the traces of slip-planes on the cross-section of the specimen. It will be seen from photograph No. 16 that these traces divide the cross-section into four quadrants, the diameters bounding these, corresponding roughly with the reference planes 2–8 and 5–11. The markings in any one quadrant conform very accurately to one direction. Further, this direction is the same in opposite quadrants. Hence, examination of the cross-section suggests that slip has proceeded on two sets of planes, each of which is associated only with two opposite quadrants.

It will be remembered that at all stages of the test the observed slip-bands included a closely-spaced series which was almost parallel to the axis of the specimen at all reference points. It is apparent that unless these traces were due to a set of planes which were truly parallel to the axis of the specimen, large variations in their inclinations must have occurred at some reference points. Such variations were not observed, yet the small variations recorded were sufficiently regular to suggest that they were not due to errors of observation of a set of planes parallel to the axis of the specimen. This difficulty, however, disappears if slip on two sets of planes be considered, each set being confined to a pair of opposite quadrants. Reference to Table X will show that there are two octahedral planes which are nearly parallel to the axis of the specimen (*i.e.*, whose θ-co-ordinates are nearly 90°), namely, the 111 and $\bar{1}11$ planes. The angle between the trace of either of these planes on the cross-section and the reference plane (6 – 0) can be deduced immediately from the table, the values being 70° for the 111 plane and —0° 30′ for the $\bar{1}11$ plane. This reference plane has been marked in its correct position on photograph No. 16, and direct comparison will show that the two sets of markings on the cross section previously mentioned are parallel to the theoretical traces of the 111 and 411 planes respectively within close limits. Those occurring in the quadrants 5 – 2 and 8 – 11 correspond to the 111 plane, and those in the quadrants 5 – 8 and 2 – 11 to the $\bar{1}11$ plane. In Table XV are recorded the measurements (after correction for twist) of the horizontal series of slip-bands at each stage of test together with the theoretical traces of the 111 and $\bar{1}11$ planes.

TABLE XV.

Reference Mark.	Measured Traces.				Theoretical Traces.	
	After 0·24 tons/in.^{2}	After 0·98 tons/in.^{2}	After 1·46 tons/in.^{2}	After 1·75 tons/in.^{2}	111	$\bar{1}11$
0	— 86° 30′	— 87° 36′	— 88° 6′	— 87° 36′	79° 52′	— 88° 50′
3	— 87° 15′	— 88° 45′	— 88° 38′	— 88°	— 86° 17′	— 23° 8′
6	87° 45′	87° 42′	86° 36′	87° 36′	— 79° 52′	+ 88° 50′
9	88° 54′	88° 5′	86° 51′	87° 56′	+ 86° 17′	+23° 8′

It will be seen that the traces at 3 and 9 agree fairly closely with those calculated for the 111 plane. These reference marks are in the quadrants in which the cross-section markings agree with traces of the 111 plane. In the same way, both on the surface and on the cross-section, the traces at 0 and 6 agree with the $\bar{1}11$ plane. Thus, it appears that slipping has proceeded on two sets of octahedral planes (111 and $\bar{1}11$), slip on the 111 plane being restricted to the quadrants 5 – 2 and 8 – 11, and on the $\bar{1}11$ plane to the quadrants 5 – 8 and 2 – 11.

It may be pointed out that slipping of the above nature might have been predicted if it had been assumed that slip, in any part of the specimen, would take place only on that octahedral plane on which the shear stress, in the direction of one of the principal lines of atoms, was greatest. The same considerations of stress would lead in the present case to the conclusion that the two planes would have a common direction of slip—namely, their line of intersection. Whilst no evidence is forthcoming from the test as to the direction of slip, it may be pointed out that the direction of the line of intersection of the two octahedral planes concerned was nearly parallel to the axis of the specimen, and a longitudinal direction of shear is indicated in photomicrograph No. 14.

The two remaining series of slip-bands mentioned in the description of the test agree fairly closely with the two remaining octahedral planes, but their appearance suggested that the part played by these planes in the test must have been insignificant. This view is confirmed by the fact that they did not reappear in the final stage of the test.

3. *Behaviour of Single Crystals subjected to a Tensile Impact.*

Tensile Impact Tests on Specimens Nos. BLL11a and BLL11b.—These specimens, of the form shown in fig. 1, were machined from a long crystal supplied specially by Miss Elam. The specimen had previously been X-rayed and the original reference marks on the surface of the bar were preserved on the enlarged ends of the test-pieces, so that no further analysis was necessary before test. The spherical co-ordinates of the four octahedral planes are given in Table XVI.

TABLE XVI.

Octahedral planes		111	$\bar{1}11$	$1\bar{1}1$	$1\bar{1}1$
Spherical co-ordinates	θ	84° 15′	29° 30′	45°	74° 45′
Reference Plane 4–8	ψ	114° 40′	— 34° 45′	— 179° 30′	43′

The original diameter of both test-pieces was 0″·28 (area 0·062 inch²), and both were polished and etched over the whole of the parallel portion.

The machine employed was of the pendulum type, in which both the hammer and anvil are freely suspended with a maximum striking energy of 2404 ft.-lbs.

In the case of the first specimen (BLL11a) the maximum striking energy of the machine was applied. After the blow, the specimen was found to have drawn down to an elliptical cross-section and to have fractured in the parallel portion. Very marked local drawing-down was apparent, the actual fracture being almost wedge-shaped. The measured increase in length from shoulder to shoulder was 1″·65 on an original length of 2″·25 : an extension of 73 per cent. Two sets of slip bands were observed, but no further measurements were made on this specimen.

It was estimated that the energy absorbed in fracture was about 150 ft.-lbs., and, therefore, in the case of the second specimen the striking energy was reduced to 160 ft.-lbs. as an approximation to the minimum energy required. This specimen fractured in precisely the same manner as the former. The measured extension from shoulder to shoulder was again 73 per cent. on an original length of 2″·25. Two series of slip-bands were observed, and are shown in photomicrographs Nos. 17 and 18. The envelope of the cross-section of the specimen at points not near to the fracture was found to agree very closely with an ellipse of major axis 0″·275 and minor axis 0″·153 ; the axes being situated 33° from the reference planes 1–5 and 3–7 respectively. The inclinations of the two series of slip-bands were measured at the ends of the major and minor axes of the ellipse, and the results are given in Table XVII.

TABLE XVII.

Reference Mark on Specimen.	Inclination of Trace.	
	Series 1.	Series 2.
1 + 33°	— 51°	+ 62° 30′
3 + 33°	+ 39° 30′	+ 7° 0′
5 + 33°	+ 52° 30′	— 60° 30′
7 + 33°	— 38° 30′	— 3° 30′

Spherical co-ordinates of the slip-planes were calculated from these readings and are given in Table XVIII, together with the results of a second X-ray analysis made after fracture.

TABLE XVIII.

Octahedral planes		111	$\bar{1}11$	$1\bar{1}1$	$1\bar{1}1$
Spherical co-ordinates as deduced from X-ray analysis	θ	83°	26° 15′	61°	58° 15′
Reference plane 4–8	ψ	118°	— 65°	— 170° 20′	47°
Spherical co-ordinates of slip-planes	θ	—	—	60° 19′	56° 20′
Reference plane 4–8	ψ	—	—	— 170° 55′	44° 20′

It will be seen that Series 1 agrees very closely with the $11\bar{1}$ plane, while Series 2 agrees with the $1\bar{1}1$ plane; the actual errors as measured on a stereographic net being 3° and 1° respectively. It should be mentioned that Series 2 was much more clearly marked than Series 1, and it would appear that the greater part of the distortion resulted from shear on the $1\bar{1}1$ plane. Reference to Table XIV will show that the normal to this plane was inclined at 45° to the axis of the specimen before test, and that it was therefore a plane of maximum shear stress for tensile loading. At the end of the test the inclination of the normal had changed to 61°, while that of the $11\bar{1}$ plane had changed from 74° 45′ to 58° 15′. These results are in accordance with those recorded for the Haigh specimen BLL7A, and indicate that distortion at first takes place by slip on that set of planes on which the shear stress in the direction of one of the principal lines of atoms is the greatest. This slip proceeds until the tendency to slip on a second set of octahedral planes becomes the greater, from which point slipping takes place alternately on both sets until fracture occurs.

Nature of the Fracture.—The actual fracture was wedge-shaped and possessed a well-marked line of cleavage which was inclined at about 70° to the axis of the specimen, and was nearly in the direction of the major axis of the cross-section. The direction of this line agrees very closely with that of the intersection of the $1\bar{1}1$ and $11\bar{1}$ planes. It is estimated that the local reduction of area before fracture must have been at least 90 per cent. It may be remarked that in the case of the Haigh specimen BLL7A, the local reduction at fracture was only about 60 per cent. A comparison between Tables 2 and 14 will show that there was no very marked difference in the original orientation of the crystal axis in these specimens, and therefore the large differences between their respective reductions of area can only be accounted for by the difference in the nature of the tests.

4. *Behaviour of Single Crystals subjected to Slow Cycles of Repeated Tensile Loading.*

*Tensile Tests on Specimen No. BLL*13.—The main object of these tests was to investigate the behaviour of a single crystal of aluminium when subjected to slow cyclical variations of tensile stress. In particular, information was sought on the following points :—

(*a*) The extent, if any, to which a single crystal conforms to Hooke's Law.

(*b*) The nature of the stress strain diagram when the limit of proportionality has been exceeded.

(*c*) The effect of subsequent slow reversals of load on the initial stress strain diagram.

In general, it was hoped to effect a comparison between the cyclic state of a single crystal and that of an aggregate.

The specimen was of the form shown in fig. 1, having a circular cross-section of area 0·2424 sq. in. The testing machine used was of the single-lever type, with a maximum capacity of 500 lbs. Strains were recorded by means of a mirror extensometer of the Marten's type over a gauge length of 4″. Readings of the extensometer scale could be estimated to 0·1 mm., corresponding to an extension of 2×10^{-6} inches between the gauge marks.

The maximum loads of the cycles studied varied from 40 lbs. (stress : 0·073 tons/inch^2) to 500 lbs. (stress : 0·92 tons/inch^2). Considerations of space forbid a full description of the many cycles of loading applied.

The results are summarised below, only a few typical and important features being described in full.

Range of Loading 10–40 *lbs.*—Under the first reversal of this range of loading, a small but perceptible permanent set resulted. After a few subsequent reversals, no further permanent set could be detected. The total strain was, however, so small that the existence or absence of a hysteresis loop at this range cannot be stated. The readings taken during the first reversal are plotted in fig. 4 (*a*).

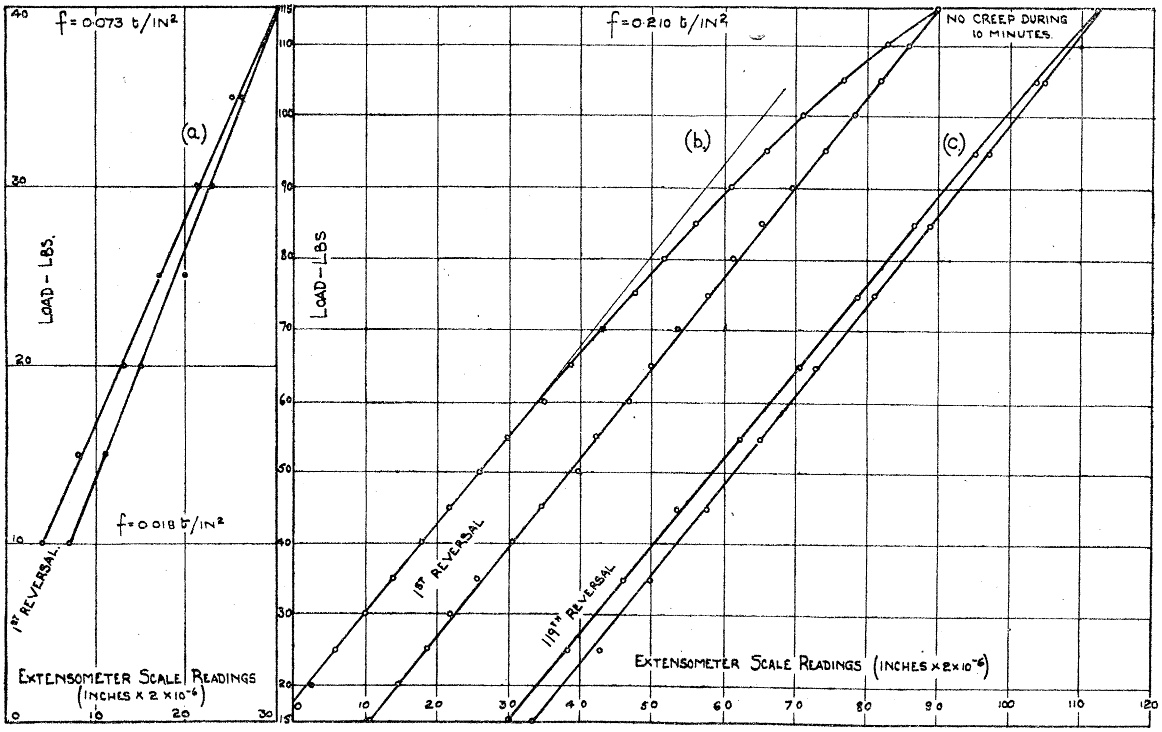


Fig. 4.

Range of Loading 10–60 *lbs.*—On increasing the maximum load of the cycle to 60 lbs., a permanent set was again recorded during each of the first three reversals. No set was detected on subsequent loadings. Again it was impossible to obtain information as to hysteresis.

Range of Loading, 15–115 *lbs.*—The readings taken during the 1st reversal of this range have been plotted in fig. 4 (*b*). It will be seen that the stress-strain relation was approximately linear up to the maximum load of the cycles previously applied. The unloading curve was linear to the order of accuracy of the extensometer. There was a marked permanent set. After 119 reversals of this range of load, the permanent set occurring in each cycle had diminished considerably, but had not disappeared entirely. The 119th reversal has also been plotted in fig. 4 (*c*). Evidently the number of reversals was insufficient to produce a cyclic state in the specimen.

Range of Loading, 20–500 *lbs.*—The complete load elongation diagram obtained during the first cycle of loading is reproduced in fig. 5. It will be seen that marked discontinuities occurred at various loads, and it should be pointed out that there is no justification for drawing a smooth average curve through these points. In fig. 5, the portions BC and CD of the curve correspond to equal increments of load, but it will be seen that the strains due to these increments are widely different, being 2060 scale divisions in one case as against 270 in the other. The actual phenomena observed through the extensometer telescope also differ considerably in the two cases. On raising the load to the point corresponding to C, there is an appreciable time-lag before any movement is detected. The specimen then commences to extend, the rate of extension increasing to a maximum and then decreasing rapidly until movement ceases, the total time of movement being of the order of 3 or 4 seconds. On the other hand, the whole movement over the portion CD is of a slow uniform character with no appreciable lag. In neither case can any creep be observed if the load be maintained for a long time.

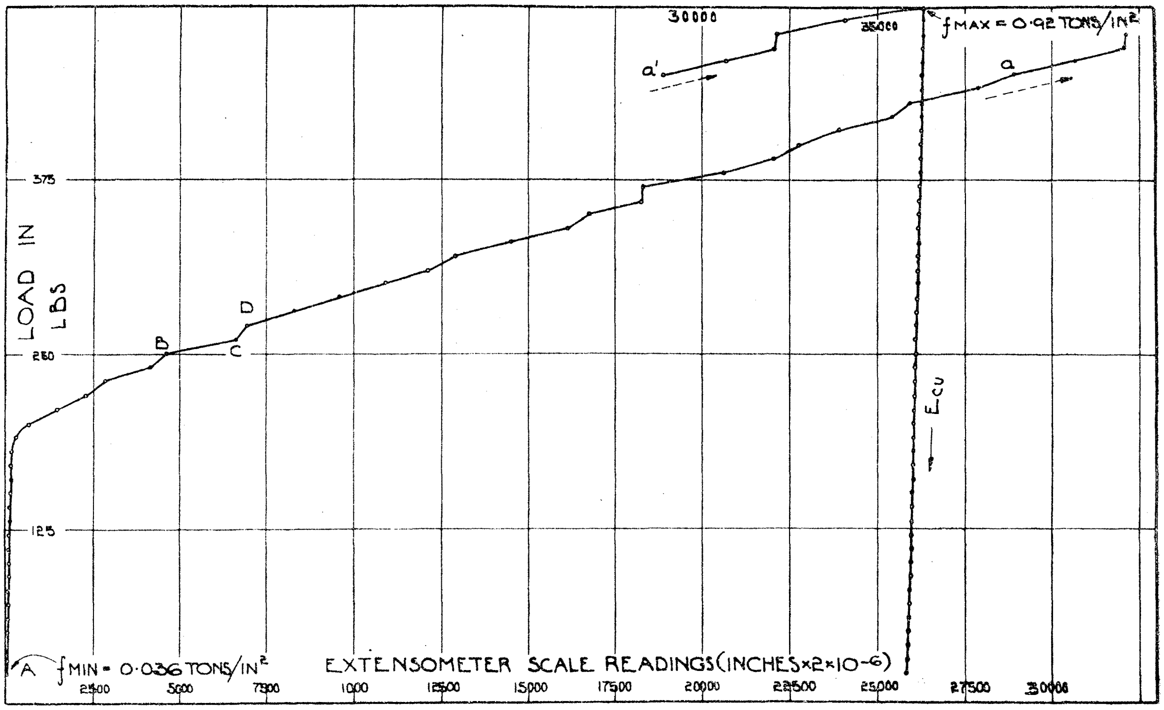


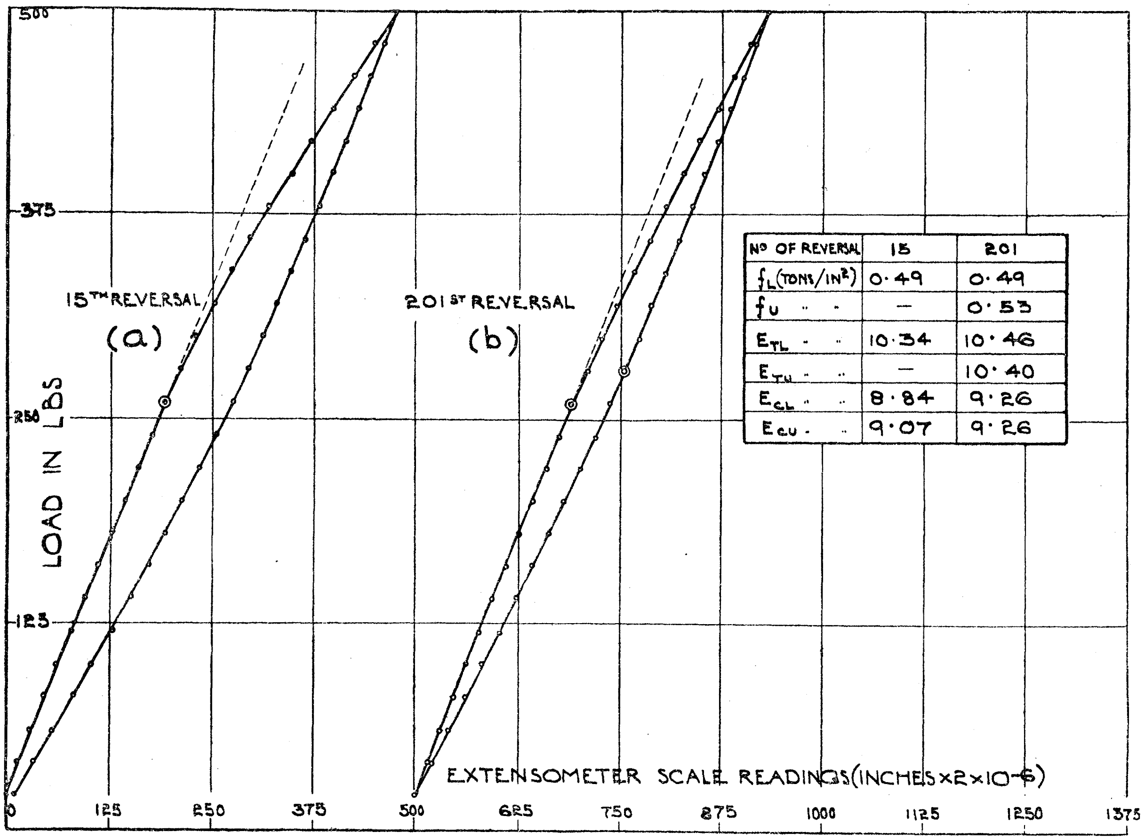
Fig. 5.

The unloading curve plotted to the scale of the figure is apparently a straight line, but when reproduced to a much larger scale it is seen to be concave to the load axis.

Fourteen reversals of the same range of loading were then given, during which the hysteresis loop was steadily closing up. The 15th reversal is shown in fig. 6 (*a*), and it will be seen that the loop is not yet completely closed. A definite limit of proportionality is indicated on the loading curve, but the unloading curve is nowhere linear. It may be mentioned that this type of unloading curve was always associated, in the present tests, with an unclosed loop.

After the 17th reversal, the specimen was subjected to the maximum load for some 17 hours. The next loop (18th) was narrower than either the preceding or the succeeding one. This shows that a single crystal can " recover " under maximum load in exactly the same manner as a crystalline aggregate, but that this " recovery " is only temporary.

A large number of reversals were then given without full extensometer records being taken. After 100 reversals, the loop was still not quite closed, but after 200 reversals a closed loop was obtained. The 201st reversal has been plotted in fig. 6 (*b*).



Nº OF REVERSAL	15	201
f_L (TONS/IN^2)	0·49	0·49
f_U " "	—	0·53
E_{TL} " "	10·34	10·46
E_{TU} " "	—	10·40
E_{CL} " "	8·84	9·26
E_{CU} " "	9·07	9·26

Fig. 6.

The specimen having been put into the cyclic state under the range of loading 20–500 lbs., some experiments were made to investigate the cyclic state under ranges of load whose maximum and minimum loads fall within the limits of the large cycle.

This has been investigated in the case of crystalline aggregates by GUEST and LEA,* and a comparison with their results should be of interest.

The cycle of loading employed in the 202nd reversal was as follows :—20 lbs–500 lbs.–220 lbs.–500 lbs.–260 lbs.–500 lbs.–20 lbs. The readings at 20 lbs. and 500 lbs. were always constant during this test. The general shape of loop obtained is indicated in fig. 7 (*a*), while the readings are plotted in fig. 7 (*b*). In this figure the hysteretic effect has been magnified without reference to total strain, by shearing back the diagram by an amount equal to the elastic strain, this being calculated from the value of E corresponding to the straight parts of the cycle. The specimen was rested for three days. The next loop taken was apparently closed but of smaller width than the 202nd. The effect of rest is again apparent. Under subsequent reversals, the loop widened out and very small permanent sets were recorded.

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* 'Roy. Soc. Proc.,' A, vol. 93, p. 313 (1916-17).

Eventually after 100 reversals a closed loop of constant width was obtained. Figs. 7 (*c*) and (*d*) show the shape of loop obtained. Six complete cycles of the range of load 500–300 lbs. were then traced. No point was removed from the elastic line DE by more than ± 0·1 mm. scale reading of the extensometer. This figure represents the limit of accuracy of the observations. The long pointed areas superposed on the main diagram of fig. 7 (*d*) represent the limits within which all the readings over this and other subsidiary cycles fell.

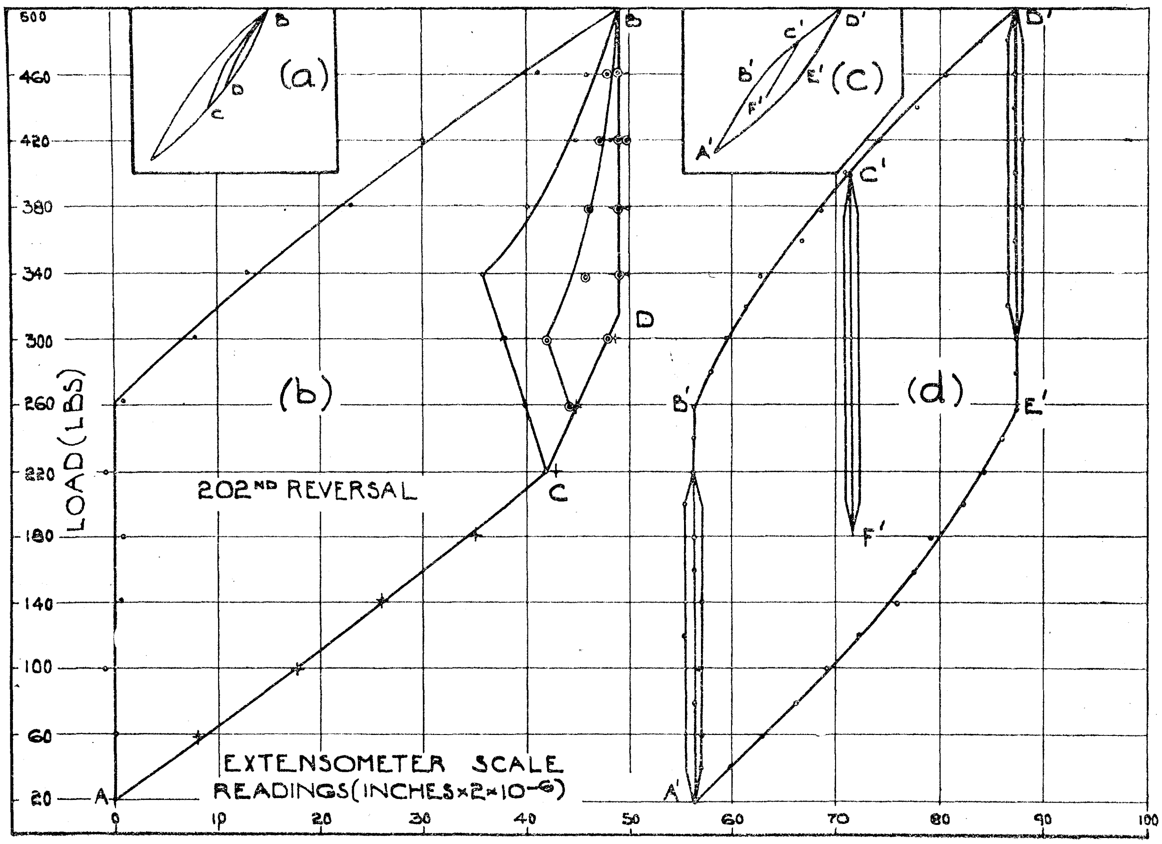

Fig. 7.

During six subsequent reversals of the main cycle, 20–500 lbs., the points followed exactly their original path. The range 20–220 lbs. was then examined, and gave results precisely similar to those recorded for the 500–300 lbs. range. After a rest of 15 hours the specimen was given 50 reversals of the full range, after which a loop was traced which was similar in all respects to that previously obtained (figs. 7*c* and *d*). The range 400–200 lbs. was then studied, an apparently elastic state being again exhibited. The full range was then applied, and the original path was followed throughout.

The total permanent elongation of the specimen during these tests was 0″·13 on a length of 6″, *i.e.*, 2·2 per cent. The measured reduction of area was 1·9 per cent.

Conclusions Drawn from the Repeated Tensile Tests.

The principal conclusions that result from the above tests are :

(i) The primitive limit of elasticity of the material is less than 0·07 tons/inch^2. Further, the slope of the stress strain diagram at the 10–40 lbs. range of load suggests that no primitive state of elasticity existed.

(ii) Repetitions of loading tended to produce a cyclic state which could not be identified with a state of perfect elasticity.

(iii) When a cyclic state has been reached, the cyclical stress-strain relations corresponded in every respect with the known phenomena exhibited by crystalline aggregates.

General Conclusions Drawn from the Results of the Present Research.

(1) The crystals possessed no primitive state of elasticity ; plastic strain occurring under the lowest stresses applied.

(2) In all the cases studied, this plastic strain consisted of shear in the direction of a principal line of atoms on one or more of the octahedral planes of the crystal. The slip-bands appearing on the polished surfaces of the test-pieces were the traces of these planes.

(NOTE.—It will be seen that the type of distortion encountered in the present experiments where alternating and impact stresses were employed is of the same nature as that previously determined by TAYLOR and ELAM for static tensile strain.)

(3) The effect of slip on any plane was at first to increase its resistance to further slip. At the same time a similar hardening effect was produced on other planes—

(*a*) on planes parallel to the original slip-planes,
(*b*) on planes intersecting the original slip-planes.

The experiments indicated that the resistance to slip was increased in a greater degree on planes of type (*b*) than on those of type (*a*).

(4) The fact that extension always took place under reversed stresses suggests that the resistance to slip on any plane was greater when the normal stress across the plane was compressive than when it was tensile. Apart from this effect, slip in any part of a specimen appeared to be confined to that octahedral plane on which the shear stress in one of the principal atomic directions was the greatest.

(5) The hardening effects mentioned above appear to be connected in some way with a permanent distortion of the lattice of the crystal. A similar conclusion has been reached by several other workers. In particular, CARPENTER and ELAM* suggest that this distortion may be a uniform bending of the crystal planes ; it is considered that the present tests do not confirm this view.

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* 'Roy Soc. Proc.,' A, vol. 107, p. 174 (1925) (references to other workers are also given in this paper).

If the very great hardening effects produced by strain are to be explained by a uniform curvature of the lattice planes, it would appear that this curvature must be great. On the other hand, no difficulty was experienced in making X-ray analyses of the crystals in their most advanced stages of strain. A certain deterioration in the sharpness of the spots was recorded, together with an increase in the range of setting angles over which reflections from a particular plane were obtained; but no greater discrepancies occurred in the inclinations of the reflecting planes to one another, than were found in unstrained crystals. Unless any uniform curvature of the planes was very slight, these inclinations would be liable to vary considerably from their theoretical values.

Further, the agreement between the planes deduced from the observed slip-bands and those found by X-ray analysis was as close in the final stages of the tests as it was in the earlier stages. Since the X-ray figures are deduced generally from single reflections from portions of the plane necessarily near the surface, while the experimentally determined slip-planes were based on at least four measurements of inclinations of slip-bands, such agreement would not be found if any considerable uniform curvature existed.

These considerations indicate that the distortion of the crystal planes is such that the average curvature over a portion whose area is of the same order as that of the X-ray beam is small, while at the same time more severe local curvatures may exist. The type of distortion which the authors have in mind may be described as a "rumpling" of the planes. In such a case, large local strains in the lattice would exist in the neighbourhood of the "peaks" of the distorted planes. The authors suggest that local breakdown of the crystal begins when any of these strains exceeds a certain limiting value. Small discontinuities produced in this way would not necessarily lead to immediate fracture, particularly under a static load. A distortion of the type outlined above would, however, necessarily be accompanied by uneven stress distribution on the slip planes themselves. A probable consequence of this would be further slip during the unloading portion of repeated stress cycles, accompanied presumably by an adjustment of the distortion of the planes. In this way an accumulation of discontinuities, leading eventually to fracture, might be expected under repeated application of a load considerably lower than that necessary to produce fracture on a single application.

The work has been carried out for The Aeronautical Research Committee in The Engineering and Metallurgical Departments of The National Physical Laboratory. Reference has already been made to the authors' indebtedness to Miss C. F. Elam, M.A., for her invaluable assistance, and they also wish to acknowledge the help of Mr. W. M. Wheeler, Laboratory Attendant, who has carried out the necessary photographic and polishing work, and whose skill and care have so largely contributed to the progress of the research.

DESCRIPTION OF PLATES.

PLATE 1.

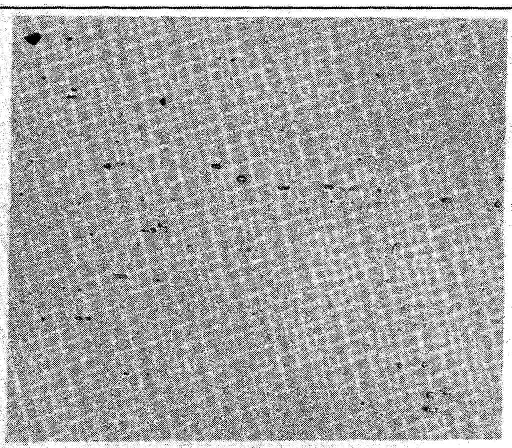
Fig. 1.—BLL7A, after preliminary polishing and etching. (×105.)
,, 2.—BLL7A, ,, $6{\cdot}834 \times 10^{6}$ reversals of $\pm 0{\cdot}0394$ tons load : at reference mark 9. (×105.)
,, 3.—BLL7A, ,, $3{\cdot}382 \times 10^{6}$,, $\pm 0{\cdot}071$,, ,, ,, 4. (×105.)
,, 4.—BLL7A, ,, $3{\cdot}382 \times 10^{6}$,, $\pm 0{\cdot}071$,, : Gap at reference mark 8. (×105.)
,, 5.—BLL7A, ,, $0{\cdot}054 \times 10^{6}$,, $\pm 0{\cdot}104$,, : at reference mark 5. (×105.)
,, 6.—BLL7A, ,, $0{\cdot}054 \times 10^{6}$,, $\pm 0{\cdot}104$,, ,, ,, 8. (×420.)

PLATE 2.

Fig. 7.—BLL7A, after $0{\cdot}220 \times 10^{6}$ reversals of $\pm 0{\cdot}251$ tons load : near reference mark 11. (×105.)
,, 8.—General appearance of BLL7A after " necking."
,, 9.—BLL7A, after " necking " : at end of minor axis. (×105.)
,, 10.—BLL7A, ,, ,, ,, ,, (×105.)
,, 11.—LAUÉ photograph through " necked " portion of BLL7A.
,, 12.—BLL8A, after $0{\cdot}247 \times 10^{6}$ reversals of $\pm 4{\cdot}44$ inch/lbs. : at reference mark 6. (×105.)

PLATE 3.

Fig. 13.—BLL8A, after $0{\cdot}592 \times 10^{6}$ reversals of $+ 18{\cdot}13$ inch-lbs. : at reference mark 8. (×105.)
,, 14.—View of crack in BLL8A. (×210.)
,, 15.—BLL8A, after cracking : at reference mark 9. (×105.)
,, 16.—Polished cross-section of BLL8A. (×7.) *Note.*—For reference mark 0–9, read 6–0.
Compare diagram on page 19.
,, 17.—BLL11B, after fracture : at end of major axis. (×105.)
,, 18.—BLL11B, ,, ,, ,, ,, (×105.)



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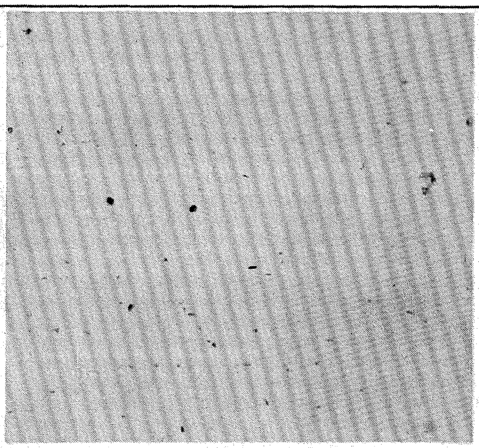

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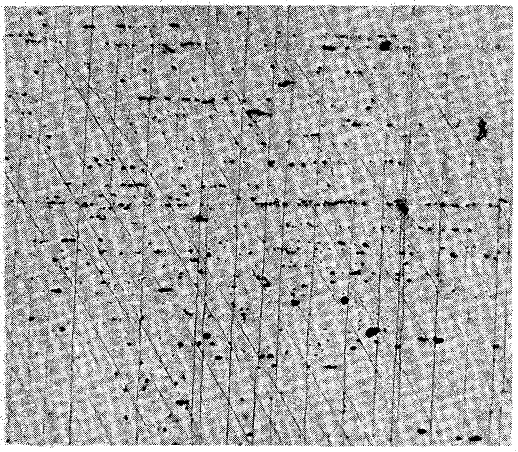

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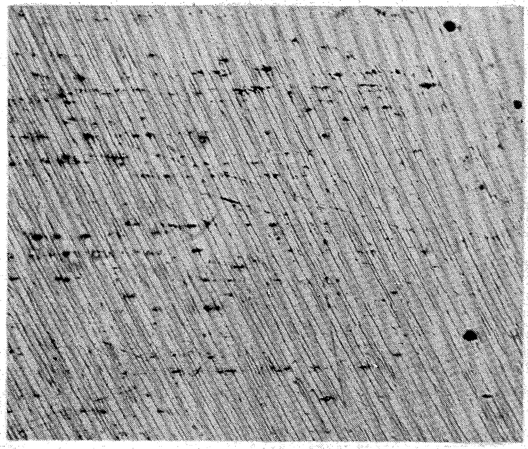

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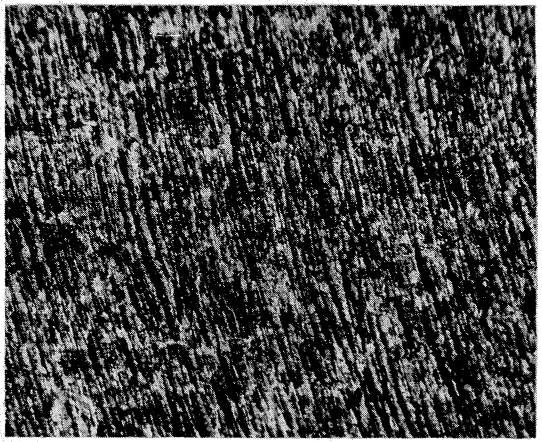

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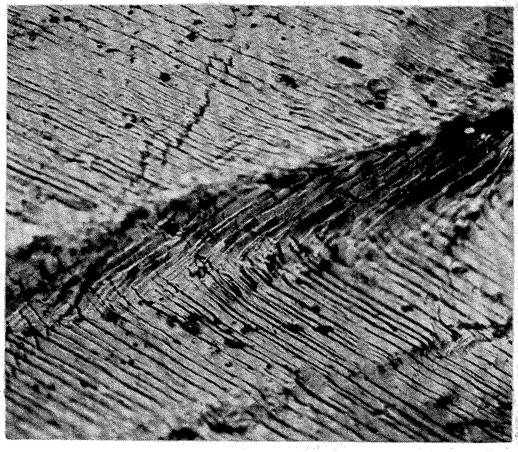

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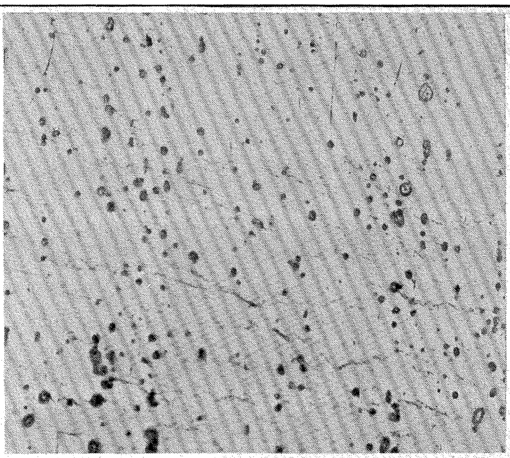

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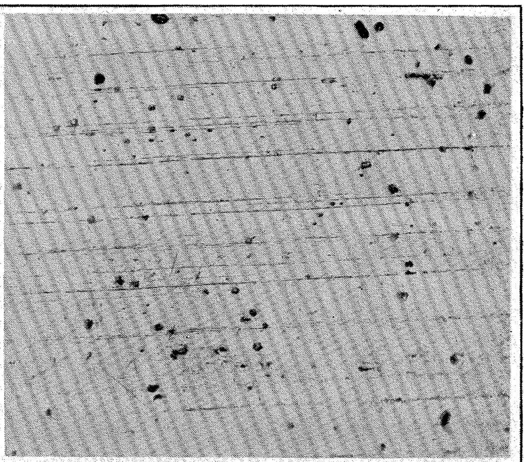

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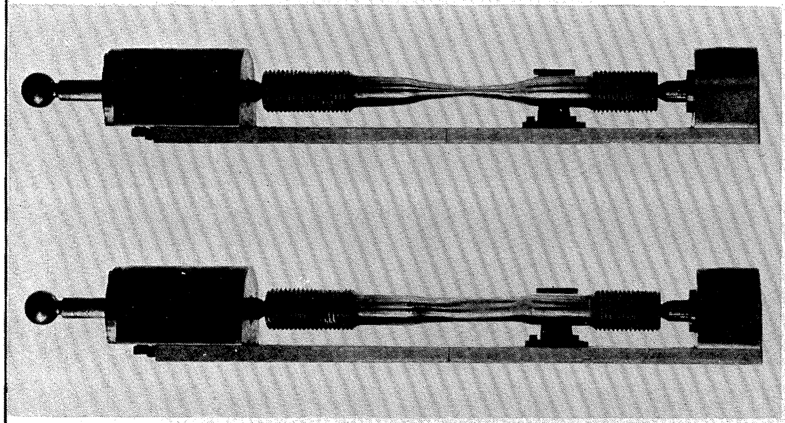

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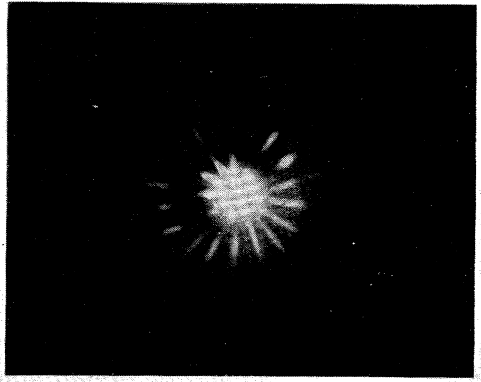

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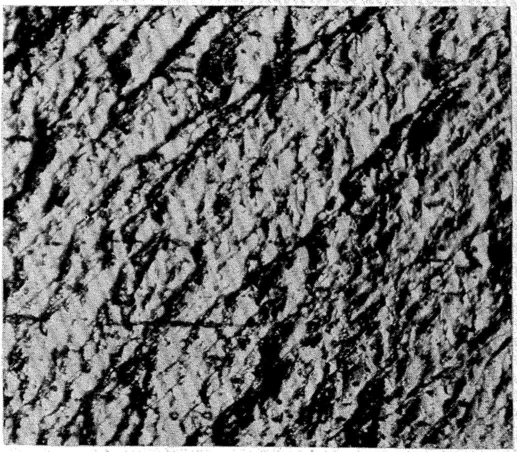

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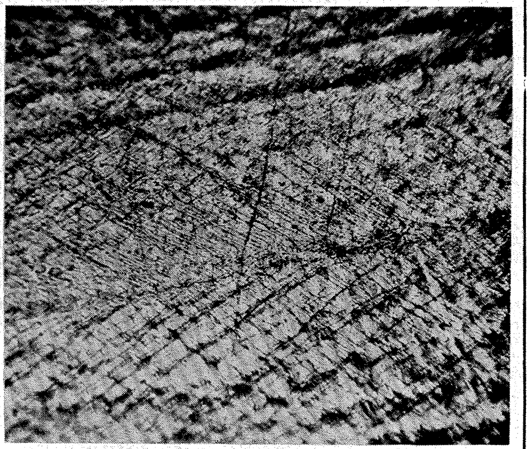

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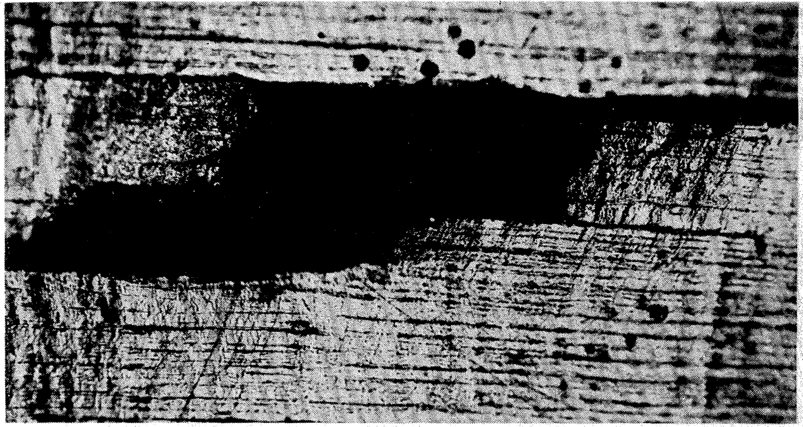

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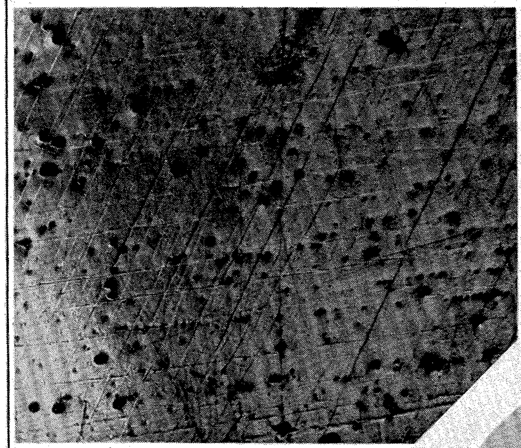

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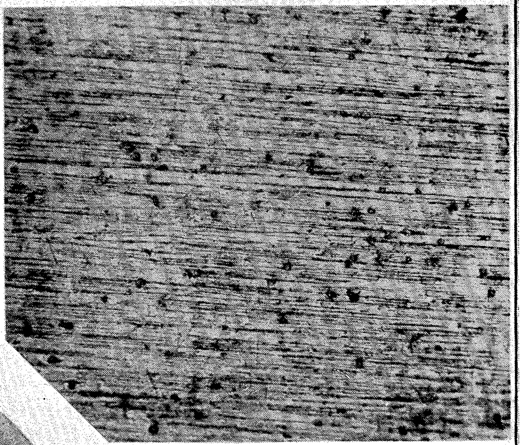

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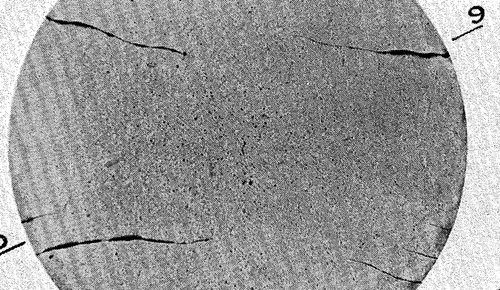

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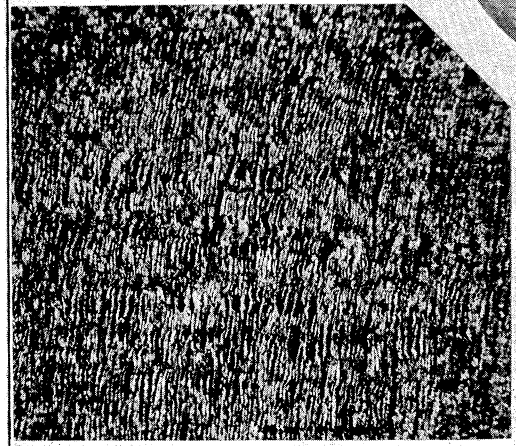

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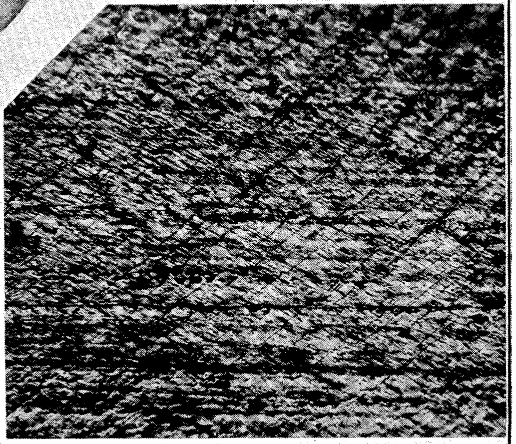

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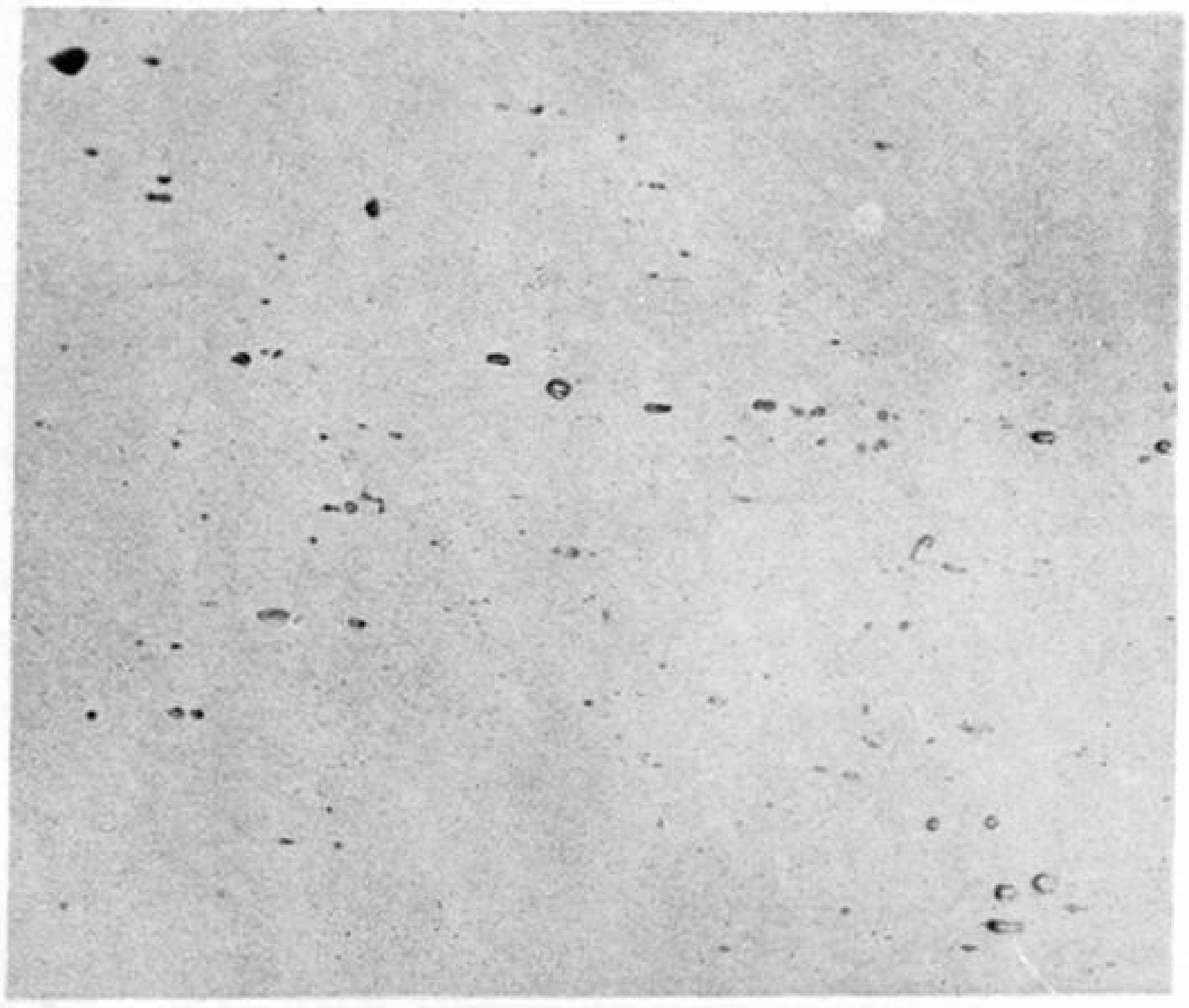
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



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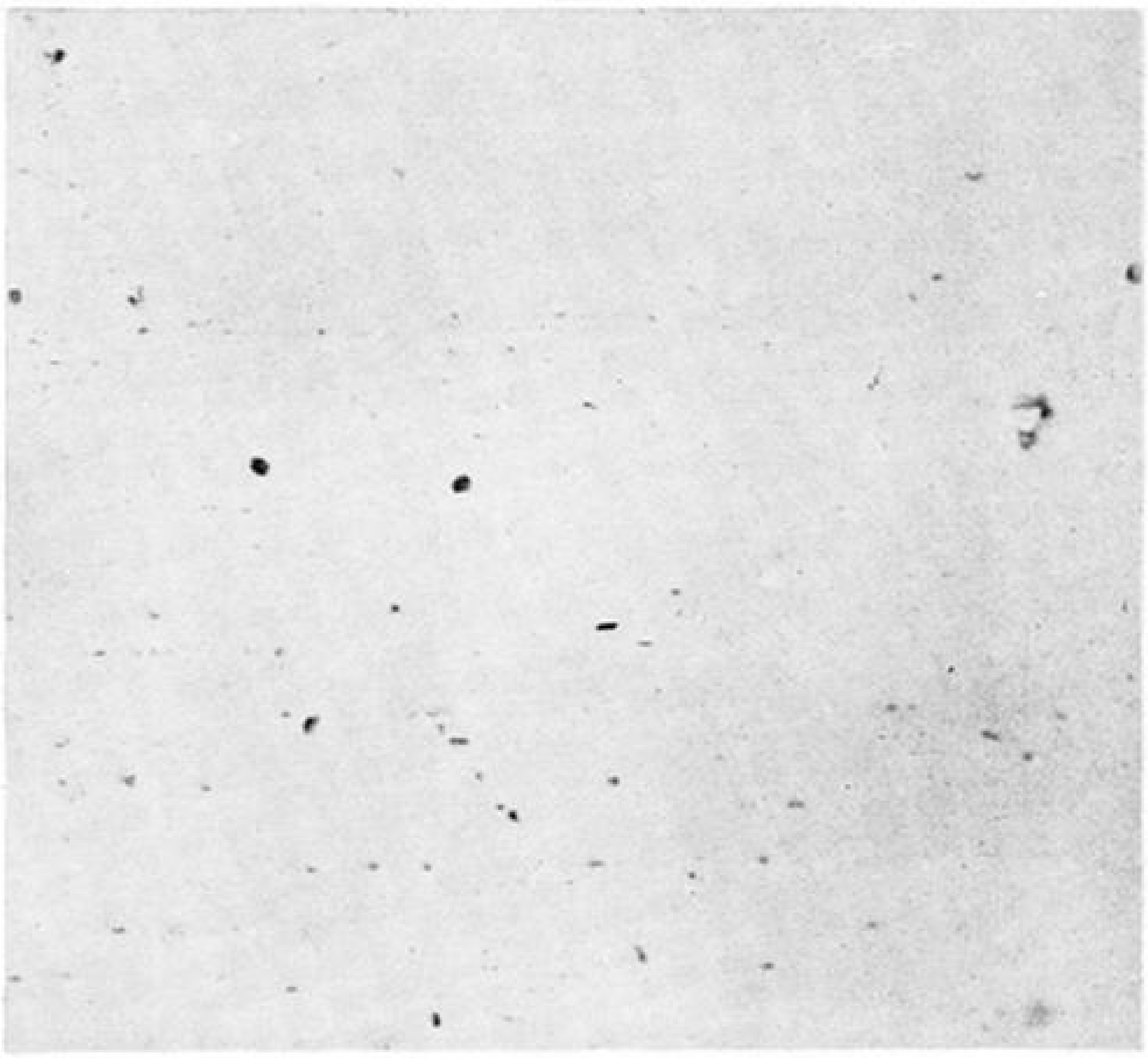

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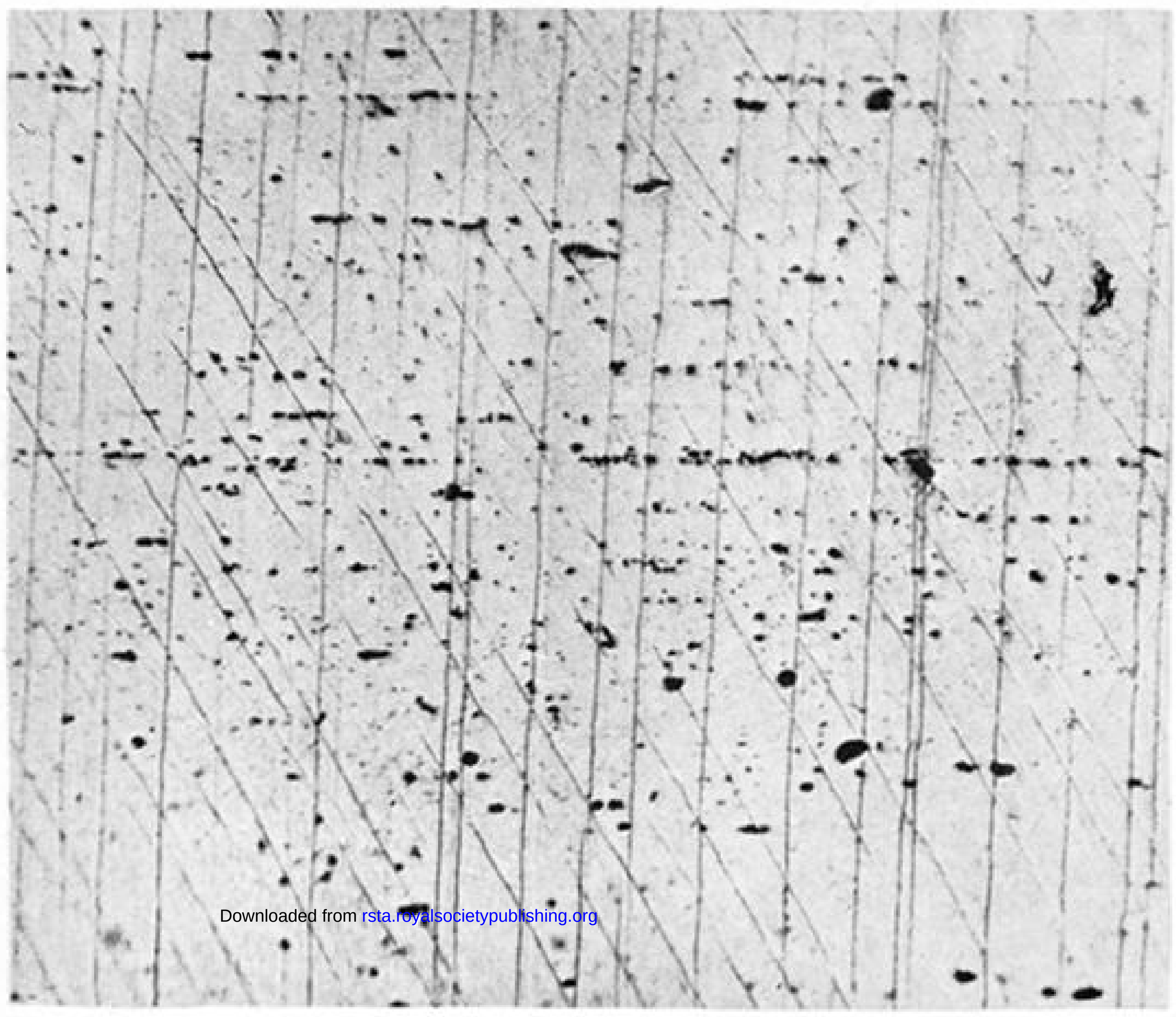

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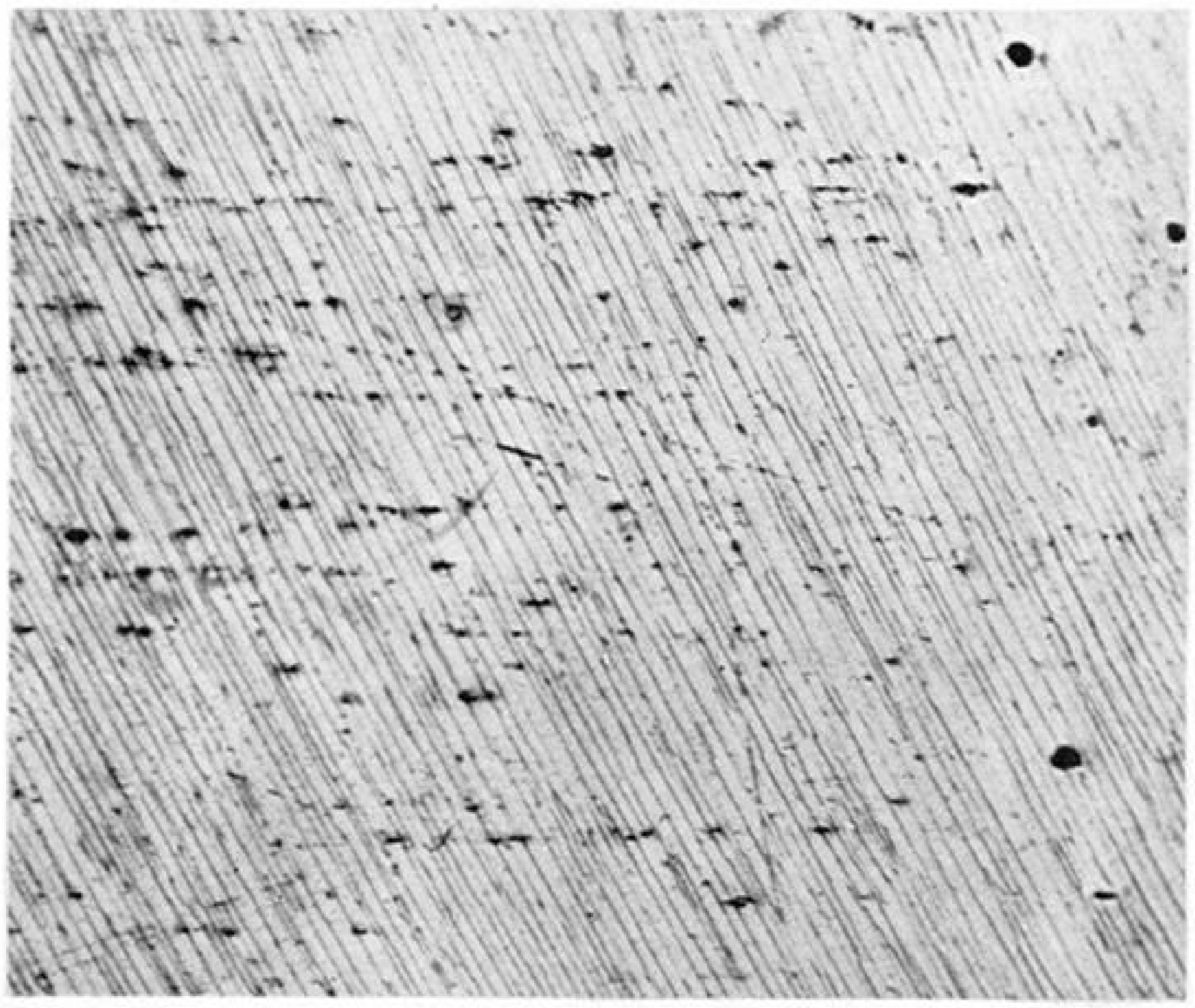

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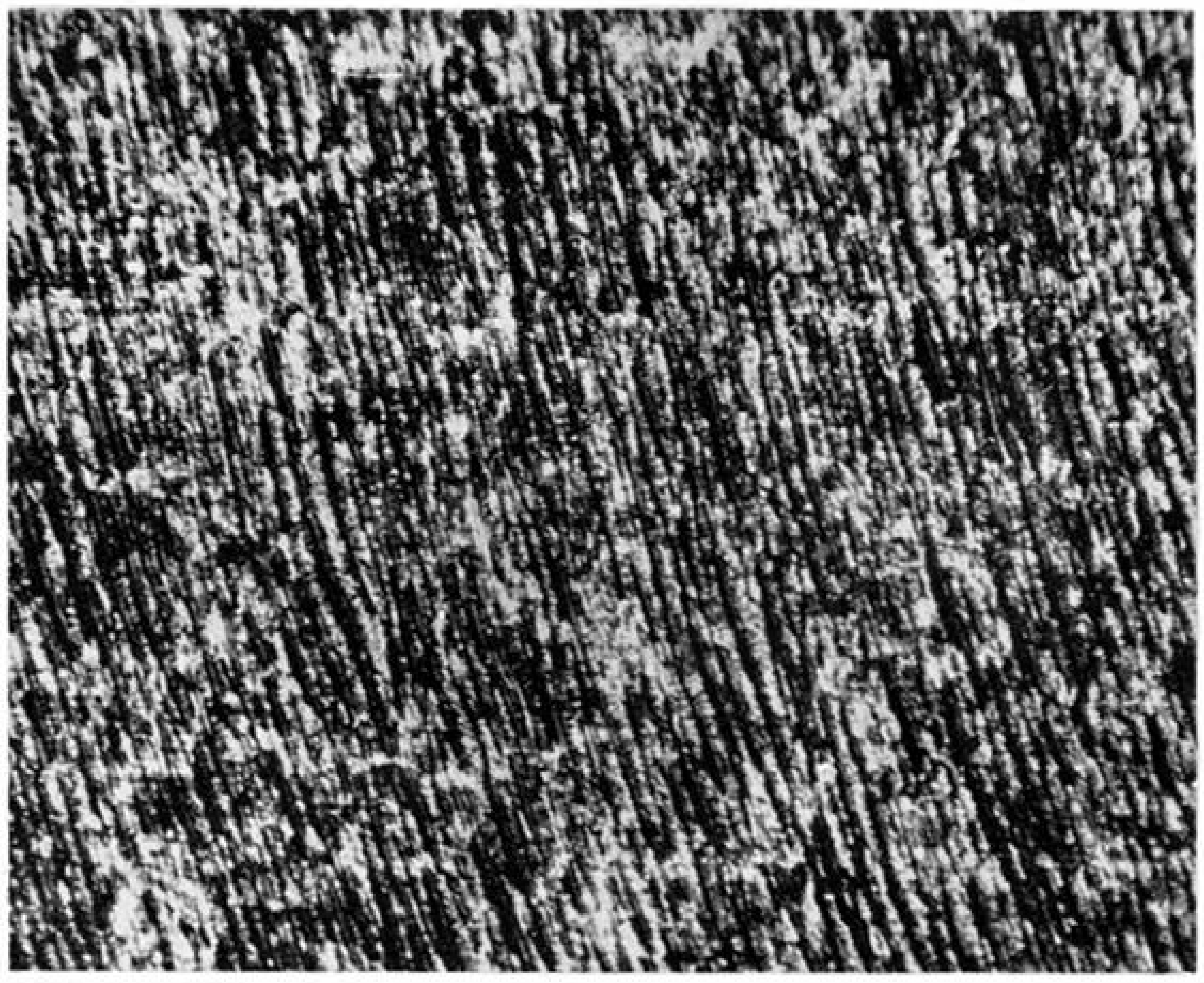

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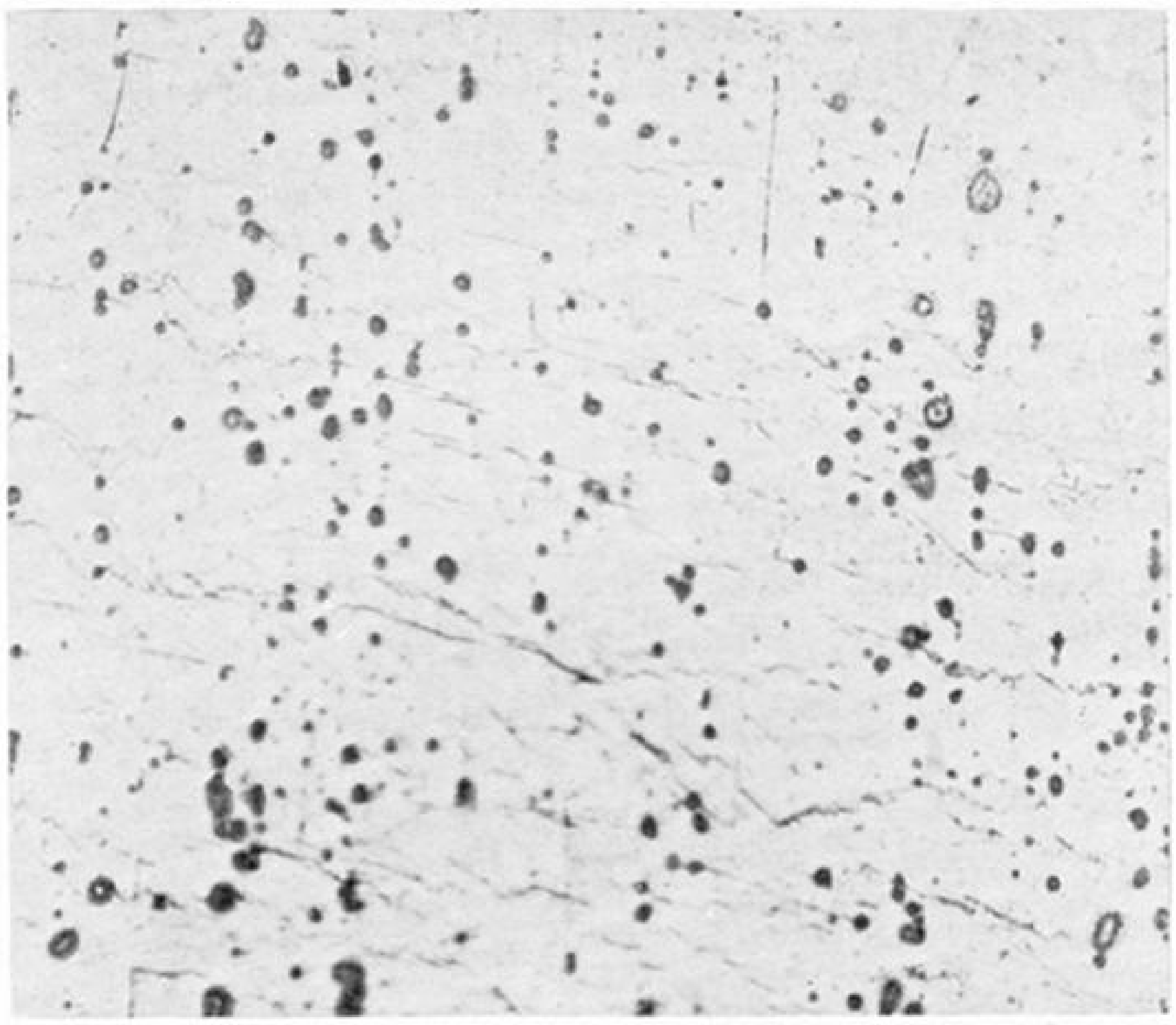

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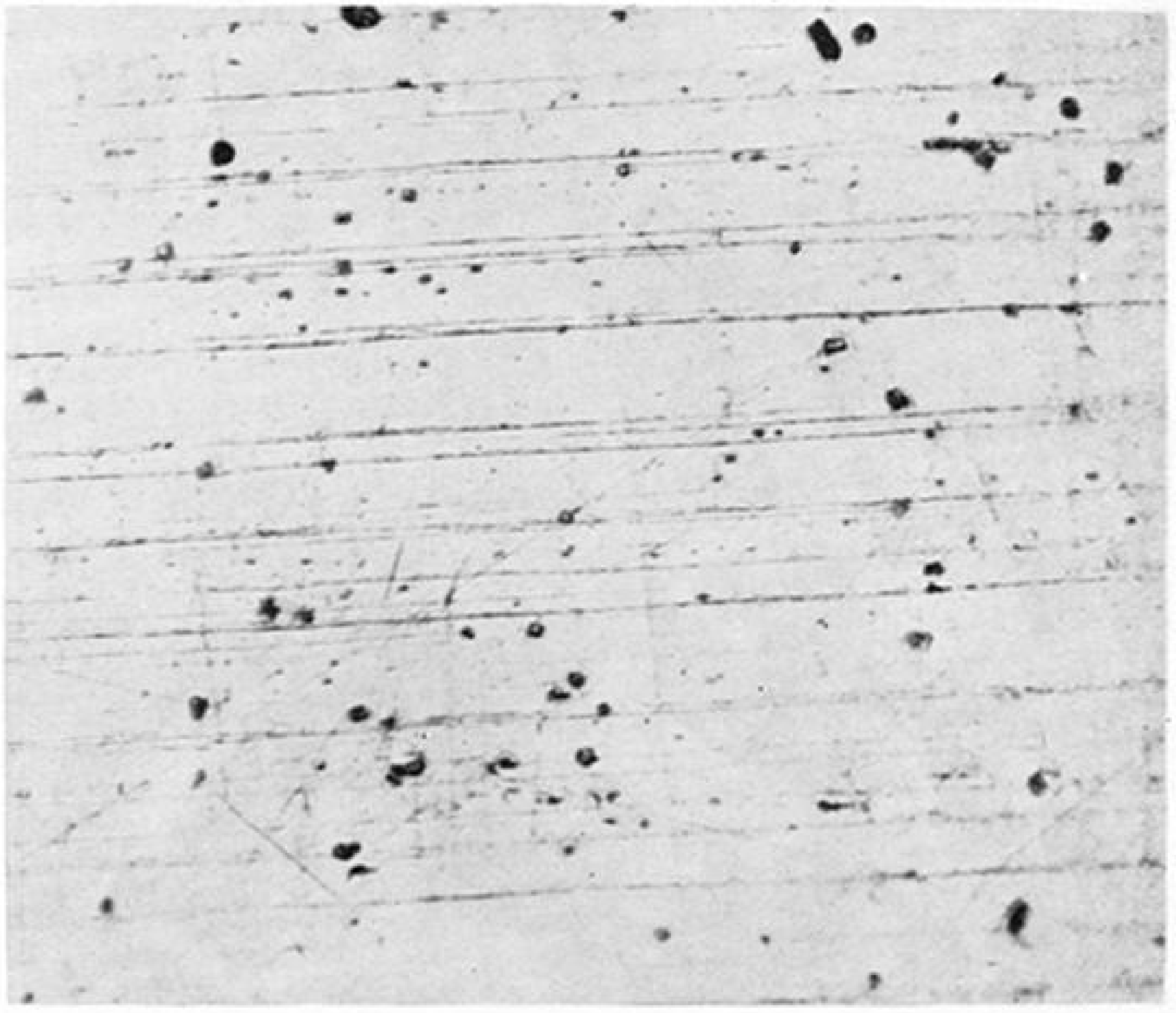

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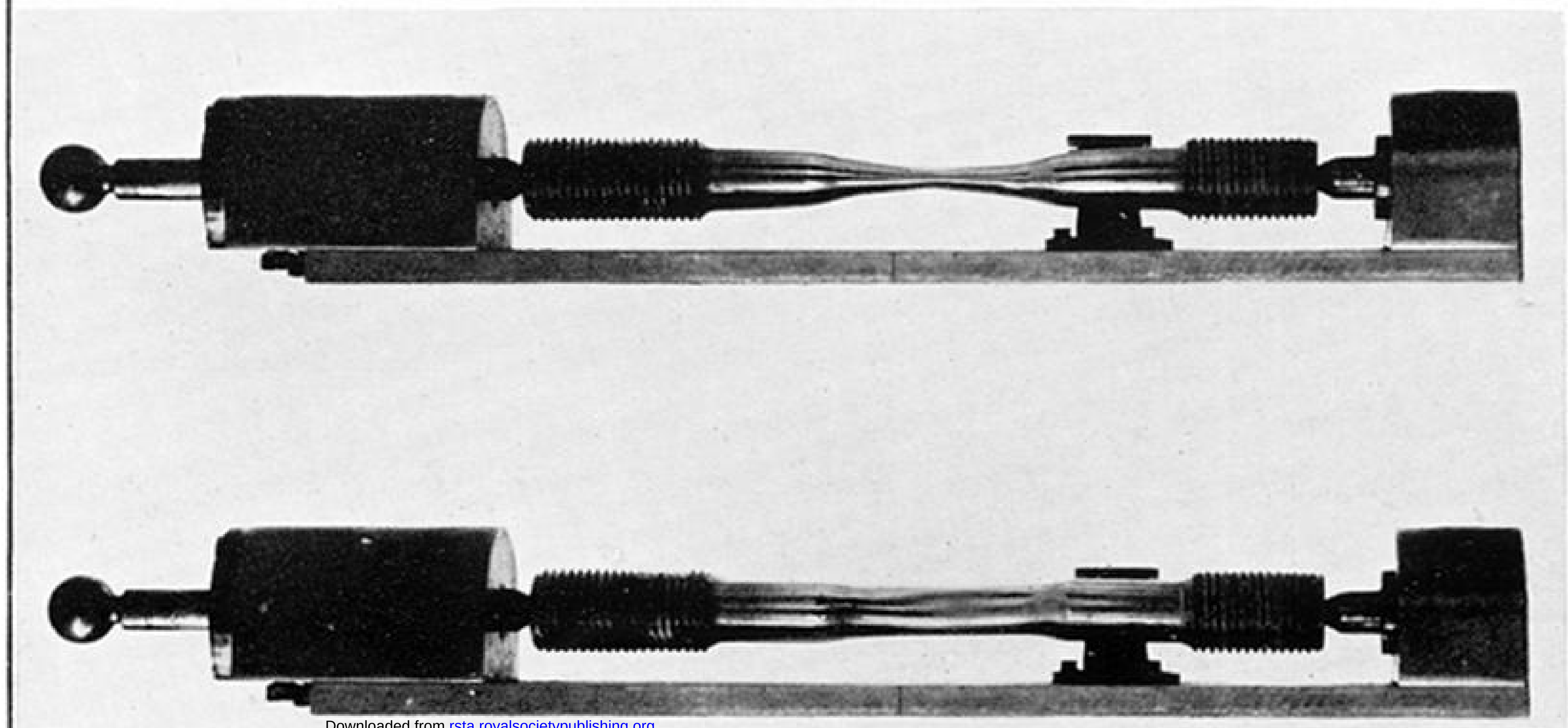

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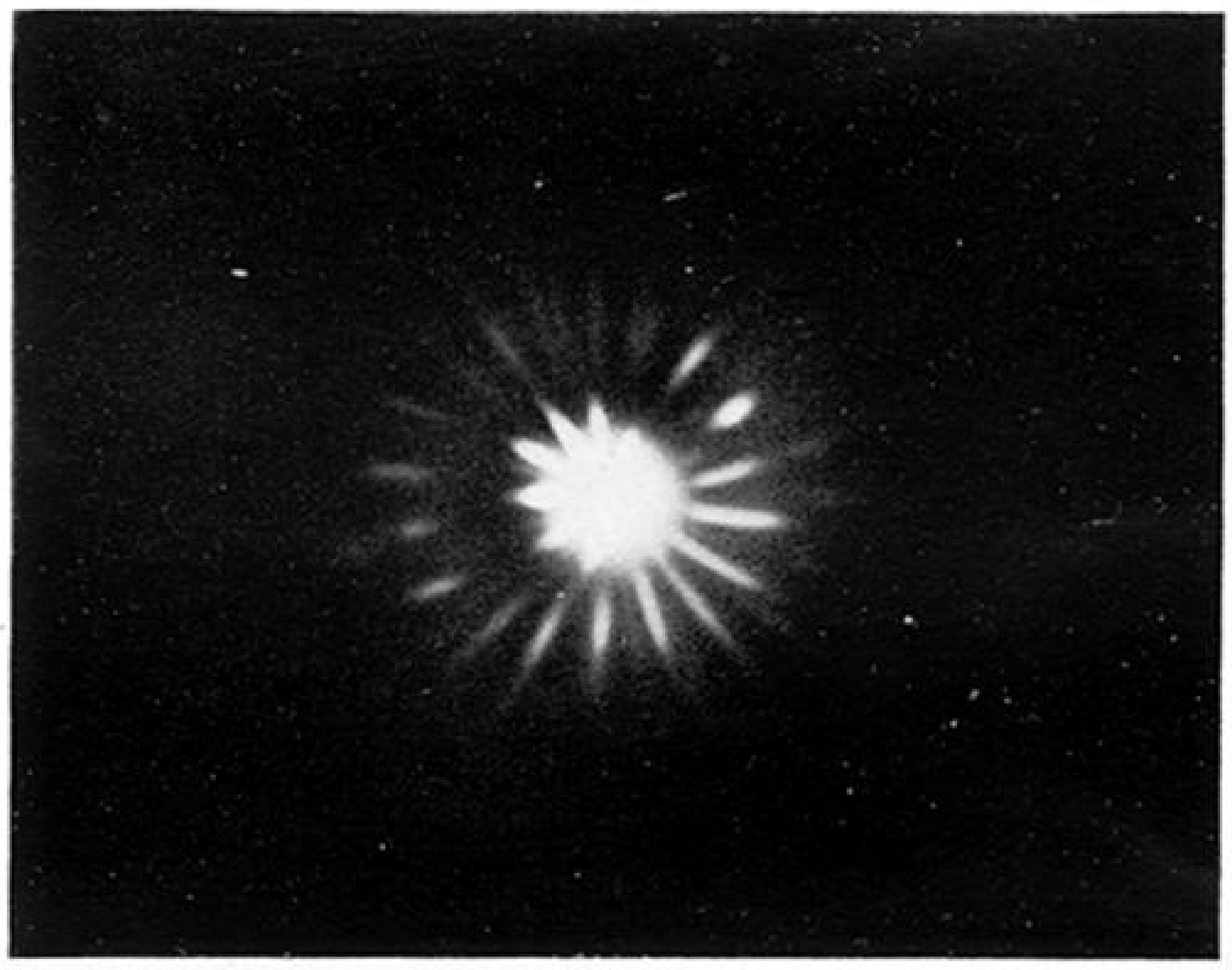

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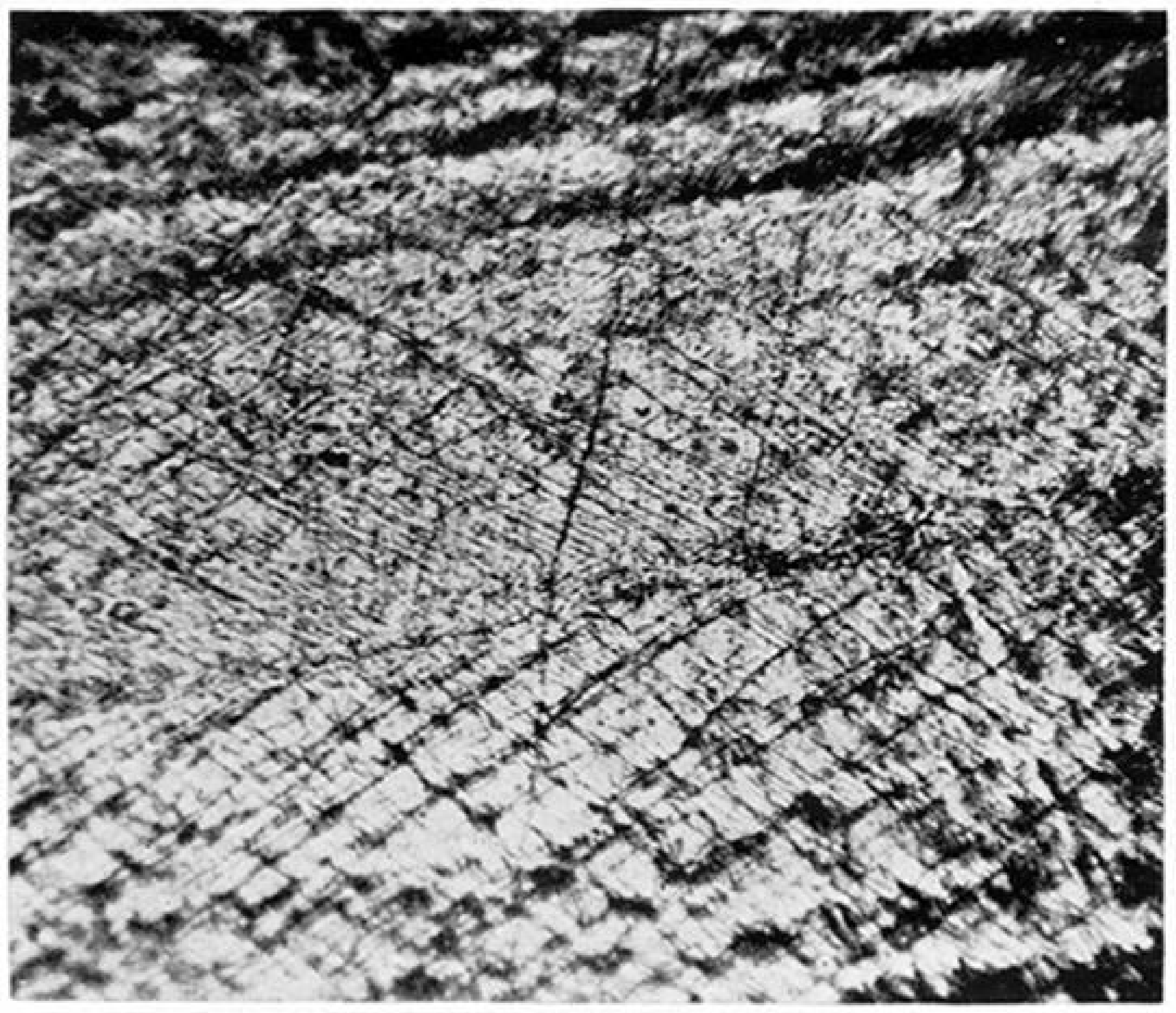

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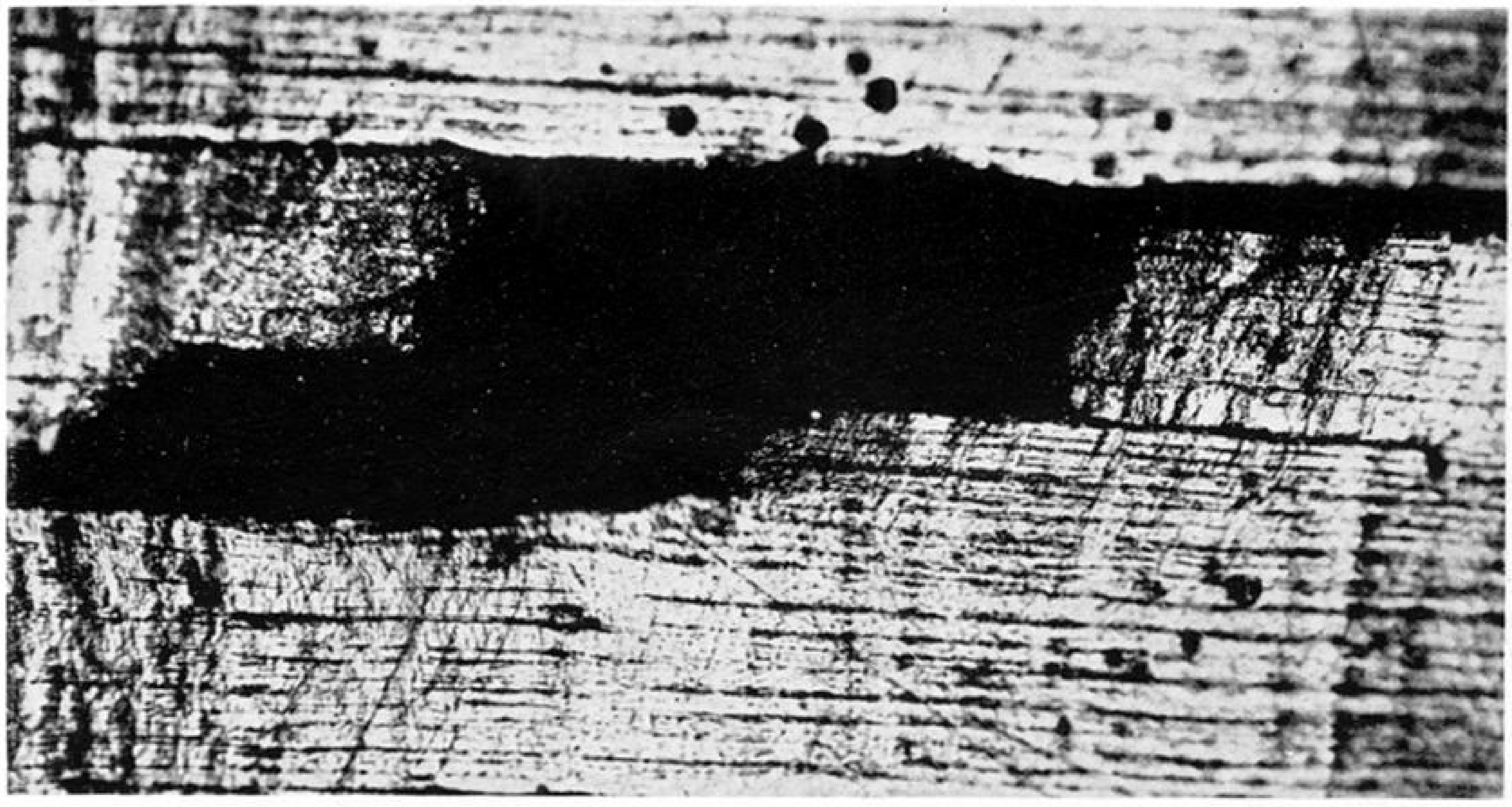

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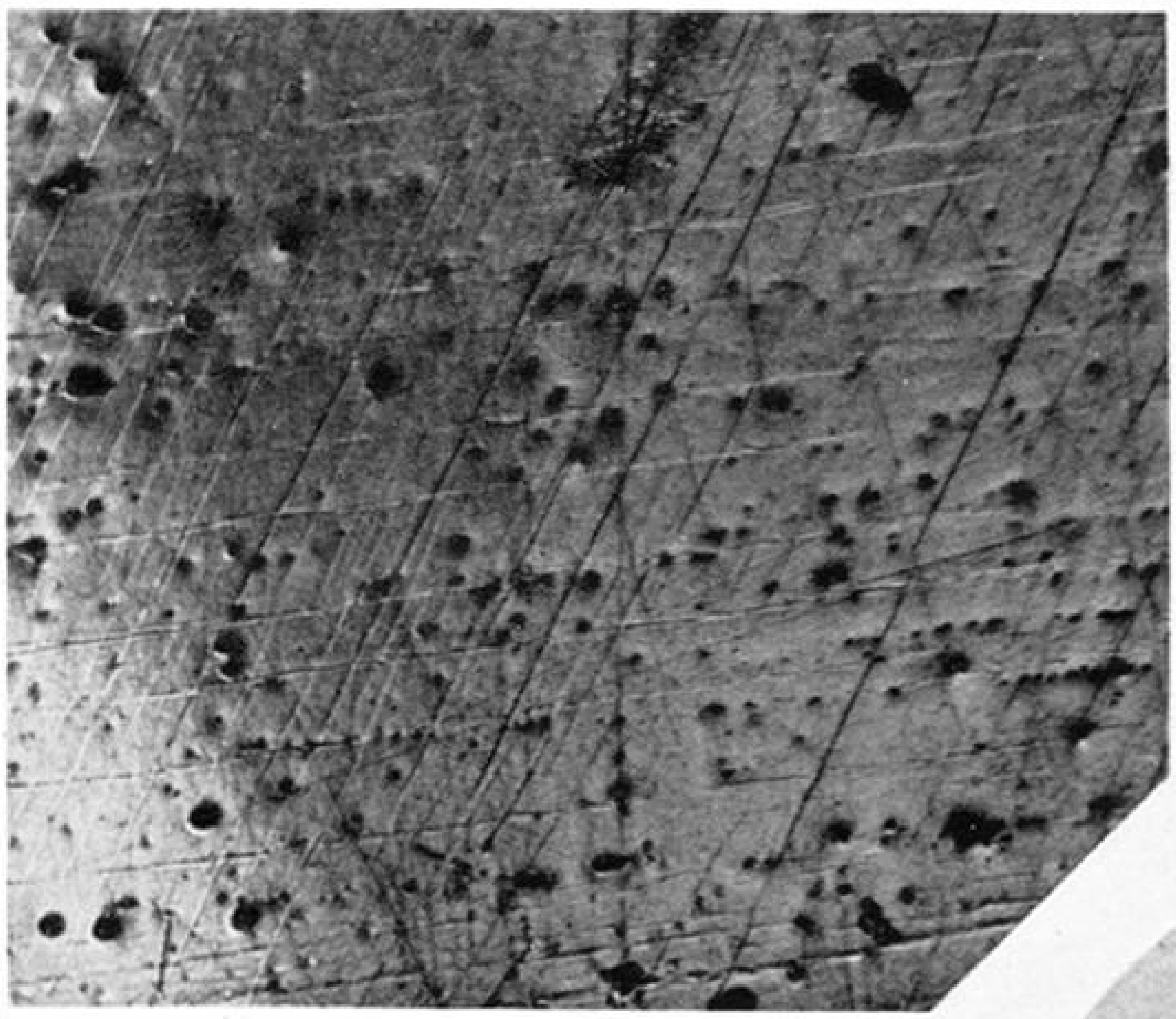

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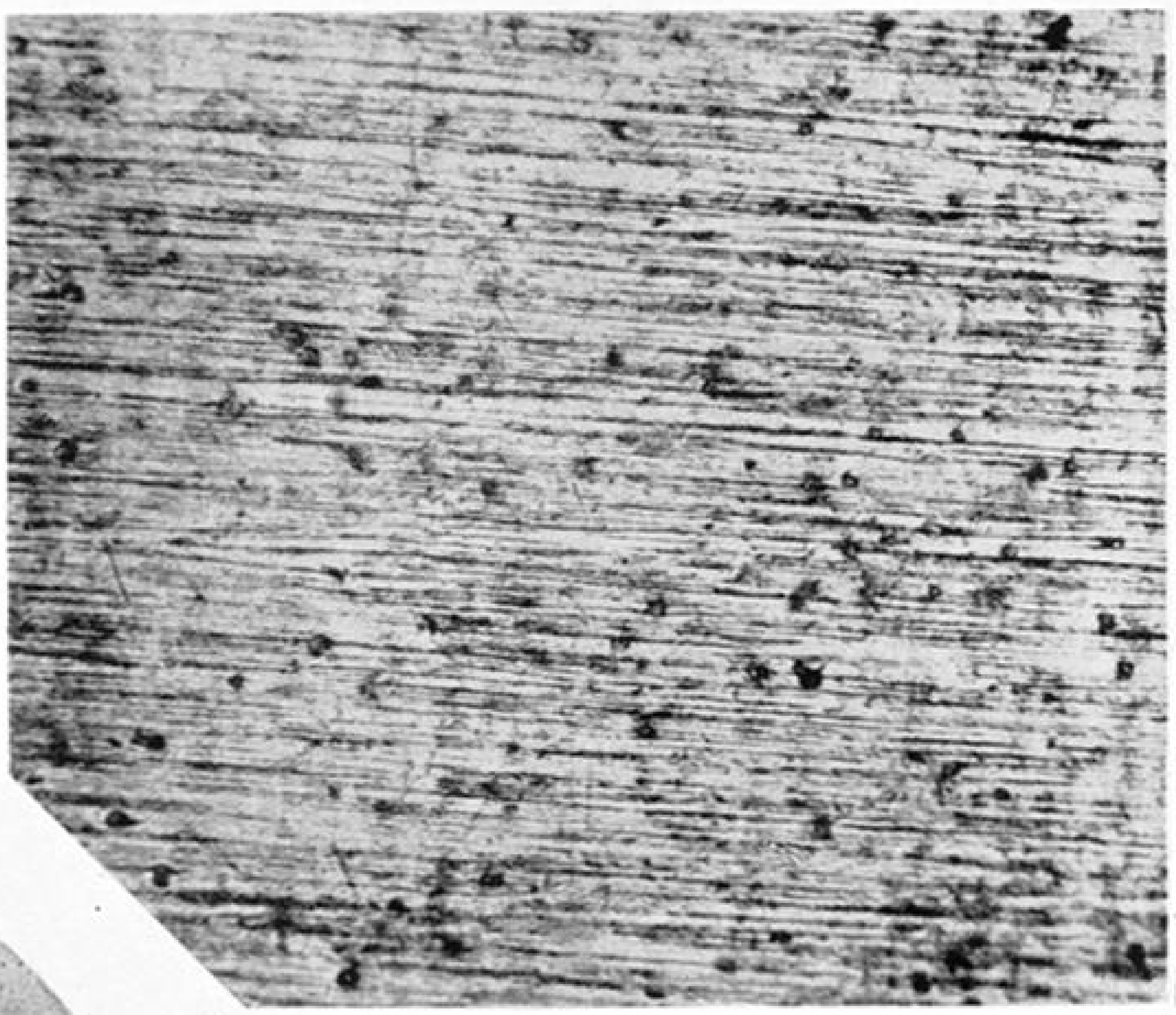

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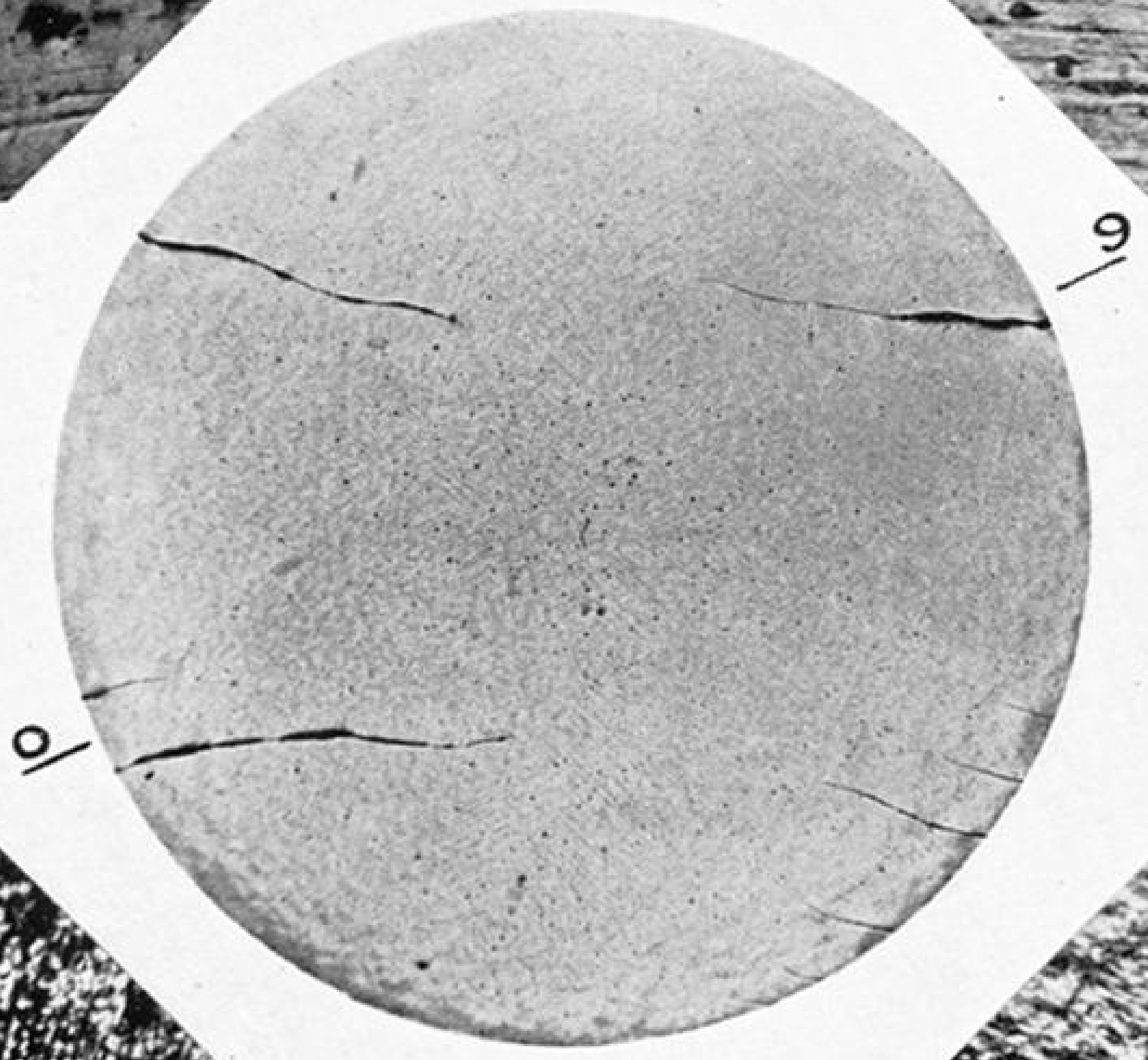

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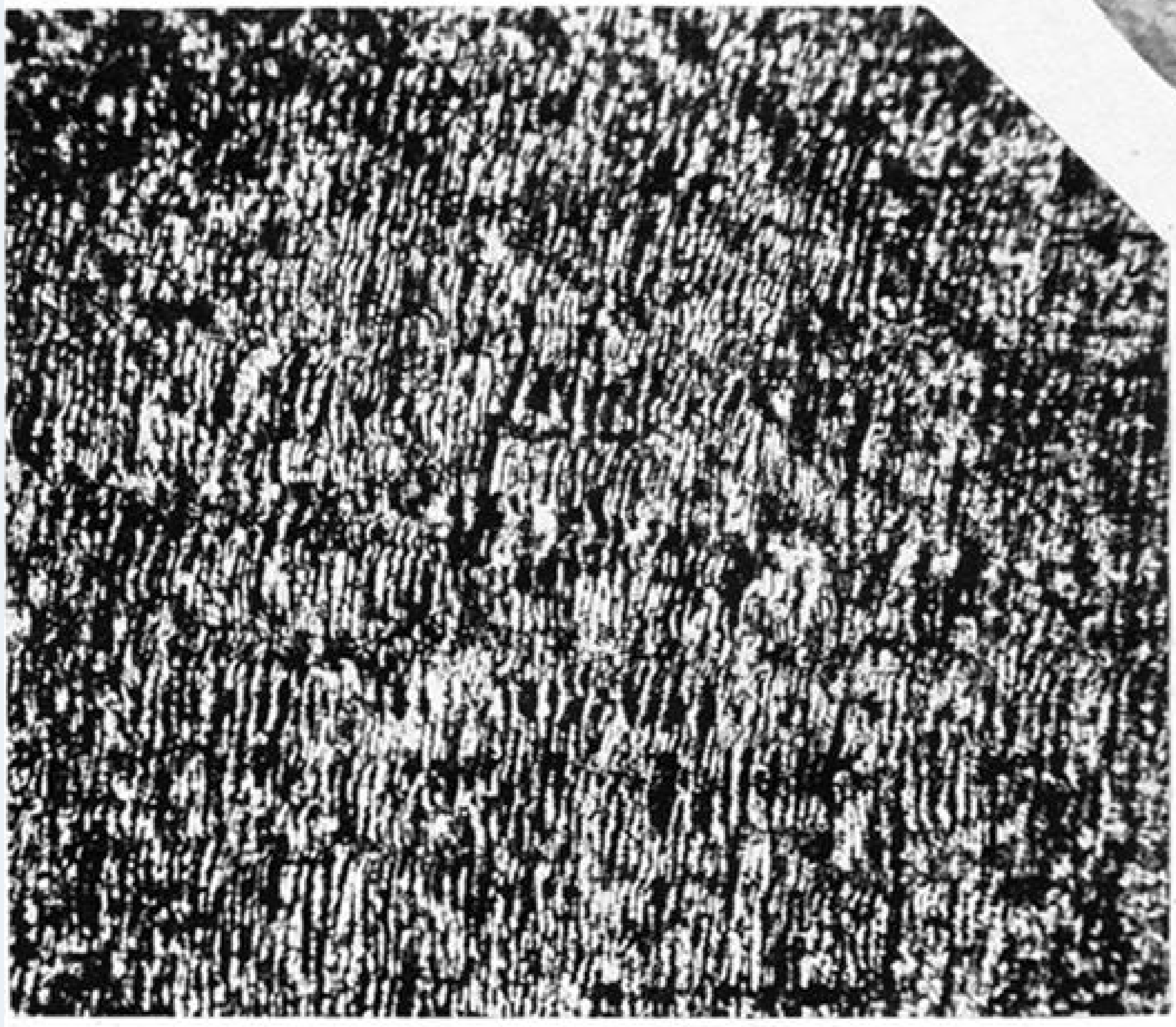

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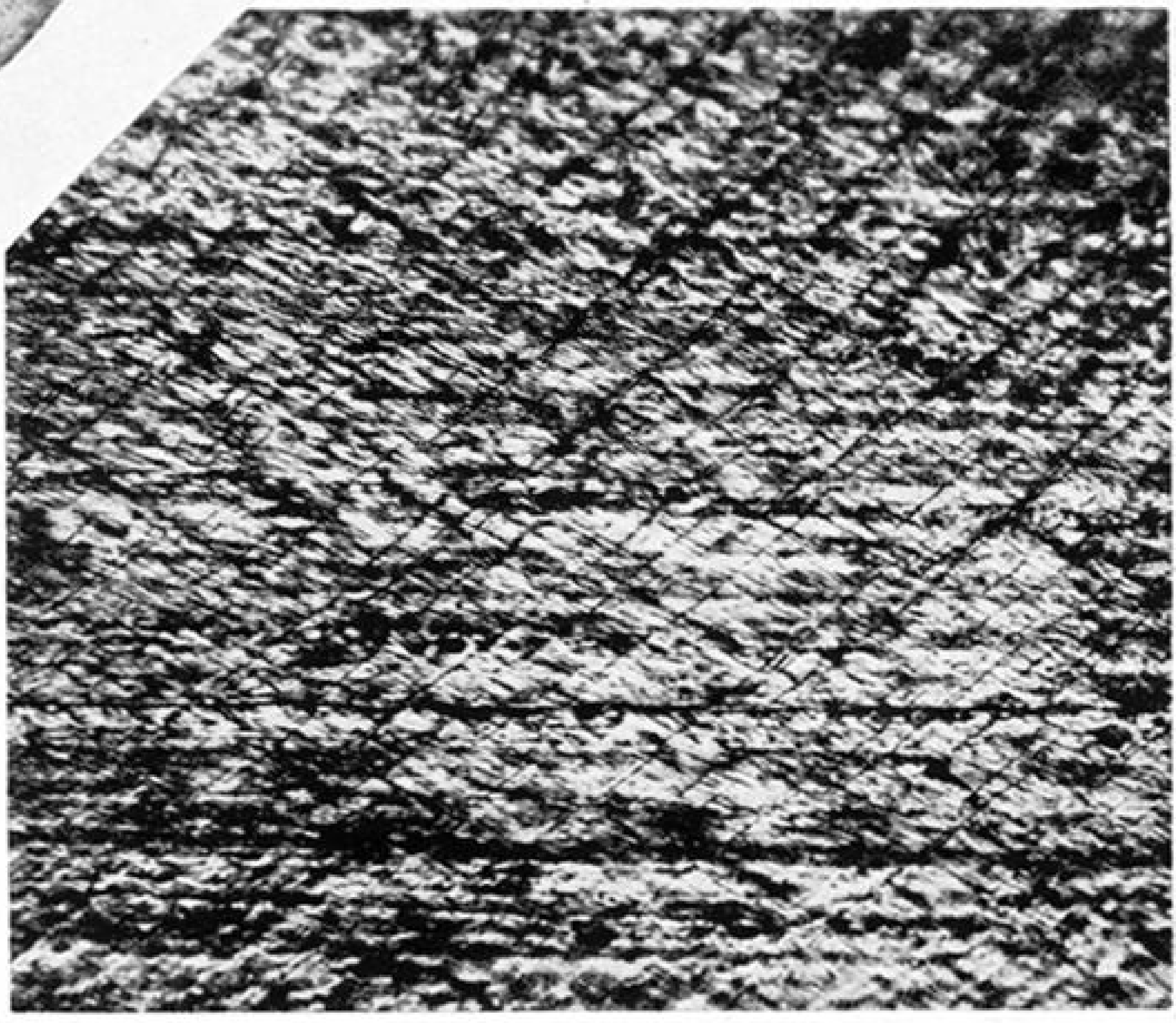

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